Slovak University of Technology in Bratislava

Faculty of Electrical Engineering and Information Technology

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

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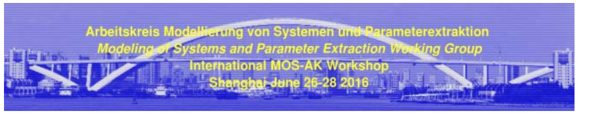
Outline

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

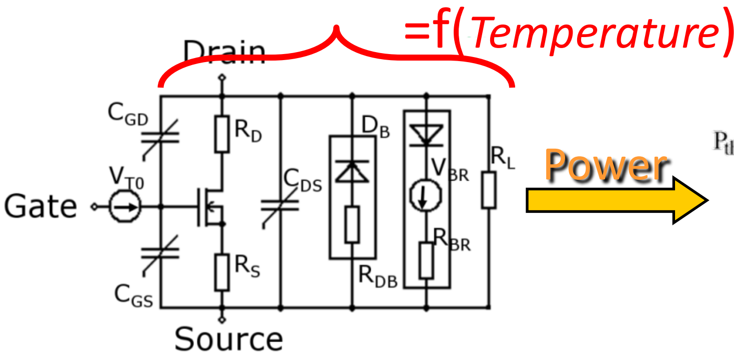


Introduction

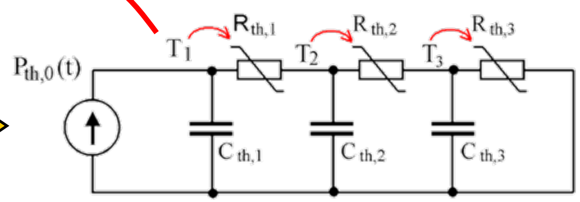
- Multifinger HEMT devices with compact layout are required for high-power operation
- SPICE-like simulations provide faster results but in general do not take into account nonlinear thermal dependences of certain parameters
- 3-D FEM electrothermal simulations are very time consuming and require powerful 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

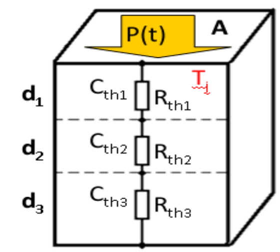
Direct method



Electrical equivalent of thermal system



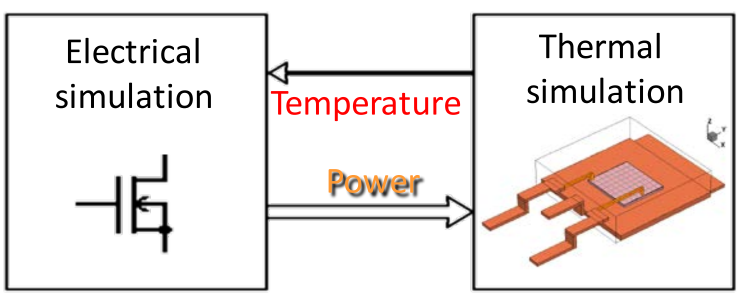
Thermal system



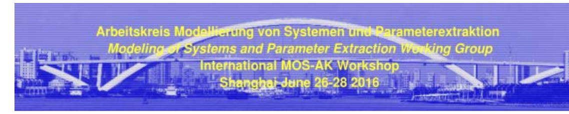
- 1-D heat flow
- Extraction from measurement and/or thermal FEM simulation
- Simplification for 3-D RC network

Relaxation method

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



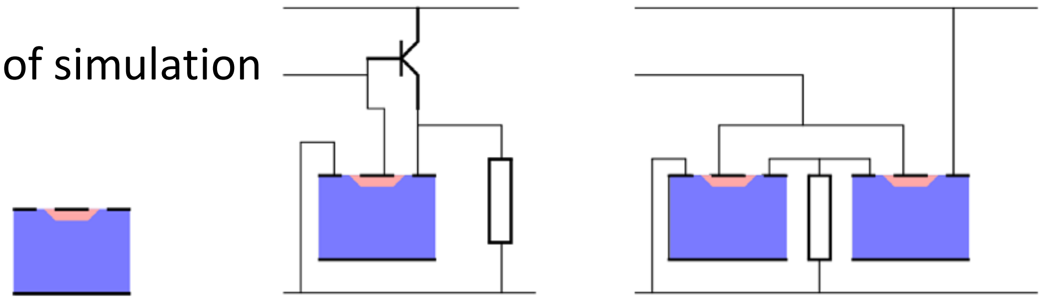
- Two softwares
- Synchronization and data transfer



Introduction

Mixed-mode setup in Synopsys TCAD Sentaurus

Three types of simulation

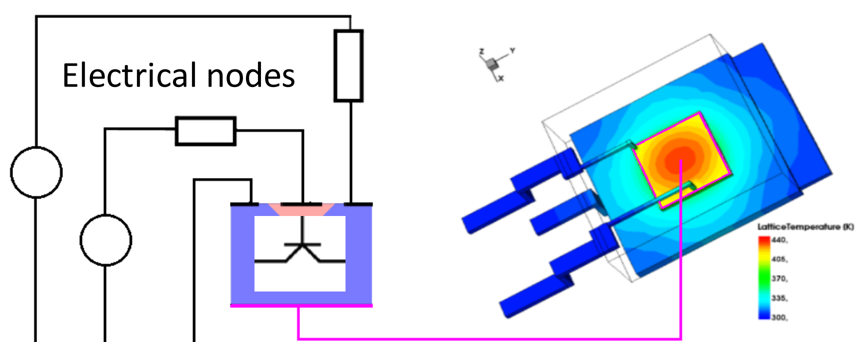


Single Device Single Device with Circuit Multiple Devices with Circuit

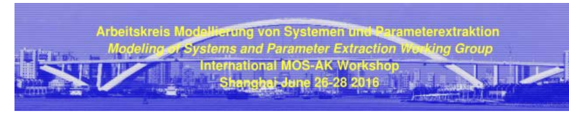
Electrical nodes (electrodes)
– current, voltage

Thermal nodes (thermodes)
– heat flux, temperature

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



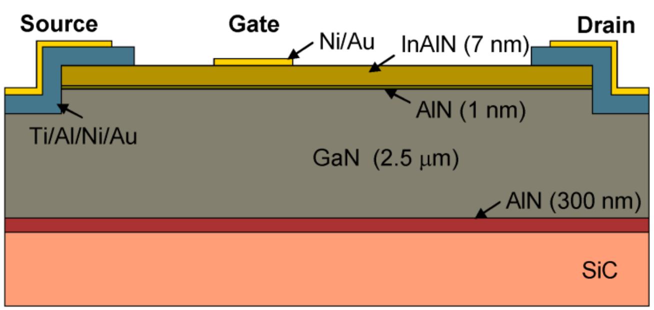
Synopsys, San Jose, CA, USA. (1986). Technology Computer-Aided Design. [Online]. Available: http://www.synopsys.com/Tools/TCAD/Pages/default.aspx

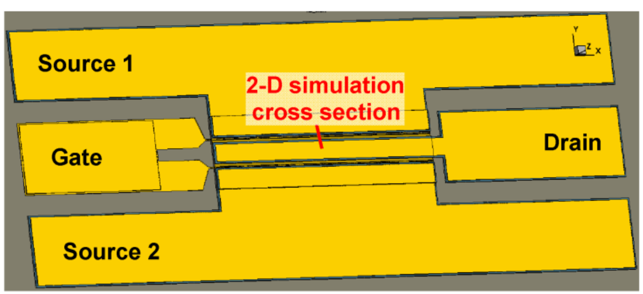


3-D electrothermal device simulation

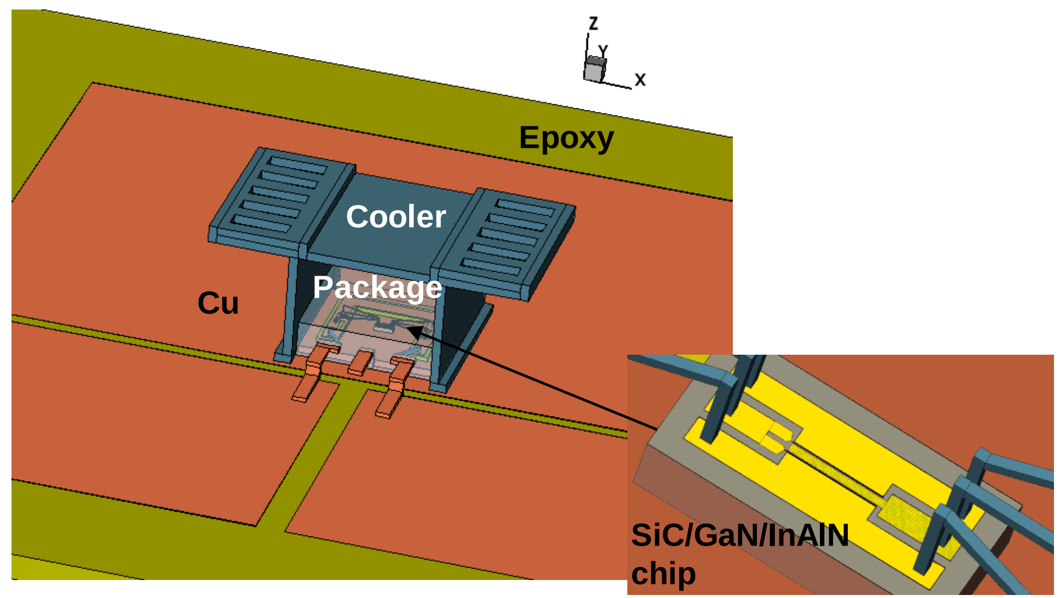
InAlN/GaN HEMT structure

2-D cross section of HEMT



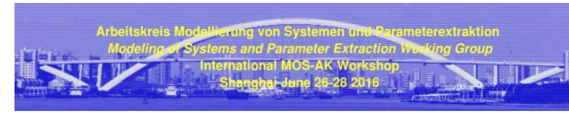


Package and cooling assemblies



Complex system

Full 3-D FEM simulation very time consuming



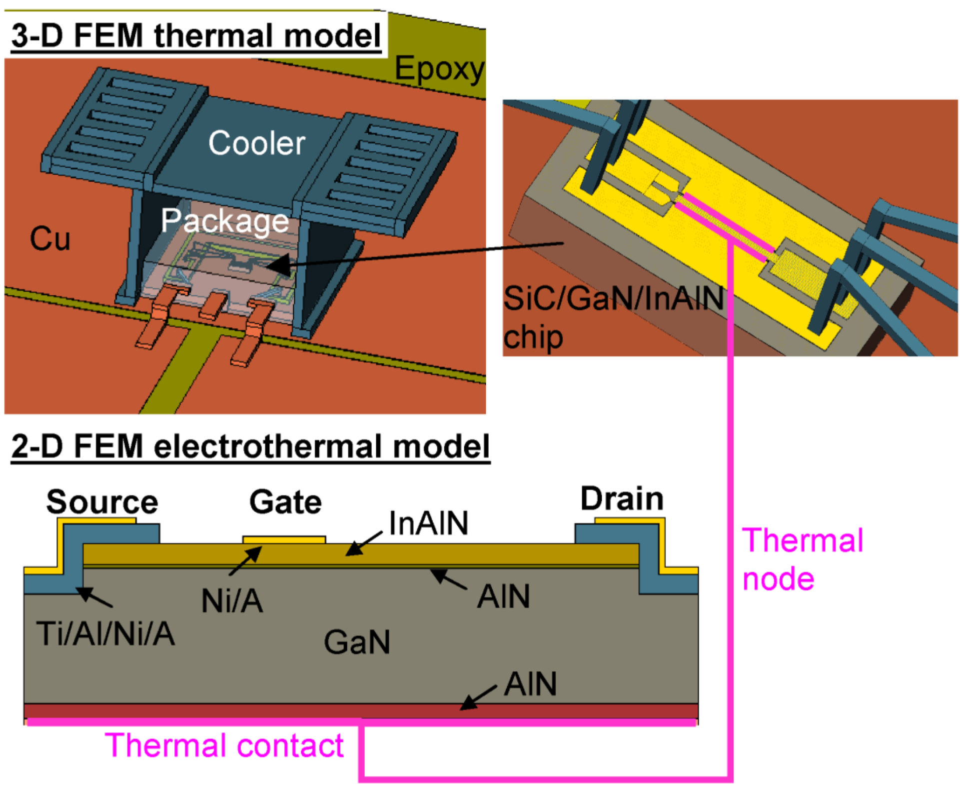
3-D electrothermal device simulation

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



Nallet, F. et al., Proc. 26th Int. Symp. Power Semicond. Devices IC's, p. 334, 2014

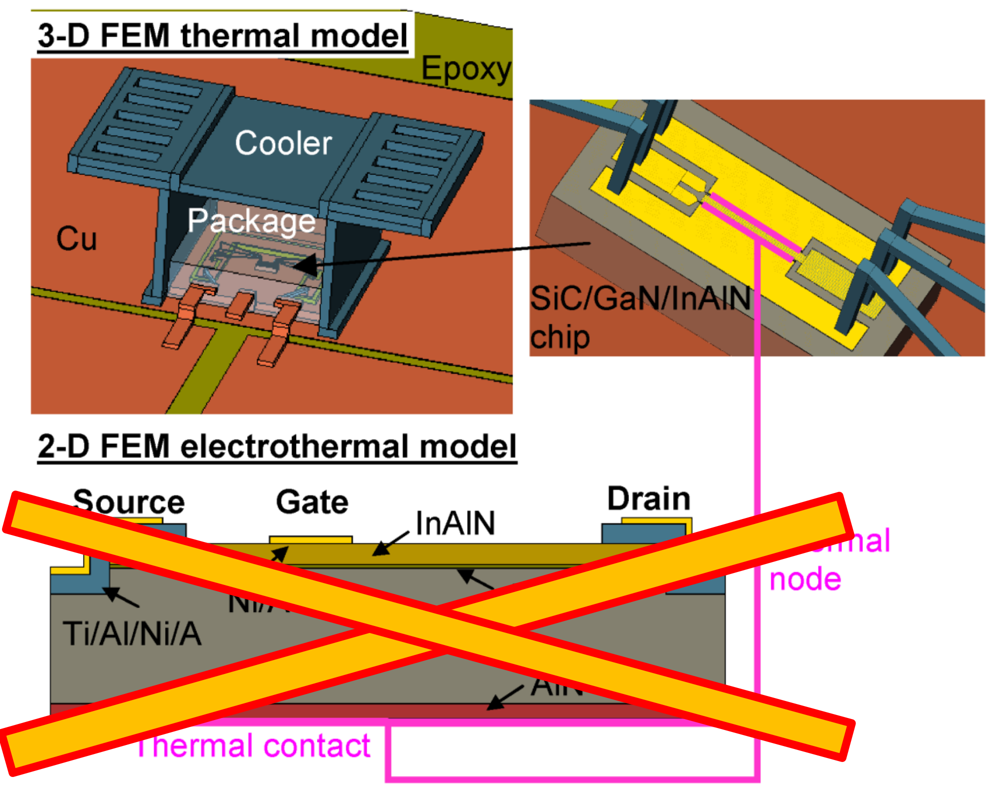
3-D electrothermal device simulation

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

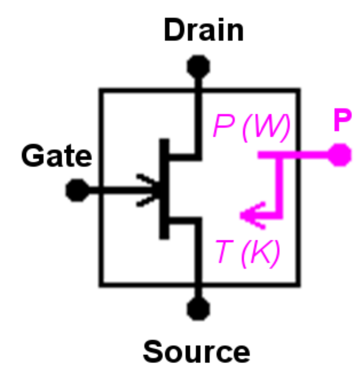
3-D thermal model of the package

~~2-D electrothermal model of one elementary cell~~

Heat flux exchange via thermal node



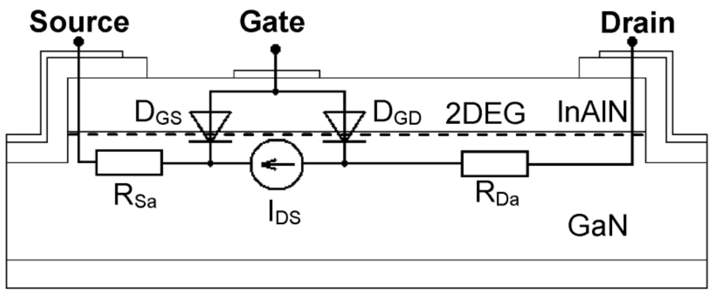
Temperature dependent equivalent circuit model



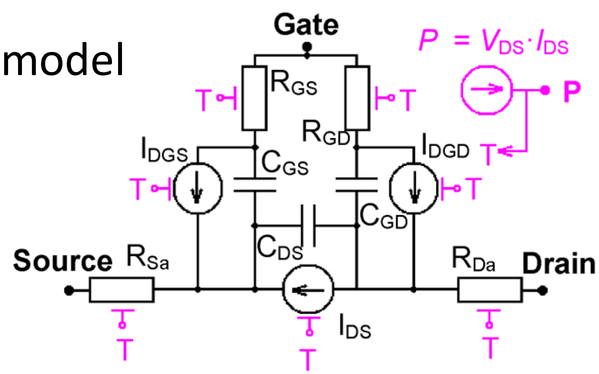
Chvala, A. et al., IEEE Trans. Electron Devices, vol. 62, no. 3, p. 828, 2015

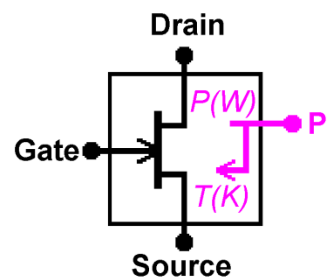
HEMT equivalent circuit model

HEMT structure

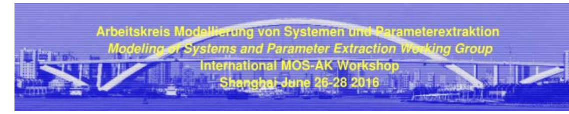


Equivalent circuit model





- I_{DGS}, I_{DGD}: Schottky gate current
- I_{DS}: drain–source current
- R_{Sa}, R_{Da}: access regions
- C_{DS} , C_{GS} , C_{GD}: nonlinear capacitors
- P: power source



HEMT equivalent circuit model

Schottky gate current

Thermionic emission + tunneling

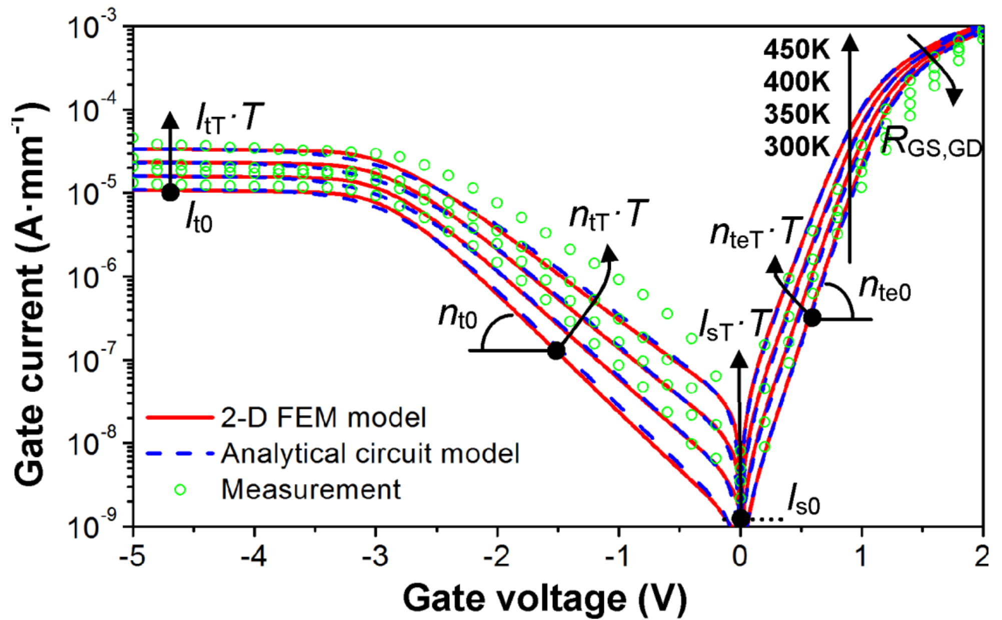
$$I_{\mathrm{te(GS,GD)}} = I_s(T)\cdot\left(\exp\left(\frac{V_{\mathrm{GS,GD}}}{n_{\mathrm{te0}} + n_{\mathrm{te}T}\cdot T}\right) - 1\right)$$

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

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

$$I_{\mathrm{DS}} = \mathrm{FA}(V_{\mathrm{GS}}) \cdot \mathrm{FB}(V_{\mathrm{DS}}) \cdot \mathrm{FC}(V_{\mathrm{DS}})$$

$$\mathrm{FA}(V_{\mathrm{GS}}) = I_{\mathrm{pk}} \cdot (1 + \tanh(\psi))$$
$$\mathrm{FB}(V_{\mathrm{DS}}) = (1 + \lambda V_{\mathrm{DS}})$$
$$\mathrm{FC}(V_{\mathrm{DS}}) = \tanh(\alpha V_{\mathrm{DS}})$$

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

Angelov, I. et al., in Proc. Asia-Pacific Microw. Conf., p. 279, Dec. 2006

Modified Angelov expression

$$\mathrm{FA}(V_{\mathrm{GS}}) = I_{\mathrm{Vt0}} \exp(I_{\mathrm{VtT}} T) \cdot \exp\left((s_{\mathrm{ln0}} + s_{\mathrm{ln}T} T)\left(V_{\mathrm{GS}} - V_{t0} - \frac{(s_{\mathrm{lin0}} + s_{\mathrm{lin}T} T)}{\mathrm{FB}(V_{\mathrm{GS}}) \cdot \mathrm{FC}(V_{\mathrm{GS}})}\right)\right)$$

- Better fit in log scale
- Included temperature dependence

HEMT equivalent circuit model

Drain–source current

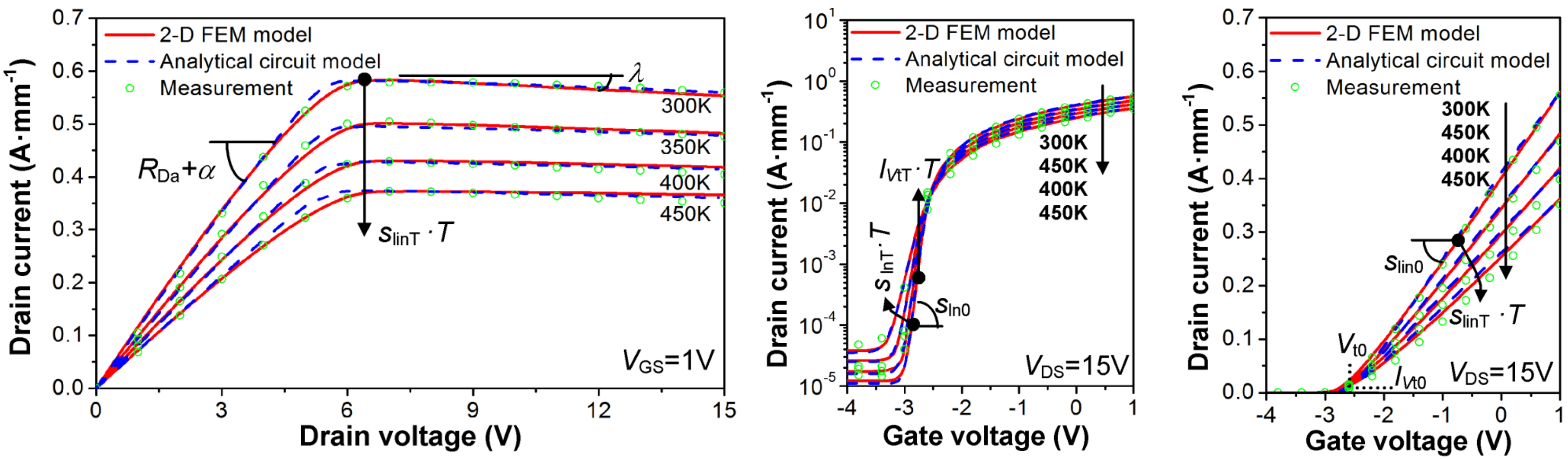
Modified Angelov expression

$$\mathrm{FA}(V_{\mathrm{GS}}) = I_{\mathrm{Vt0}} \exp(I_{\mathrm{VtT}} T) \cdot \exp\left((s_{\mathrm{ln0}} + s_{\mathrm{ln}T} T)\left(V_{\mathrm{GS}} - V_{t0} - \frac{(s_{\mathrm{lin0}} + s_{\mathrm{lin}T} T)}{\mathrm{FB}(V_{\mathrm{GS}}) \cdot \mathrm{FC}(V_{\mathrm{GS}})}\right)\right)$$

$$\mathrm{FB}(V_{\mathrm{DS}}) = (1 + \lambda V_{\mathrm{DS}})$$

$$\mathrm{FC}(V_{\mathrm{DS}}) = \tanh(\alpha V_{\mathrm{DS}})$$

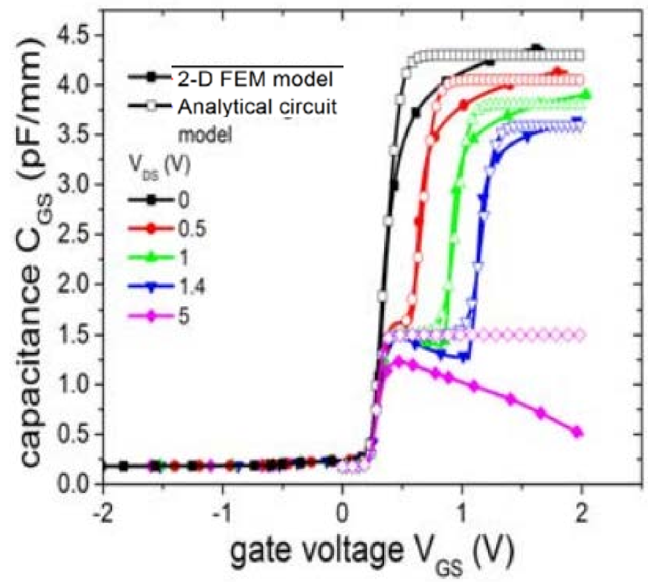
Output and transfer characteristics at different temperatures



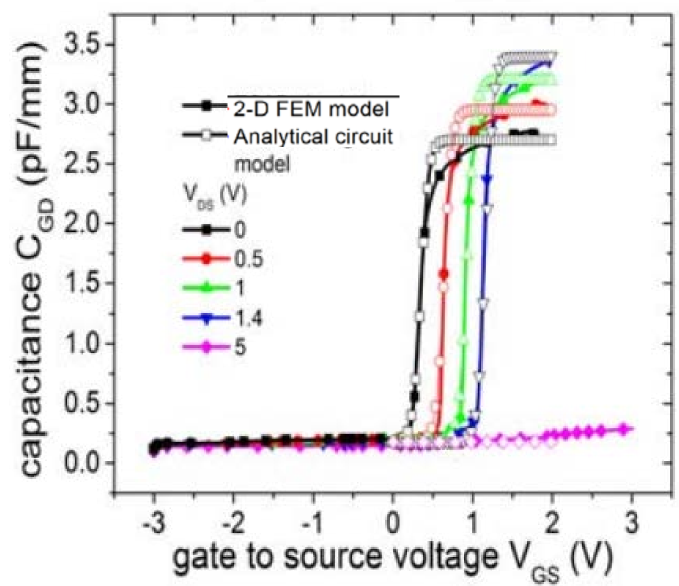
HEMT equivalent circuit model

Nonlinear capacitors

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



$$C_{GD}(V_{GS},V_{DS}) = C_{GDA1} + \frac{C_{GDA2} - C_{GDA1} - C_{GDA2VD} \times V_{DS}}{2} \times \times \left(1 + \tanh\left(C_{GDB2} \times (V_{GD} - C_{GDC2} - C_{GDC2VD} \times V_{DS})\right)\right)$$

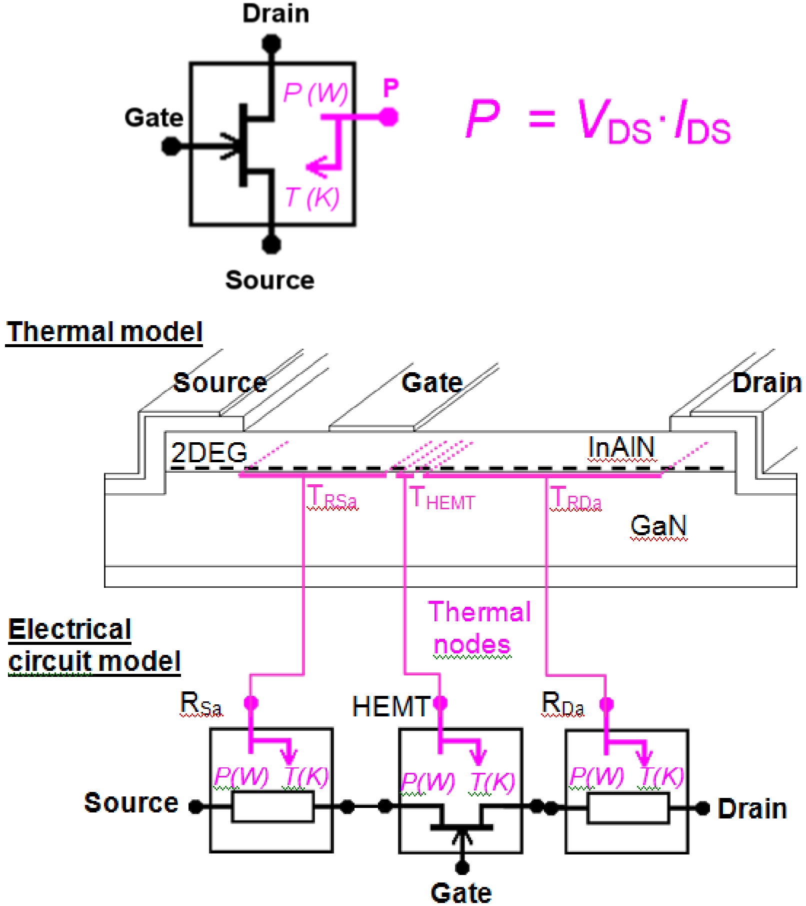


C-V curves at different voltage bias

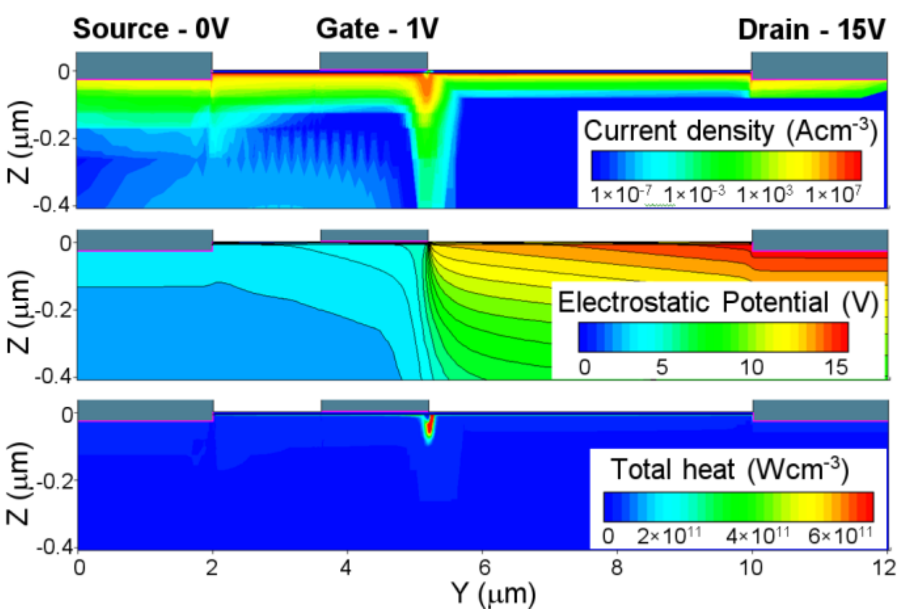
HEMT equivalent circuit model

Power source

Thermal node P represents heat generation inside the structure



2-D FEM electrothermal simulation

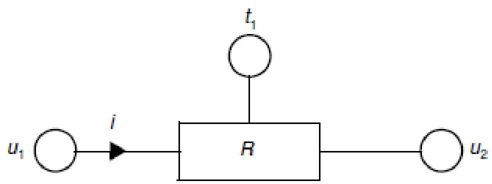


HEMT equivalent circuit model

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

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

Jacobian

$$\frac{d}{dz} f_R(t, z(t)) = J_{f_R} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 1 & -1 & -\frac{dR}{dt_1} \cdot i & -R \end{bmatrix}$$

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

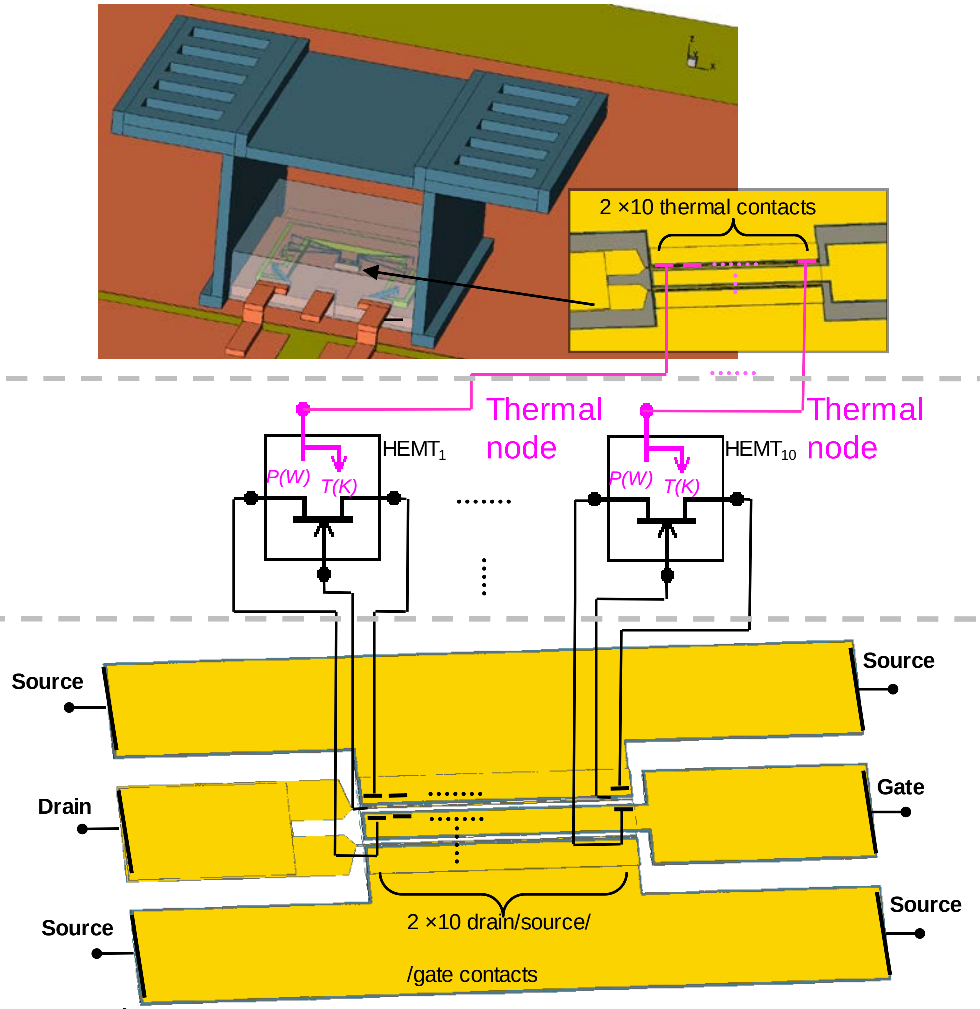
Thermal equation

Electrical circuit HEMT model

Circuit equation

3-D FEM electrical model of metallization

Poisson equation



Chvala, A. et al., In Proc. SISPAD, Washington, DC, p. 116, Sep. 2015

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

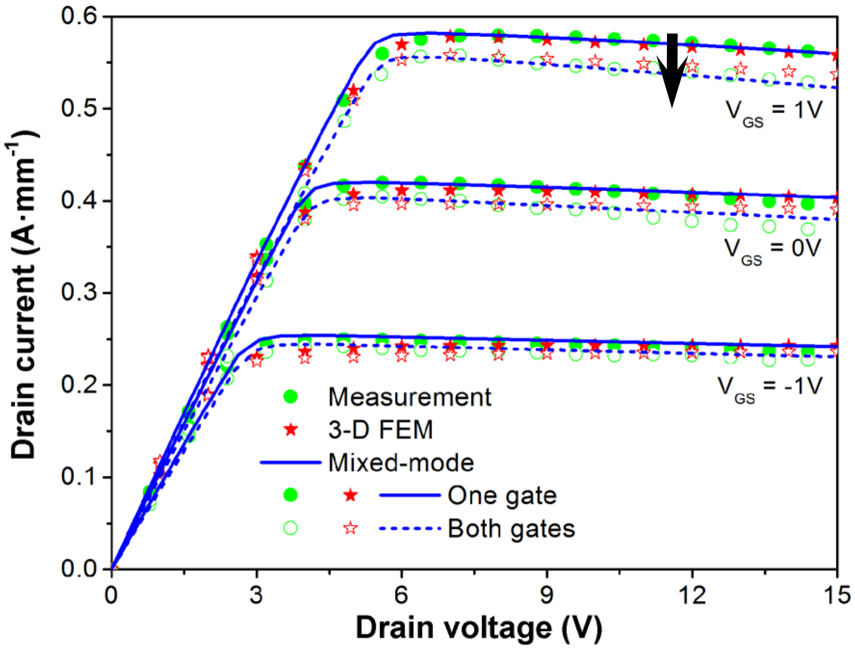
Mixed-mode setup (3-D thermal + equivalent circuit model)

Simulation time: **2 min** @ 140 000 package mesh elements
4 500 metallization mesh elements
20 HEMTs

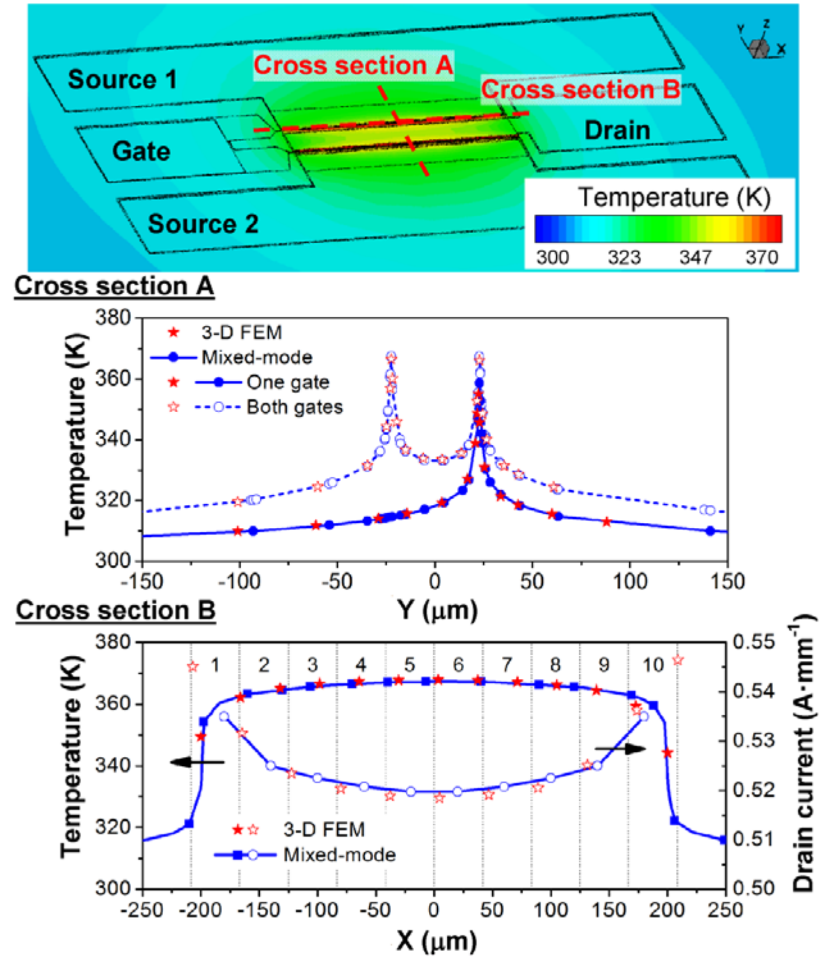
- ☺ High speed of simulation
- ☺ Allows 3-D heat flux in whole system
- ☺ Calculates current distribution in metallization

Electrothermal analysis of multifinger HEMT

Comparison of measured and simulated output characteristics

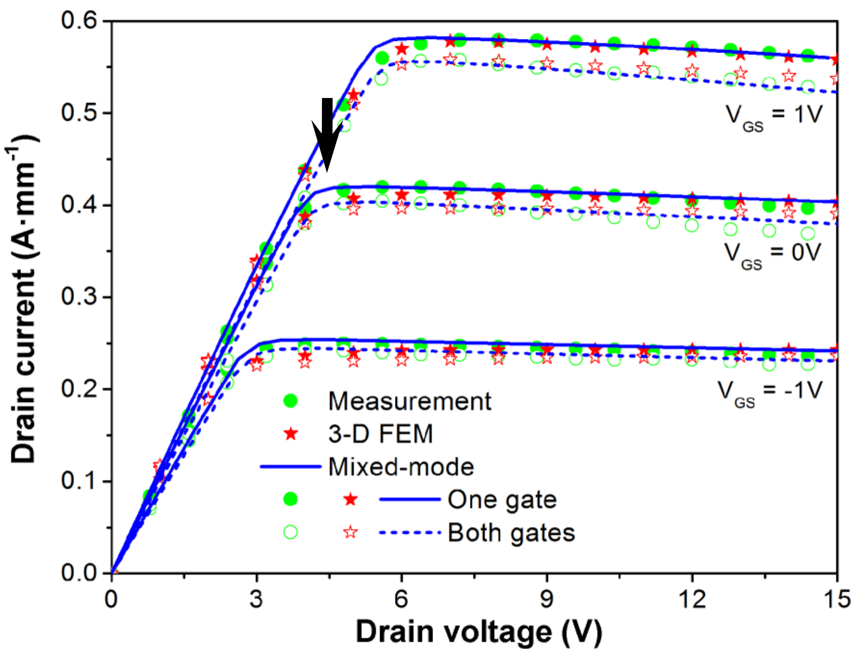


Temperature distribution in the HEMT device

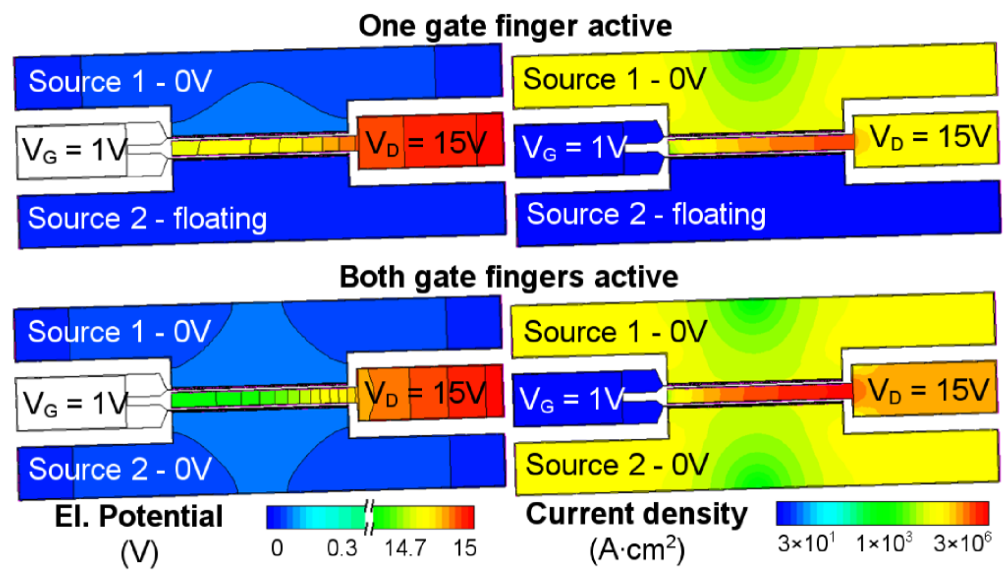


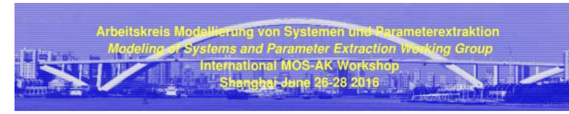
Electrothermal analysis of multifinger HEMT

Comparison of measured and simulated output characteristics



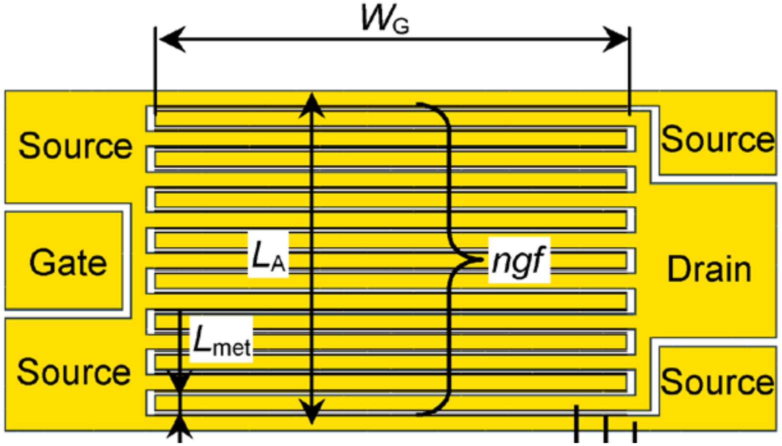
Electrostatic potential and current flow in the metallization



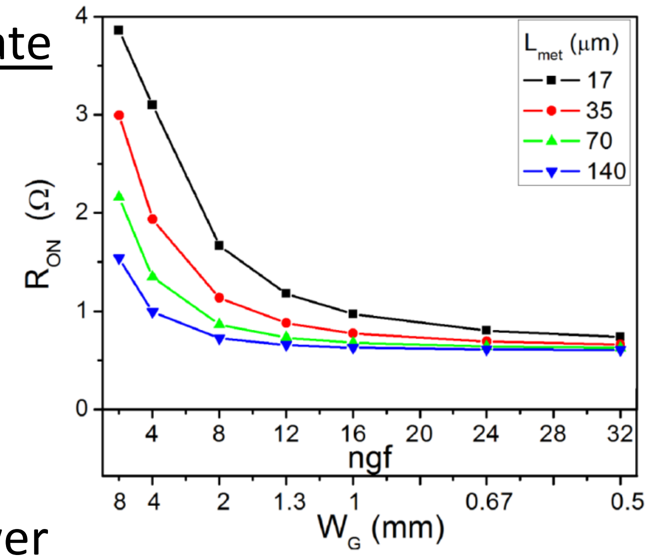


Electrothermal analysis of multifinger HEMT

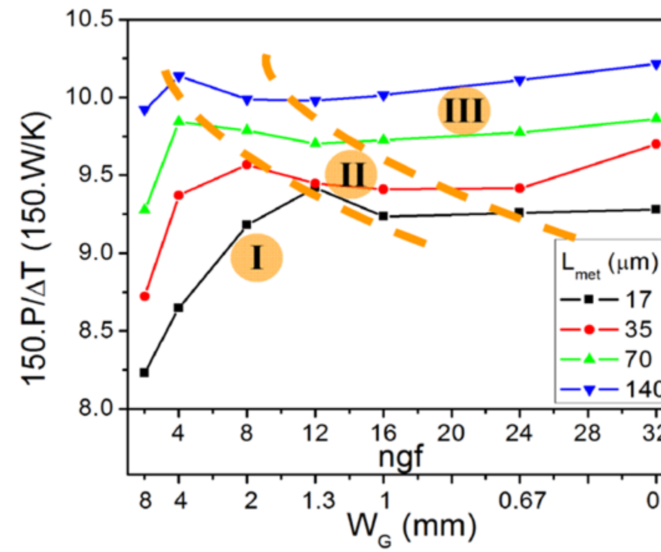
Metallization of multifinger HEMT structure



Resistance at on-state



Dissipated power capability

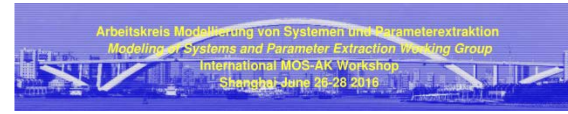


Investigated variables:

- number of gate fingers ***ngf***
- gate finger width $\boldsymbol{W_G}$ ($ngf \times W_G$=16mm)
- drain/source metallization width $\boldsymbol{L_{met}}$ (finger spacing)

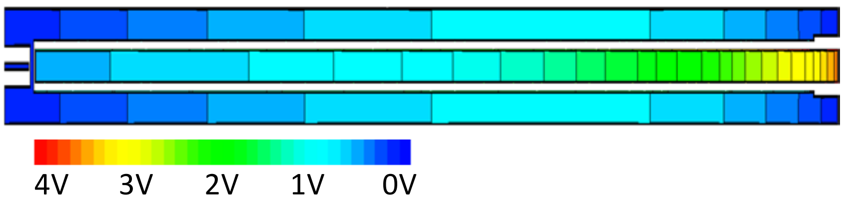
Simulation time: ~15 min

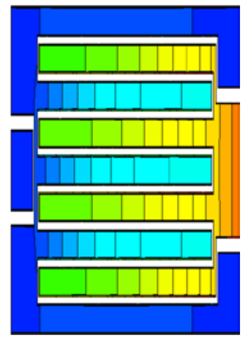
(@ ~250 000 package, ~50000 metallization)



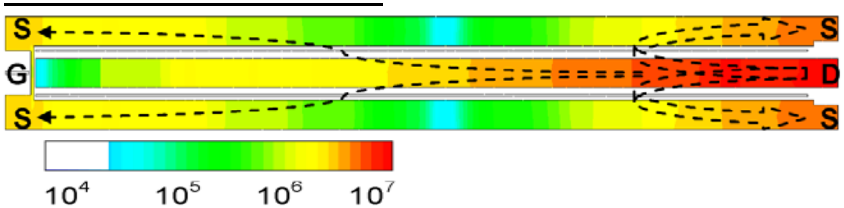
Electrothermal analysis of multifinger HEMT

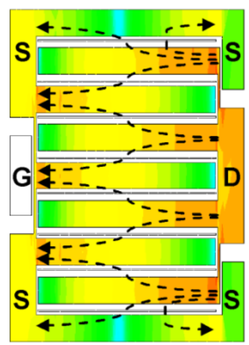
Electrostatic potential in the metallization



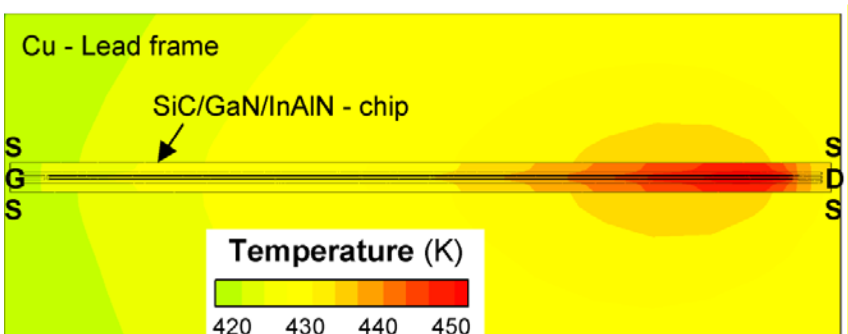


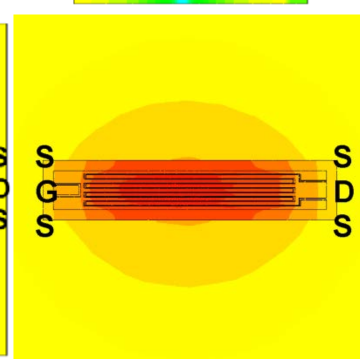
Current density distribution in the metallization

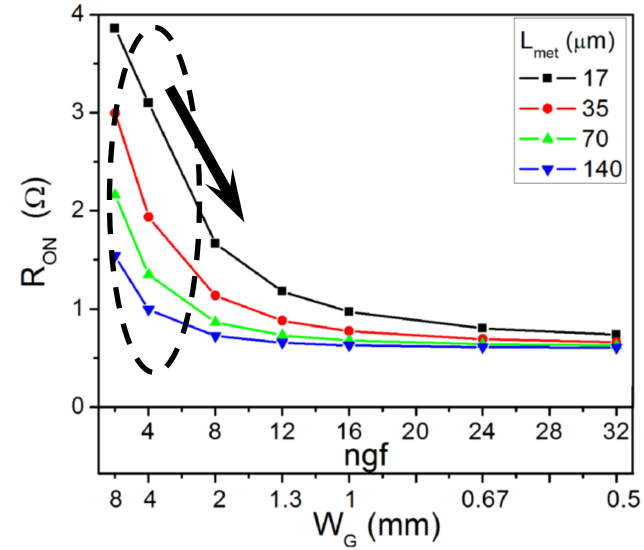


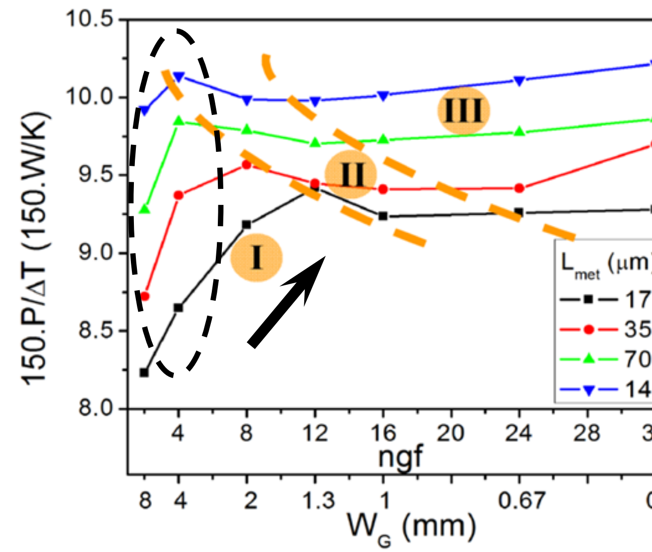


Temperature distribution



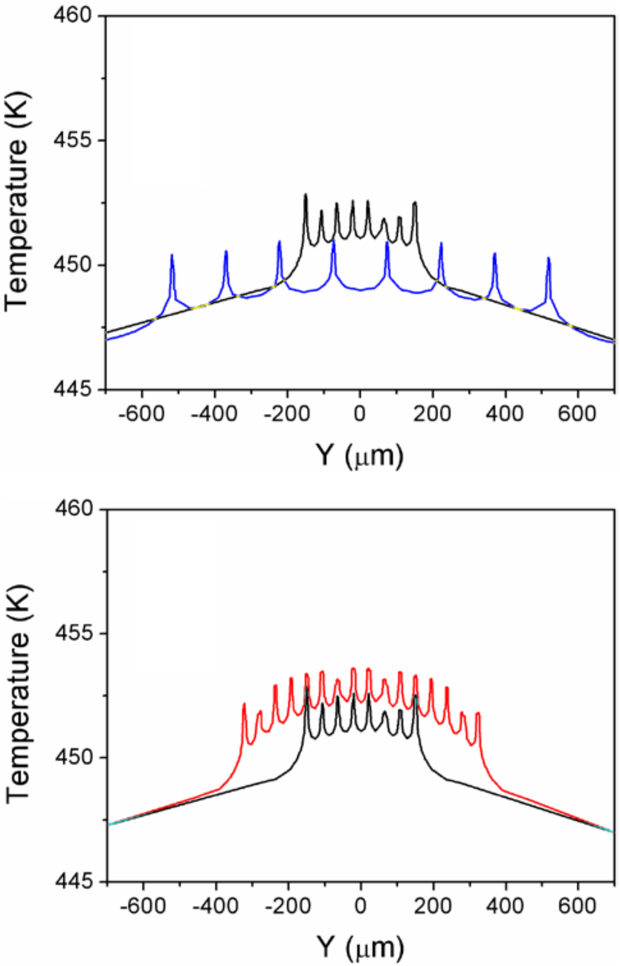




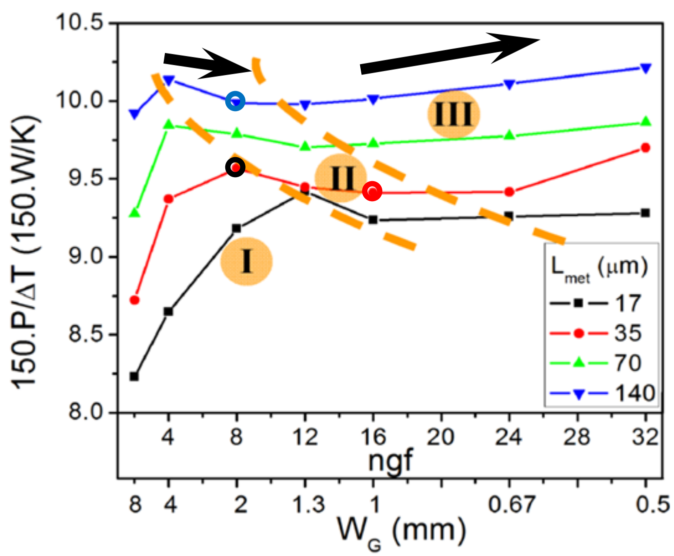


Electrothermal analysis of multifinger HEMT

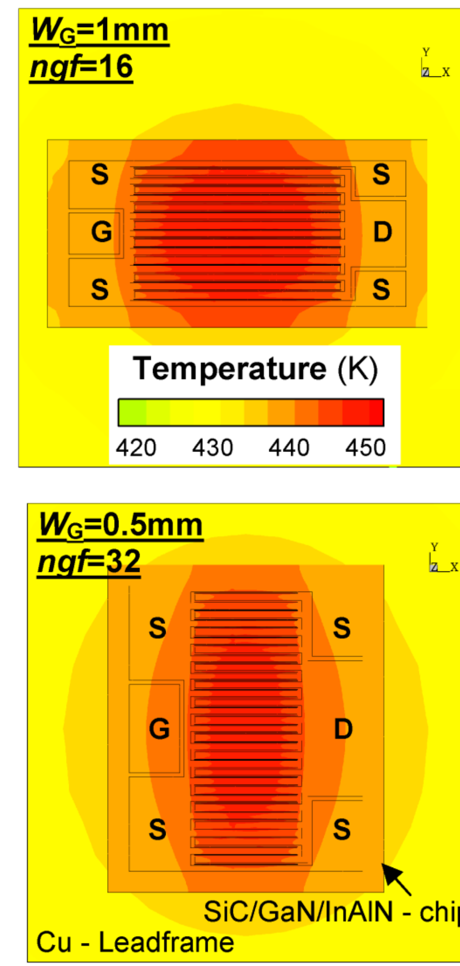
Temperature distribution across gate fingers



Dissipated power capability



Temperature distribution



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

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