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Model of power InAlN/GaN HEMT for 3-D Electrothermal Simulations

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Outline

• Introduction
• HEMT equivalent circuit model
• Methodology for fast 3-D electrothermal device simulation
• Electrothermal analysis of multifinger HEMT
• Conclusions
Introduction

- Multifinger HEMT devices with compact layout are required for high-power operation

- SPICE-like simulations provide faster results but in general do not take into account nonlinear thermal dependences of certain parameters

- 3-D FEM electrothermal simulations are very time consuming and require powerful hardware equipment, particularly for complicated 3-D structures

- Methodology for fast 3-D electrothermal device simulation is important for the analysis and optimization of self-heating induced thermal crosstalk between individual gate fingers
Introduction

Direct method

- 1-D heat flow
- Extraction from measurement and/or thermal FEM simulation
- Simplification for 3-D RC network

Relaxation method

- Separately solved thermal and electrical equations
- FEM for thermal simulation
- SPICE-like program for electrical simulation

- Two softwares
- Synchronization and data transfer
Introduction

Mixed-mode setup in Synopsys TCAD Sentaurus

Three types of simulation

- **Electrical nodes** (electrodes)
  - current, voltage
- **Thermal nodes** (thermodes)
  - heat flux, temperature

Direct interconnection of FEM thermal model and electrical circuit model via thermal nodes

3-D electrothermal device simulation

InAlN/GaN HEMT structure

2-D cross section of HEMT

Complex system

Full 3-D FEM simulation very time consuming
Mixed-mode setup (3-D thermal + 2-D electrothermal)

3-D thermal model of the package
2-D electrothermal model of one elementary cell
Heat flux exchange via thermal node

3-D electrothermal device simulation

Mixed-mode setup (3-D thermal + equivalent circuit model)

3-D thermal model of the package

2-D electrothermal model of one elementary cell

Heat flux exchange via thermal node

Temperature dependent equivalent circuit model

HEMT equivalent circuit model

- **$I_{DG_S}$, $I_{DG_D}$**: Schottky gate current
- **$I_D$**: drain–source current
- **$R_{Sa}, R_{Da}$**: access regions
- **$C_{DS}, C_{GS}, C_{GD}$**: nonlinear capacitors
- **$P$**: power source

HEMT structure

Equivalent circuit model
HEMT equivalent circuit model

Schottky gate current

Thermionic emission + tunneling

\[ I_{te(GS, GD)} = I_s(T) \cdot \left( \exp \left( \frac{V_{GS, GD}}{n_{te0} + n_{teT} \cdot T} \right) - 1 \right) \]

\[ I_{t(GS, GD)} = \left( I_s(T) \cdot \left( \exp \left( \frac{-V_{GS, GD}}{n_{t0} + n_{tT} \cdot T} \right) - 1 \right)^{-1} + I_t(T)^{-1} \right)^{-1} \]

Temperature dependence

\[ I_{s,t}(T) = I_{s0,t0} \cdot \exp(I_{sT,tT} \cdot T) \]

I–V characteristics of the gate electrode at different temperatures
HEMT equivalent circuit model

**Drain–source current**

**Empirical Angelov expression**

\[ I_{DS} = FA(V_{GS}) \cdot FB(V_{DS}) \cdot FC(V_{DS}) \]

\[ FA(V_{GS}) = I_{pk} \cdot (1 + \tanh(\psi)) \]

\[ FB(V_{DS}) = (1 + \lambda V_{DS}) \]

\[ FC(V_{DS}) = \tanh(\alpha V_{DS}) \]

\[ \psi = \sinh[P_1(V_{GS} - V_{pk}) + P_2(V_{GS} - V_{pk})^2 + P_3(V_{GS} - V_{pk})^3]. \]


**Modified Angelov expression**

\[ FA(V_{GS}) = I_{Vt0} \exp(I_{VtT} T) \]

\[ \cdot \exp((s_{ln0} + s_{lnT} T) \left( V_{GS} - V_{t0} - \frac{(s_{ln0} + s_{lnT} T)}{FB(V_{GS}) \cdot FC(V_{GS})}\right)) \]

- Better fit in log scale
- Included temperature dependence
HEMT equivalent circuit model

Drain–source current

Modified Angelov expression

\[ FA(V_{GS}) = I_{Vt0} \exp(I_{VtT}T) \cdot \exp\left((s_{in0} + s_{inT}T)(V_{GS} - V_{t0} - \frac{(s_{in0} + s_{inT}T)}{FB(V_{GS}) \cdot FC(V_{GS})})\right) \]

\[ FB(V_{DS}) = (1 + \lambda V_{DS}) \]
\[ FC(V_{DS}) = \tanh(\alpha V_{DS}) \]

Output and transfer characteristics at different temperatures
HEMT equivalent circuit model

Nonlinear capacitors

\[
C_{GS}(V_{GS}, V_{DS}) = \left( C_{GSA1} + \left( \frac{C_{GSA2} - C_{GSA1}}{2} \right) \times (1 + \tanh(C_{GSB2} \cdot (V_{GS} - C_{GSC2})) \right) + \\
\left( \frac{C_{GSA3} - (C_{GSA3VD} \cdot V_{DS}) - C_{GSA2}}{2} \times \right. \\
\left. \times (1 + \tanh(C_{GSB3} \cdot (V_{GS} - C_{GSC3} - C_{GSC3VD} \cdot V_{DS}))) \right)
\]

\[
C_{GD}(V_{GS}, V_{DS}) = C_{GD1} + \frac{C_{GDA2} - C_{GDA1} - C_{GDA2VD} \cdot V_{DS}}{2} \times \\
\times (1 + \tanh(C_{GDB2} \cdot (V_{GD} - C_{GDC2} - C_{GDC2VD} \cdot V_{DS})))
\]

C-V curves at different voltage bias
HEMT equivalent circuit model

Power source

Thermal node $P$ represents heat generation inside the structure

\[ P = V_{DS} \cdot I_{DS} \]
HEMT equivalent circuit model

Implementation to Sentaurus Device

• Sentaurus Compact Model Interface (CMI)
• Model is implemented in C++ and linked to simulation at run-time

Temperature dependent resistance

Vector of unknowns

\[ z(t) = \begin{bmatrix} u_1 \\ u_2 \\ t_1 \\ i \end{bmatrix} \]

Right-hand side

\[ f_R(t, z(t)) = \begin{bmatrix} i \\ -i \\ 0 \\ u_1 - u_2 - R \cdot i \end{bmatrix} \]

Solving of Jacobian by MATLAB

```matlab
syms u1 u2 t1 i
jacobian([ i, -i, 0, u1-u2-R*i], [u1, u2, t1, i])
```

Jacobian

\[
\begin{bmatrix}
0 & 0 & 0 & 1 \\
0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 \\
1 & -1 & \frac{dR}{dt_1} \cdot i & -R \\
\end{bmatrix}
\]

TCAD Sentaurus User Manual, Version L-2016.03, Synopsys, San Jose, CA, USA, 2016
3-D electrothermal device simulation

Mixed-mode setup for multifinger HEMT simulation

3-D FEM thermal model of package

Electrical circuit
HEMT model

3-D FEM electrical model of metallization

Electrothermal analysis of multifinger HEMT

2-D FEM simulation
Simulation time: **5 min** @ 16 500 mesh elements
- No 3-D thermal flow inside package
- No inhomogeneity in third dimension

3-D FEM simulation
Simulation time: **5 hours** @ 500 000 mesh elements
- Slow
- Reduced mesh → low accuracy and convergence problem

Mixed-mode setup (3-D thermal + equivalent circuit model)
Simulation time: **2 min** @ 140 000 package mesh elements
- 4 500 metallization mesh elements
- 20 HEMTs
- High speed of simulation
- Allows 3-D heat flux in whole system
- Calculates current distribution in metallization
Electrothermal analysis of multifinger HEMT

Comparison of measured and simulated output characteristics

Temperature distribution in the HEMT device
Electrothermal analysis of multifinger HEMT

Comparison of measured and simulated output characteristics

Electrostatic potential and current flow in the metallization
Electrothermal analysis of multifinger HEMT

Metallization of multifinger HEMT structure

Investigated variables:
- number of gate fingers $n_{gf}$
- gate finger width $W_G$ ($n_{gf} \times W_G = 16$ mm)
- drain/source metallization width $L_{met}$ (finger spacing)

Simulation time: ~15 min
(@ ~250 000 package, ~50000 metallization)
Electrothermal analysis of multifinger HEMT

Electrostatic potential in the metallization

Current density distribution in the metallization

Temperature distribution
Electrothermal analysis of multifinger HEMT

Temperature distribution across gate fingers

Dissipated power capability

Temperature distribution

$W_G = 1\, \text{mm}$
$\text{ngf} = 16$

$W_G = 0.5\, \text{mm}$
$\text{ngf} = 32$

SiC/GaN/InAlN - chip
Cu - Leadframe
Conclusions

• Equivalent temperature dependent nonlinear large signal circuit model of HEMT was described
• New methodology for fast 3-D electrothermal simulation of complex power HEMTs including the package and cooling assemblies was proposed
• The simulation approach helps to assess the device temperature and current distributions in the HEMT structures operating under different operating conditions and topology at a short time
• The effects of metallization layer design of multifinger HEMT structure were analyzed
Thank you for your attention

This work was supported in part by Grant VEGA 1/0491/15, in part by Grant APVV-14-0749 supported by Ministry of Education, Science, Research and Sport of Slovakia and in part by project ‘PowerBase’. This project has received funding from the Electronic Component Systems for European Leadership Joint Undertaking under grant agreement No 662133. This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation programme and Austria, Belgium, Germany, Italy, Netherlands, Norway, Slovakia, Spain and United Kingdom