Low Frequency Parasitic Effects in RF Transistors and their Impact on Power Amplifier Performances


(1)XLIM-CNRS/University of Limoges,
Outline

- Introduction
- Small signal measurement system
- Thermal and traps characterization
- Large signal measurements
- Impact of trapping effects
- Conclusion
Introduction

• Potential applications of HBTs (GaInP/GaAs, Si/SiGe, InP) and GaAS or AlGaN/GaN HEMTs are numerous
  o For power amplifiers of Radar T/R modules
  o For base stations PA
  o For multi-tone PA in space applications

• All those applications involve complex modulated signals
  o Pulsed, phase/frequency modulated for Radar Systems
  o Highly complex signals (OFDM, X-PSK, …)

• In all these cases the enveloppe of the signals are dynamically varying
Consequences on PA design

- Designing RF Power Amplifiers still represent a very challenging task
  - Technologies are used at their performance limits
  - Efficiency requires highly nonlinear behavior
  - Linearity is mandatory for Telecomm. Applications
  - Large bandwidth is more and more required in modern systems
  - Sub-system integration of PA is targeted
  - Stability (linear and nonlinear) must be achieved
  - Thermal effects must be managed
  - Low Frequency memory effects must be understood and managed

- Tools and methods are required for
  - Characterization
  - Modeling
  - Simulation
PA characteristics

- Linearity and efficiency are conflictual
- Trade-off must be achieved
- PA use transistors which are inherently controlled by 3 independent variables.
- The equation of the drain current is dispersive.
Different ways for characterization/modeling

- Parasitic effects still limit the performances of PA
  - Thermal effects
  - Trapping effects

- Identification through
  - Small-signal characterization
  - I-V (DC and pulse) characterization
  - Large signal characterization (in frequency and time domains)

- All these characteristics should be consistently modeled
Small signal measurements
DC(10Hz)- 40GHz S- parameters measurements

LF Set-up: 10 Hz-100 MHz

HF Set-up: 40 MHz-40 GHZ

HP 4195 A or Agilent E5061B VNA

On Wafer DUT

Thermal control: -65 °C up to 200 °C

Anritsu 37397E
Thermal and traps characterization
HBTs thermal characterization methods

**Optical methods**
- Infrared thermography
- Raman spectroscopy
- Photo reflectance

**Electrical methods**
- Input impedance (Xlim)
- Current gain (O. Mueller)
- Small signal voltage gain (cherepko)

Needs complex equipment and well prepared samples

Dependence on the size of the transistor, external loading

Hybrid parameter feedback coefficient $h_{12}$ as the thermometer
Feedback due to temperature for HBTs

GaInP/GaAs HBT DC feedback characteristics at constant $I_B$

S12 frequency characteristics with and without thermal feedback

- Choice of feedback coefficient as the temperature sensor
Thermal impedance determination

\[ V_{BE} = F_1(I_B, V_{CE}, T) \]
\[ I_C = F_2(I_B, V_{CE}, T) \]
\[ \Rightarrow h_{12} = \frac{h_{12ISO} + \varphi \tilde{Z}_{TH}I_{C0} - \gamma \tilde{Z}_{TH}V_{CEO}h_{12ISO} + \varphi h_{22ISO}\tilde{Z}_{TH}V_{CEO}}{1 - \varphi \tilde{Z}_{TH}I_{B0} - \gamma \tilde{Z}_{TH}V_{CEO}} \]

**Isothermal hybrid parameters**

\[ h_{11ISO} = \left. \frac{\partial V_{BE}}{\partial I_B} \right|_{V_{CE}, T} \]
\[ h_{12ISO} = \left. \frac{\partial V_{BE}}{\partial V_{CE}} \right|_{I_B, T} \]
\[ h_{21ISO} = \left. \frac{\partial I_C}{\partial I_B} \right|_{V_{CE}, T} \]
\[ h_{22ISO} = \left. \frac{\partial I_C}{\partial V_{CE}} \right|_{I_B, T} \]

\[ \varphi = \left. \frac{\partial V_{BE}}{\partial T} \right|_{I_B} \]

\[ \gamma = \left. \frac{\partial I_C}{\partial T} \right|_{V_{CE}} \]

**Base-Emmitter voltage thermal coefficient**

**Collector current thermal coefficient**

\[ Z_{TH}(\omega) = \frac{h_{12} - h_{12ISO}}{\varphi(I_{CO} + h_{12}I_{BO} + h_{22ISO}V_{CEO}) + \gamma V_{CEO}(h_{12} - h_{12ISO})} \]
Thermal impedance approximation

\[ h_{12,ISO} \approx 0 \]
\[ h_{22,ISO} \approx 0 \]
\[ h_{12}I_{BO} \ll I_{CO} \]
\[ \gamma V_{CEO} h_{22,ISO} \ll \varphi I_{CO} \]

\[ \Rightarrow Z_{TH}(\omega) \approx \frac{h_{12}(\omega)}{\varphi I_{CO}} \]

The feedback coefficient \( h_{12} \) is quasi independent of the size of the transistor

\[ I_{CO} \approx A_{E} J_{CO} \]
\[ Z_{TH} \approx z_{TH} / A_{E} \]

\[ \Rightarrow h_{12}(\omega) \approx \varphi \cdot J_{CO} \cdot z_{TH}(\omega) \]
Measurement process

Extraction of the feedback coefficient vs frequency and current density from LF S-parameters measurement

Measurement of the base-emitter temperature coefficient $\phi$
Results for InGaP/GaAs HBTs

- HBT 3x2x2x110 µm² GaInP/GaAs
- HBT 6x2x40 µm² GaInP/GaAs
- HBT 9x2x1x100 µm² GaInP/GaAs
Thermal impedance of SiGe HBTs

- Transistor SiGe (2x0.35x5.8 µm²)

- Infineon technology
- Polysilicon Base and Emitter
- Deep trench isolation
- $f_T = 200$ GHz and $f_{max} = 275$ GHz
Frequency variation of \( Z_{th} \) for SiGe HBTs

- Thermal dynamic up to 200 MHz → thermal time constants down to several ns can be measured
\( Z_{TH}(\omega) \) Model

\[ P_{diss} \]

\[ Z_{TH} \]

\[ R_{TH} \]

\[ c \cdot k^0 \]

\[ r \cdot k^0 \]

\[ c \cdot k^1 \]

\[ r \cdot k^1 \]

\[ c \cdot k^2 \]

\[ r \cdot k^2 \]

\[ c \cdot k^n \]

\[ r \cdot k^n \]

Transient part of the thermal impedance

Reduced number of parameters

\[ k = 2 \quad r = 300 \text{ °C/W} \quad c = 19.10^{-12} \text{ J/°C} \quad R_{TH} = 1271 \text{ °C/W} \]
# Thermal impedance of InP HBTs

<table>
<thead>
<tr>
<th>TBH</th>
<th>Emitter area (µm²)</th>
<th>$R_{TH(h_{12})}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7B3H7</td>
<td>3.7</td>
<td>2500</td>
</tr>
<tr>
<td>10B3H7</td>
<td>5.5</td>
<td>1950</td>
</tr>
<tr>
<td>3x1M10B3H7</td>
<td>16.4</td>
<td></td>
</tr>
</tbody>
</table>

$I_b = 1.8; 2.4 \text{ et } 3 \text{ mA}$
Dispersion due to trapping effects in GaN HEMTs
• $G_{d_{DC}}$ and $G_{d_{pulsed}}$ are very different, especially at $V_{gs} = -1V$, where the dissipated power is the highest.
Low frequency characteristics

- Transition frequency between DC to RF
- The variation of this S21 is close to 2dB (due either to traps or to the self-heating)
Influence of bias points in the behavior of Gd

- dissipated power corresponds to a rise of temperature around 15 °C between 5 and 15V
  (thermal resistance to 18 °C/W by 3D simulation)
Thermal characterization of GaN HEMTs
Measurement of Ron and Idss at different temperatures and Pdiss

\[ V_{gs0} = 0 \text{V} \]

\[ V_{ds0} = 0 \text{V} \]

\[ V_{ds} = 0 - 10 \text{V} \]

\[ T_{amb} \uparrow \Rightarrow I_d \downarrow \]

\[ Roon \]

\[ V_{ds} (\text{V}) \]

\[ I_{ds} (\text{mA}) \]

\[ V_{ds} = 10 \text{V} \]

\[ P_{diss} \uparrow \Rightarrow \]

\[ V_{dsm\text{ax}} = 10 \text{V} \]
Rth extraction

\[ R_{ON}(\Delta T) = R_{ON}(T_0) + \frac{dR_{ON}}{dT} \cdot \Delta T \]

\[ R_{ON}(P_{diss}) = R_{ON}(0) + \frac{dR_{ON}}{dP_{diss}} \cdot P_{diss} \]

- \( T_0 = 25 \, ^\circ C \)
- \( \Delta T = T - T_0 \)

\[ R_{TH} = \frac{\Delta T}{\Delta P_{diss}} = \left( \frac{dR_{ON}}{dP_{diss}} \right) / \left( \frac{dR_{ON}}{dT} \right) \]
DC- Thermal characterization

- $R_{th} = 21 \, ^\circ\text{C/W}$.
- Trapping effects activated above 3.6W

- $R_{th} = 21 \, ^\circ\text{C/W}$.
- Trapping effects activated above 3.6W

$3.6 \, \text{W}$

$0 \, 1 \, 2 \, 3 \, 4 \, 5 \, 10 \, 12 \, 14$

$0 \, 50 \, 100 \, 150 \, 200 \, 250 \, 300 \, 350 \, 400 \, 450$

$0 \, 50 \, 100 \, 150 \, 200 \, 250 \, 300 \, 350 \, 400 \, 450$

$0 \, 2 \, 4 \, 6 \, 8 \, 10 \, 12 \, 14$

$0 \, 1 \, 2 \, 3 \, 4 \, 5 \, 10 \, 12 \, 14$

$3.6 \, \text{W}$

$\bullet$ Bias Point

$\bullet$ Negative pulses

$Ta = 25 ^\circ\text{C}$
Comparison with 3D simulations

- Thermal Boundary resistance taken into account

- $R_{th} = 21 \, ^{°}C/W$ with
- $TBR = 2.2E^{-8} \, m^2.K/W$

(*) A. Sarua and all “Thermal Boundary Resistance Between GaN and Substrate in AlGaN/GaN Electronic Devices”

- Frequency thermal dispersion still to be characterized through electrical measurements (interaction of traps and temperature)
Nonlinear model
Nonlinear electrothermal model with trapping effects

Topology of the trapping effects model

- 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 Remission

Diode = dissymmetry of the capture and emission process

Fundamental assumption: dissymmetry of the capture and emission process
Large signal impact of traps in CW

8x75 μm AlGaN/GaN HEMT in Class AB, Vds=25 V , DC Bias , RF CW, @10 GHz

- PAE (%)
- IDS (mA)
- Gain (dB)
- Pout (W)
- Mag (Gamma_in)

Traps ON
Traps OFF
Measure

(0.000 to 0.000)

8x75 μm AlGaN/GaN HEMT in Class AB, Vds=25 V , DC Bias , RF CW, @10 GHz
Dynamic large signal RF effects

Questions:
• What is the impact of an envelope dynamically varying signal?
• How to characterize this impact?

• Two kinds of measurements have been performed through the use of dedicated test benches
  o **Time domain envelope characterization**
    ▪ test set specialized for the optimization of Envelope Tracking PA
    ▪ allows a simultaneous control and measurement of input/output characteristics and gate/drain voltages and currents
  
  o **Time domain (TD) pulsed Large Signal Network Analyzer (LSNA)**
    ▪ Allows TD multiharmonic Load Pull measurements in various pulse configurations
GaN PA demoboard 10W - 3.6 Ghz from CREE

Demoboard GaN CREE 10W, 3.6Ghz
Vdso=28V, Idso =200mA

Magnitude of the input envelope

RF input signal

RF output signal

Magnitude of the output envelope
Results: Measurement of the Average Drain Current

- At very low modulation frequencies when the input power is zero, the average drain current recovers the bias value.
- This is no longer the case when the modulation frequency increases.

Graph showing the relationship between modulation frequency and average drain current.
Minimum current value vs output power and frequency

- The minimum value decreases when the frequency and the output power increase
Pulsed LSNA-organisation
Pulsed LSNA- The set-up
Transistor HEMT AlGaN/GaN 8x75 μm @ 6GHz
Average drain current a key figure

- Load pull @ 6 GHz (pulsed)
- Drain Voltage 30V (DC)
- Drain current 84 mA
- $Z_{\text{load}}(@\text{fo}) = 0.467 e^{j34.47^\circ}$
- $Z_{\text{load}}(@2\text{fo}) = 50$ Ohms
Profile of the average drain current vs input power

- DC Bias Drain Voltage 30V & Drain current 84 mA
- Pulse duration: 80µs ; pulse period 800µs
Profile of the average drain current vs pulse duration

- The key point is that the minimum value of the drain current does not depend on the value of the duty cycle.
Profile of the average drain current vs pulse period

- pulse duration 80µs
- input power Pin = 10.9 dBm

![Graph showing the profile of the average drain current vs pulse period.](image)
Interpretation

- What is the main reason of these behaviors?
  - Self heating effects?
  - Trapping effects?
- Self heating effects are indeed present in the transistors but cannot explain the observed behavior.
  - In pulsed conditions when the pulse duration increases the minimum current should decrease as the temperature rises. This is not the case.
  - The transistor are biased at relatively low currents where temperature effects do not severely impact the current level. Even a large temperature increase could not lead to such a large current variation.
  - Complete 3D thermal simulations of the 4x75μm device have confirmed that the temperature plays a minor role in the shape of the average current.
- Trapping effects are likely to be the main responsibles.
Thermal characteristics of the 8x75µm AlGaN/GaN HEMT

- $T = -20^\circ C$
- $T = 25^\circ C$
- $T = 100^\circ C$
Pulse profile explanation (Pin=0dBm)

Pulse average current is lower than DC bias
Pulse profile explanation (Pin=8.5 dBm)

Pulse average current is equal to DC bias
Current profile for the two-tone modulation

$V_{dso}(t)$

$\tau_{emission} \gg T_{modulation}$

Charge trapped

$\tau_{emission} \sim T_{modulation}$
Discussion

- Qualitative behavior OK but quantitative Not OK
- In order to get a good fit we have to increase the trapping effect
- When trapping effects are increased good accuracy with LF characteristics
- But RF output power and PAE are not well described
Conclusions

• Trapping effects have a significant impact on the dynamics of RF modulated signals.

• They lead to complex nonlinear memory effects that have to be taken into account for system design.

• The model proposed by Jardel & Al exhibits good qualitative behavior but further investigation must be performed to accurately fit the quantitative values.
  
  o nonlinear behavior of the trapping process

  o separation of thermal and trapping effects
Time alignment procedure (input-output)

Input Baseband Signal Generated → FFT → Cross Correlation Computation → X → IFFT → Output Baseband signal Measured

Plot of the phase of the cross correlation spectra

Envelope Delay Extraction

Phase of cross correlation spectra between input and output envelope signals

\[ C(f) = e^{-j(2\pi f \tau + \varphi_0)} \]

\[ \tau = \frac{\Delta \varphi}{2\pi M} \]
Time alignment procedure (envelope-drain bias)

$|E(t)|$ is the magnitude of the input envelope signal

$|C(t)|$ is the drain bias signal

$|S(t)|$ is the magnitude of the output envelope signal

$\tau$ is tuned to minimize the hysteresis of the $|S(t)|$ versus $|E(t)|$ characteristic
Stroboscopic approach of pulsed RF receiver

All samples of IF signal are not to be considered: interesting data are only during the pulses. 2 ways:

- Adcs always running with large memory, and sorting of memory arrays;
- Adcs with trigger and burst capabilities.