Modeling and analysis of RF LDMOS for reliability issues

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Presentation outline

- Context of this study
- Objectives
- Innovative reliability bench
- DC and CV characterization
- RF LDMOS modeling
- Conclusion & prospects
Context of this study

Reliability improvement of amplifier stages for S Band radar (2-4 GHz)
Presentation outline

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Objectives (1)

- Characterization and modeling for reliability issues
- Obtaining a set of significant parameters such as transconductance ($G_M$), threshold voltage ($V_{TH}$), On-state resistance ($R_{ON}$) and capacitances ($C_{RSS}$, $C_{OSS}$, ...).
- Correlation between RF LDMOS electrical parameter drifts and any kind of degradation phenomenon, after RF Life-tests (S band radar operating conditions).

Electro-thermal modeling as a tool for RF LDMOS reliability study
Objectives (2)

- What is the Failure mechanism involved?
- A set of significant parameters
- Innovative Reliability bench
  - Modeling before RF Life-tests
  - RF performances tracking
  - Modeling after RF Life-tests
- I-V and C-V characterization
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Innovative reliability bench (1)

- RF Source
- Modulator
- 80 W amplifier
- 30 dB coupler
- 20 dB attenuator
- 40 dB attenuator
- 20 dB attenuator
- Switches RF 8 > 1
- X 8
- Circulator
- DUT
- Tuner
- Average Power Meter
- P_{IN}
- P_{OUT}
- Peak power meter
- 30 dB coupler
- 20 dB attenuator
- 40 dB attenuator
Innovative reliability bench (2)

- A microwave part
- A control/command part piloted by a dedicated software
- Thermal module for each device
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DC Characterization (1)

DC measurement setup

- BILT
- ICCAP
- Peltier module
**DC Characterization (2)**

**Results & Measurement consistency**

Measured $I_{DS}-V_{DS}$ characteristics

Measured $I_{DS}-V_{GS}$ characteristics

Consistency of Data

**Data management**

Extrapolated $I_{DS}-V_{GS}$ characteristics

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**Measured (symbols) and extrapolated (continuous lines) output characteristics**

$V_{DS}=0...26$ V with a step of 520 mV

$V_{GS}=3.5...5.8$ V with a step of 383 mV

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**Measured (symbols) and extrapolated (continuous lines) transfer characteristics**

$V_{DS}=0...26$ V with a step of 4.33 V

$V_{GS}=3.5...5.8$ V with a step of 45 mV
CV Characterization (1)
localization of capacitances

RF LDMOS device cross-section with its intrinsic capacitances
CV Characterization (2)
Primary capacitance measurements

Measured \( C_{RSS} \), \( C_{ISS} \) and \( C_{OSS} \), Freq=1MHz and \( V_{DS}=[0V, 30V] \) at room temperature
**CV Characterization (3)**

**Intrinsic capacitance measurements**

**Measured $C_{GS}$ vs. $V_{GS}$ profile ($V_{DS} = 0V$ and Freq. =1 MHz) at room temperature.**
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RF LDMOS modeling
Improved MET LDMOS Model overview

- An empirical large signal non-linear model.

- An electro thermal model including static and dynamic thermal dependencies.

- An electro thermal model, taking into account self heating effects and temperature influence on LDMOS electric behaviour.
RF LDMOS modeling

Improved MET LDMOS Model overview

Electric model

Thermal model

Large signal equivalent circuit of the MET LDMOS model
RF LDMOS modeling
Improved MET LDMOS model overview (thermal aspects)

\[ \Delta T = R_{th\_CA} \cdot P_{diss} + T_a \]

\[ P_{diss} = I_{ds} \cdot V_{ds} \]

\[ R_{th\_CA} = R_{th\_CP} + R_{th\_PH} + R_{th\_HA} \]
An ADS "SDD" (Symbolic defined device) was developed.

The SDD is a feature in ADS, which allows the user to specify a real-time model description, without compilation.

The developed SDD covers the transistor DC forward current $i_d=f(v_{GS},v_{DS})$, the series resistors $R_G$, $R_S$ and $R_D$, as well as the charges $q_{GS}$, $q_{GD}$ and $q_{DS}$.

The thermal network is implemented taking into consideration the temperature dependence of the parameters.
RF LDMOS modeling

Main parameters of the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta</td>
<td>Transconductance parameter</td>
<td>Siemens</td>
</tr>
<tr>
<td>$V_t$</td>
<td>Threshold voltage</td>
<td>V</td>
</tr>
<tr>
<td>Delta</td>
<td>$V_t$ variation according to $V_{ds}$</td>
<td>V</td>
</tr>
<tr>
<td>$V_{br}$</td>
<td>Break down voltage</td>
<td>V</td>
</tr>
<tr>
<td>$K_{1/2, M_{1/3}}$</td>
<td>Break down parameters</td>
<td>--</td>
</tr>
<tr>
<td>$V_K$</td>
<td>$I_{ds}$ equation coefficient</td>
<td>V</td>
</tr>
<tr>
<td>Alpha</td>
<td>Linear range</td>
<td>1/Ω</td>
</tr>
<tr>
<td>Gamma</td>
<td>Slope of the channel current</td>
<td>--</td>
</tr>
<tr>
<td>Lambda</td>
<td>Shapes of the $I_{ds}$ saturation</td>
<td>1/V</td>
</tr>
<tr>
<td>$V_{gexp}$</td>
<td>Term of power</td>
<td>--</td>
</tr>
<tr>
<td>$V_{ST}$</td>
<td>Sub-threshold slope coefficient</td>
<td>V</td>
</tr>
</tbody>
</table>
RF LDMOS modeling

Sub-threshold modeling: $\log(I_{DS})$ vs. $V_{GS}$

Measured transfer characteristics ($\log(I_{DS})$ vs. $V_{GS}$) with the influence of few MET LDMOS model parameters

Measured (symbols) and modelled (continuous lines) transfer characteristics, with $V_{GS}$=3.8-5.8 V (step=56 mV) and $V_{DS}$=5.2 V, 17.68 V & 26 V
RF LDMOS modeling

Transfer characteristics modeling ($I_{DS}$ vs. $V_{GS}$)

Measured transfer characteristics $I_{DS}$ vs. $V_{GS}$ with the influence of few MET LDMOS model parameters

Measured (symbols) and modelled (continuous lines) transfer characteristics, with $V_{GS} = 3.8 \text{ V} - 5.8 \text{ V}$ (step=56 mV) and $V_{DS}=5.2 \text{ V}, 17.68 \text{ V} & 26 \text{ V}$. 
RF LDMOS modeling

Output characteristics modeling: \( I_{DS} \) vs. \( V_{DS} \)

Measured output characteristics \((I_{DS} \text{ vs. } V_{DS})\) with the influence of few MET LDMOS model parameters

Measured (symbols) and modelled (continuous lines) output characteristics with \( V_{DS} = 0 - 26 \text{ V} \) (step=520 mV) and \( V_{GS} = 4.45 \text{ V}, 4.9 \text{ V}, 5.35 \text{ V} \& 5.8 \text{ V} \)
**RF LDMOS modeling**

Model parameter extraction

<table>
<thead>
<tr>
<th>MET model parameters</th>
<th>Classic DC parameter names</th>
<th>values obtained by modeling (Fitting error &lt;1%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTO_0</td>
<td>$V_{TH}$</td>
<td>4.2 V</td>
</tr>
<tr>
<td>BETA_0</td>
<td>$G_M$</td>
<td>0.53 S</td>
</tr>
<tr>
<td>VBR_0</td>
<td>$BV_{DSS}$</td>
<td>87.5 V</td>
</tr>
<tr>
<td>RD_0</td>
<td>$R_{DSON}$</td>
<td>1.4 Ohms</td>
</tr>
</tbody>
</table>

*Summary of few DC significant parameters extrapolated by modeling*
RF LDMOS modeling

$C_{GS}$ capacitance modeling

\[ CGS1 + CGS2(1 + \tanh(CGS6(vGS + CGS3))) + CGS4(1 - \tanh(vGS*CGS5)) \]
RF LDMOS modeling

CV modeling results

Measured (symbols) and modelled (continuous lines) $C_{GS}$ capacitance, $V_{GS} = [-5 \, V, 7 \, V]$ and $V_{DS} = 0 \, V$, with $Freq=1 \, MHz$.

Measured (symbols) and modelled (continuous lines) $C_{ISS}$, $C_{OSS}$ & $C_{RSS}$ capacitances, $V_{DS} = [0 \, V, 26 \, V]$, $V_{GS}=0\,V$, and $Freq=1 \, MHz$. 
RF LDMOS modeling

Thermal simulation results

![Graph showing temperature vs. VDS for different VGS values.](image)
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An improved MET LDMOS model (three thermal cells), taking into account self-heating effects and the temperature influence was developed.

- The DC and CV modeling results fitted well with those obtained from the measurements.

- A set of significant parameters has been extrapolated by modeling and used to help identifying a degradation phenomenon after RF life-tests.
Prospects

- S parameter measurements and simulations are in progress, to get a complete compact model and have a large significant parameter set.

- Simulation in Harmonic Balance ($P_{OUT}$ vs. $P_{IN}$, IMD, ...) for RF LDMOS performance predictions after RF life-tests.

- Channel temperature measurement in order to confirm the thermal model.
Questions
RF Life-test conditions (1)

- **DC**
  \[
  \begin{align*}
  V_{DS} &= 44 \text{ V}, \\
  V_{GS} &= 3.79 \text{ V} \text{ with } I_{DQ} = 3 \text{ mA} \text{ at } 25^\circ \text{C}.
  \end{align*}
  \]
  \[
  \text{Fréq} &= 2.9 \text{ GHz}.
  \]

- **RF**
  \[
  \begin{align*}
  \text{Pulse length/duty cycle} &= 500 \mu\text{s}/50\%. \\
  P_{IN} &= 30.5 \text{ dBm}, \quad P_{OUT} = 43\text{--}44 \text{ dBm}.
  \end{align*}
  \]

- **Thermal**
  \[
  T (^\circ \text{C}) = 10, 80, 110 \text{ et } 150^\circ \text{C}.
  \]
## RF Life-test conditions (2)

<table>
<thead>
<tr>
<th>Device base plate temperature (°C)</th>
<th>$P_{IN}$ (dBm)</th>
<th>$P_{OUT}$ (dBm)</th>
<th>$P_{REF}$ (dBm)</th>
<th>$I_{DQ}$@ device base plate temperature (mA)</th>
<th>$I_{DSS}$ during RF pulses (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>30.5</td>
<td>43.8</td>
<td>23.9</td>
<td>1.76</td>
<td>557.89</td>
</tr>
<tr>
<td>80</td>
<td>30.5</td>
<td>43.57</td>
<td>22.2</td>
<td>5.023</td>
<td>550</td>
</tr>
<tr>
<td>110</td>
<td>30.5</td>
<td>42.6</td>
<td>17.3</td>
<td>7.5647</td>
<td>537.68</td>
</tr>
<tr>
<td>150</td>
<td>30.5</td>
<td>40.2</td>
<td>22.2</td>
<td>13.348</td>
<td>500</td>
</tr>
</tbody>
</table>
Results obtained after RF Life-test

RF saturated output power evolution over ageing time (1500h) for various temperature conditions.

Drain source current evolution over ageing time (1500h) for various temperature conditions.
RF LDMOS modeling

Thermal aspects

Drift region: Hot spots