Ciro Scognamillo

Analysis of heat propagation and electrothermal effects in electronic devices and circuits

Tutor: Prof. Vincenzo d'Alessandro

Cycle: XXXV

Year: 2021/2022

Background information

- **Background**: BSc and MSc in Electronics Engineering – Università degli Studi di Napoli Federico II
- **Research group/laboratory**: Thermal and Electrothermal Analyses Research Group (ING-INF/01)
- **PhD start and end dates**: 01/11/2019 – 31/01/2023
- **Cooperations**: Politecnico di Milano, Universitè de Bordeaux, Kyoto University of Advanced Science, Qorvo, Primes Laboratories, Deep Concept

Scholarship

The funding for my Ph.D. was generously donated by the Rinaldi family **in the memory of Prof. Niccolò Rinaldi**.

Summary of study activities

Year	Course Title	Type	Credits
1	Matlab Foundamentals	Ad hoc course	2
1	Scientific Programming and Visualization with Python	Ad hoc course	2
1	Innovation management, entrepreneurship, and intellectual property	Ad hoc course	5
1	Design and Implementation of Augmented Reality Software Systems	Ad hoc course	4
1	Machine Learning	Ad hoc course	3.6
1	Topics on Microelectronics	Ad hoc course	5
2	MATLAB Associate Certification	Ad hoc course	3.0
2	Real Time Embedded Systems	Ad hoc course	2.5
3	Deep Learning and Neural Networks	External course	6

PhD Year	Institution	Hosting tutor	Period
1st	Primes Laboratories, Tarbes, France	Dr. Philippe Lasserre	13/01/2020 – 17/01/2020
3rd	Université de Bordeaux, Bordeaux, France	Prof. Thomas Zimmer Dr. Sebastien Fregonese	15/10/2021– 15/04/2022

Oral and poster presentations

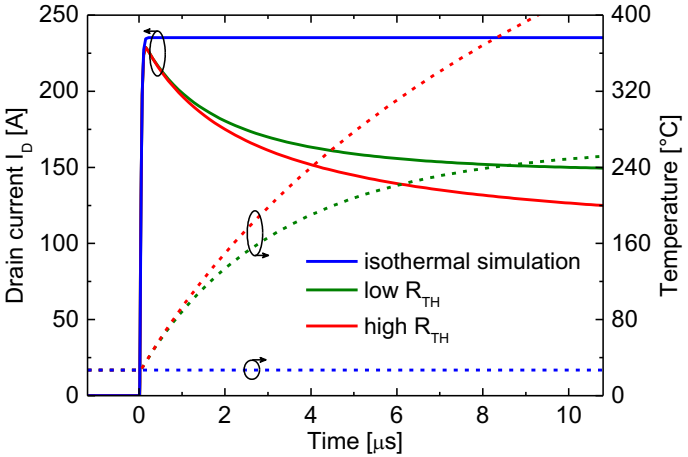
***8* oral** and ***1* poster** presentations at**:**

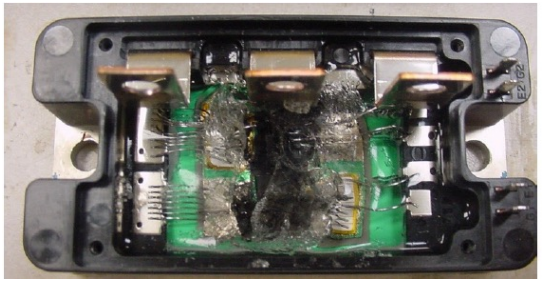
- THERMINIC 2020, 2021 (2), 2022
- EuroSimE 2020
- ESREF 2020
- ISPSD 2021
- PRIME 2022
- SIE 2022

Research area

Devices heat up as they dissipate power:

- Influence of **temperature** on **electrical characteristics**
- Reduced **long-term reliability** and increased **failure likelihood**





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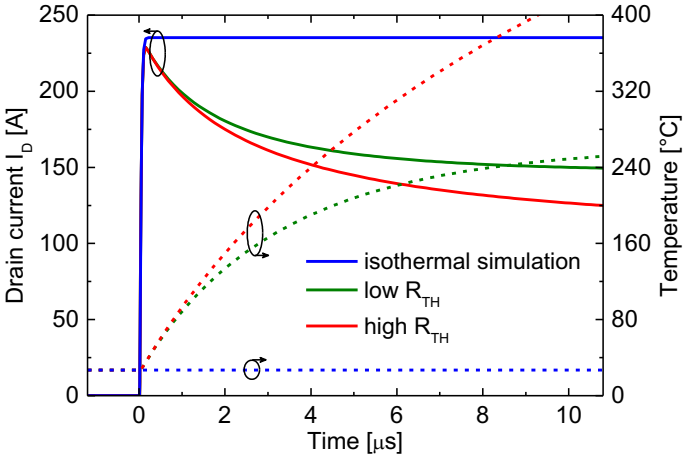
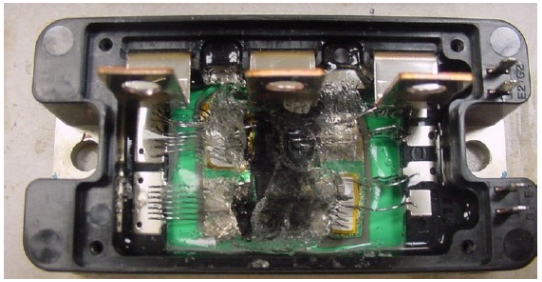
- **Miniaturization** (higher power density)
- **New manufacturing solutions** (hindering the heat propagation)
- **Innovative materials** (lower *k* values)





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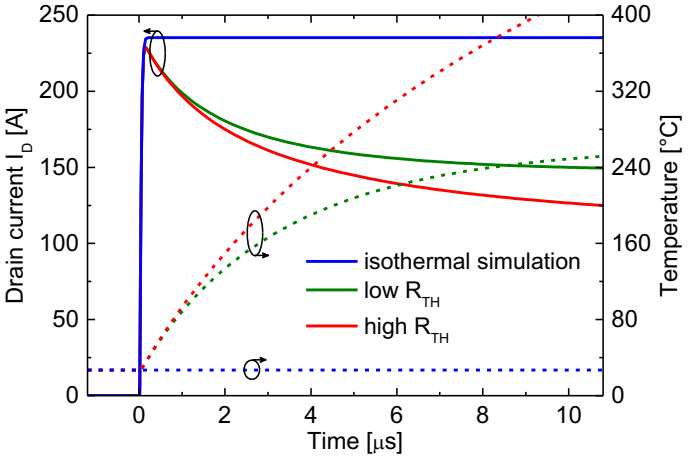

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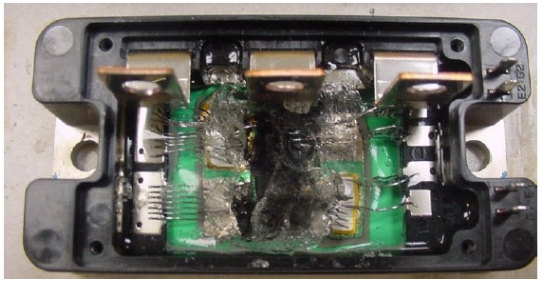

Analysis of the **thermal** and **electrothermal behavior** of electronic devices and circuits aimed at **efficient** and **accurate electrothermal (ET) simulations.**

PhD thesis overview

- Problem statement

  ET simulations *are* ***time-*** *and* ***CPU-/memory-demanding***

  Designers would ***benefit from fast and accurate tools***

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  Accurate extraction of thermal metrics *(R_{TH} and Z_{TH}) and solve the* ***ET feedback within the SPICE environment***

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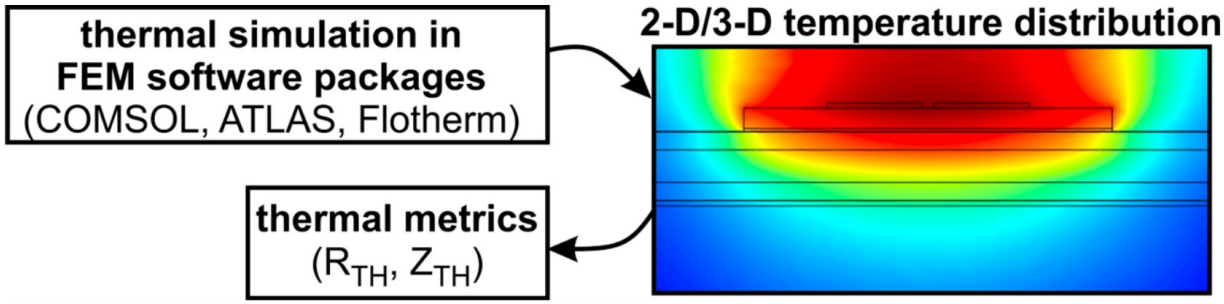
- Methodology

  FEM thermal simulations, ***MOR-based approaches****, innovative experimental technique for the* ***in-situ extraction of Z_{TH}***

PhD thesis
Analysis of heat propagation and electrothermal effects in electronic devices and circuits



FEM-based thermal analysis

PhD thesis
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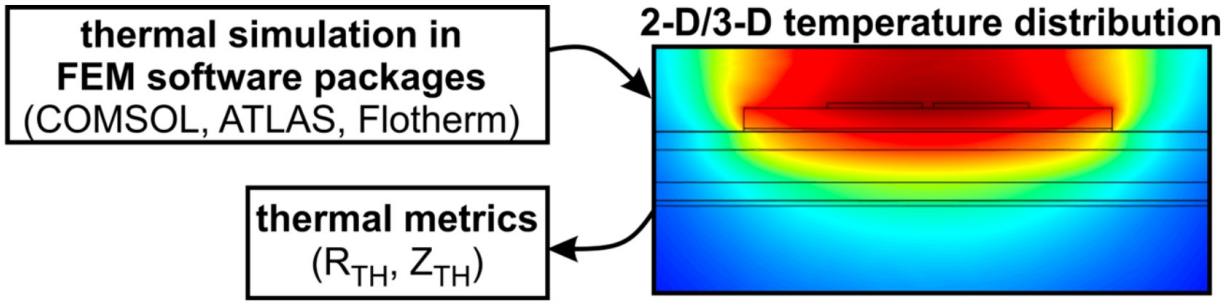
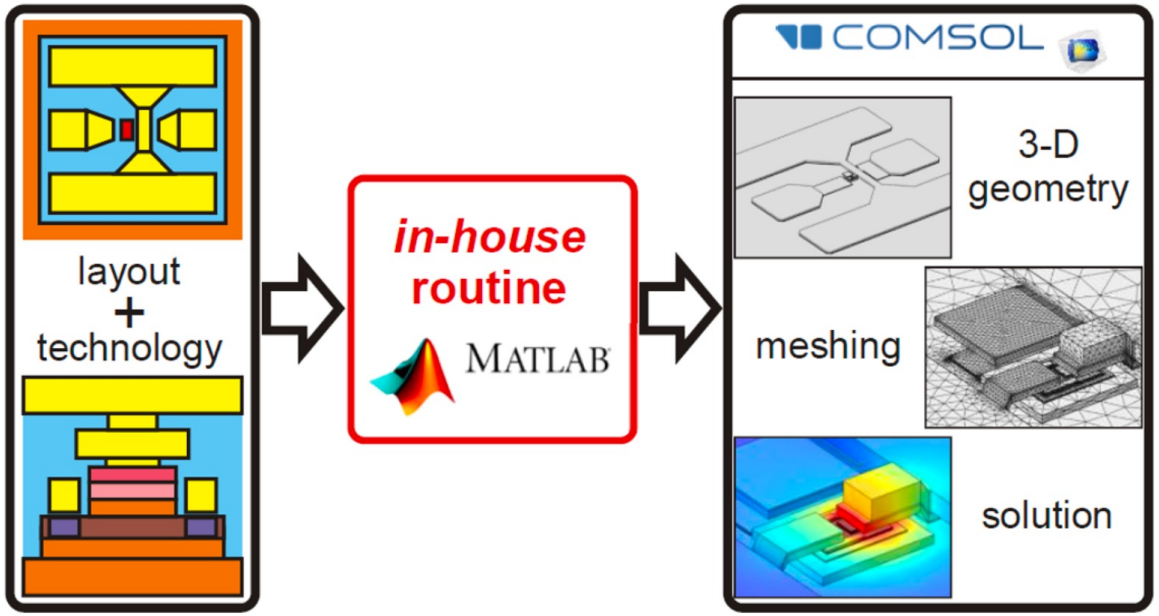


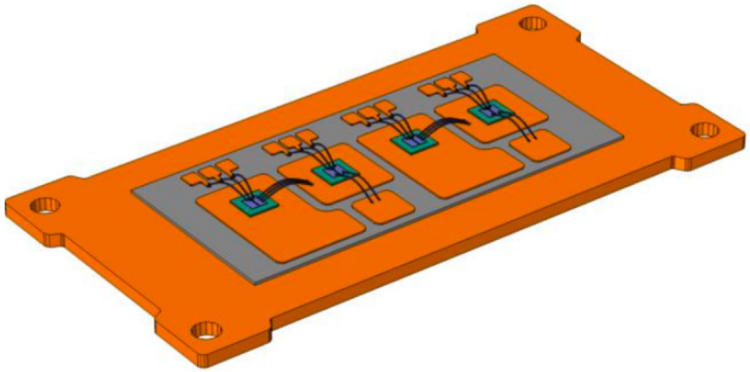
FEM-based thermal analysis

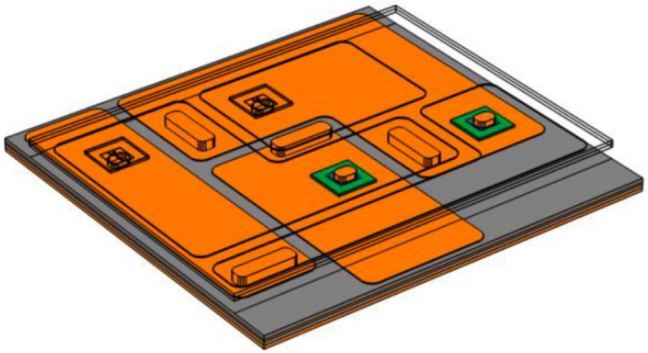
***in-house* routine** to automatically (i) **evaluate thermal metrics** and (ii) **obtain temperature distributions**



PhD thesis

SSC vs. DSC





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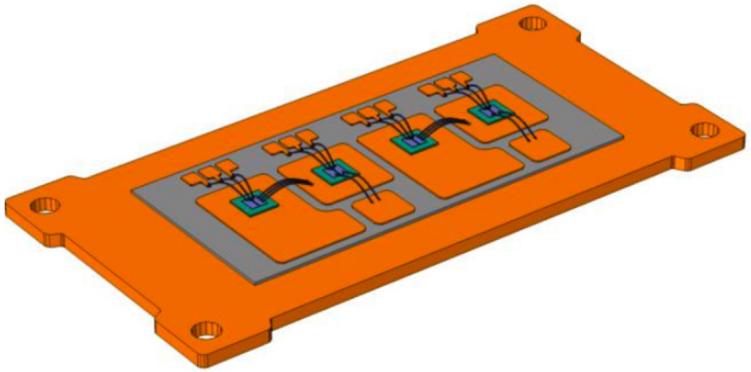
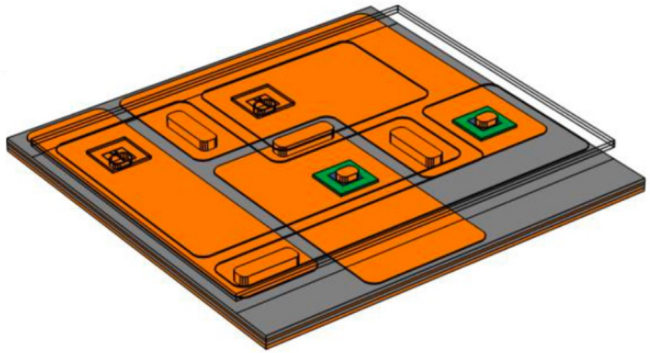
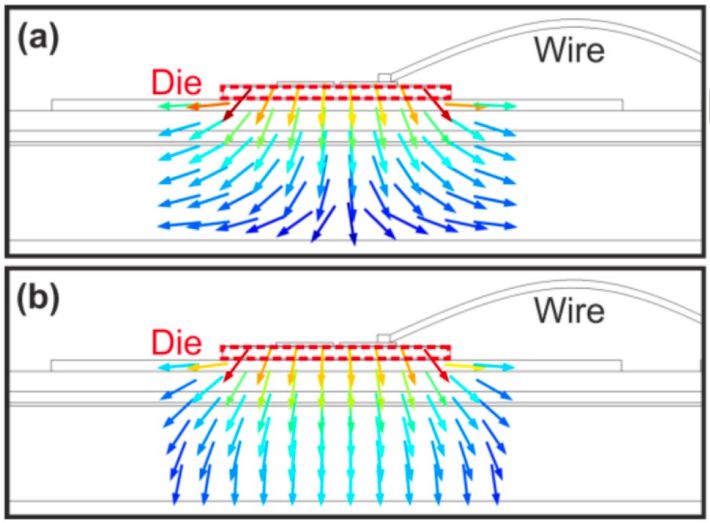




low *h*

high *h*



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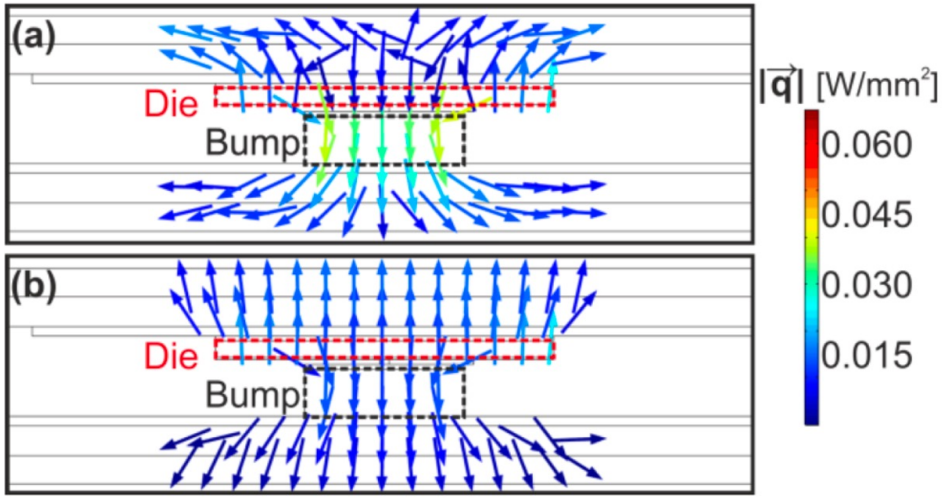
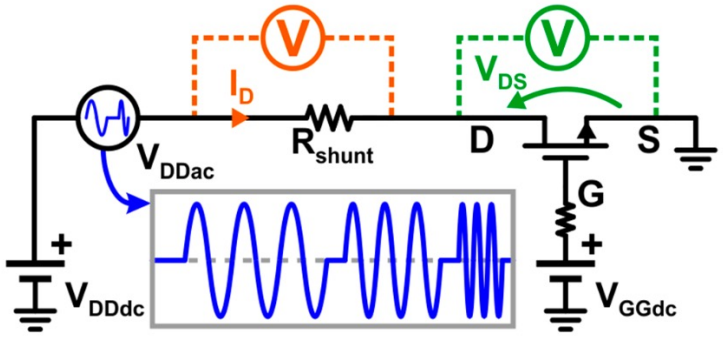


PhD thesis

Innovative *in-situ* technique to <u>measure</u> thermal metrics (Z_{TH})



$$g_o = \frac{RMS\left(I_D\left(t\right) - I_{Ddc}\right)}{RMS\left(V_{DS}\left(t\right) - V_{DSdc}\right)} = \frac{RMS\left(I_{Dac}\left(t\right)\right)}{RMS\left(V_{DSac}\left(t\right)\right)}$$

- Purely-electrical measurements
- No need for laboratory equipment
- Accounts for environmental conditions

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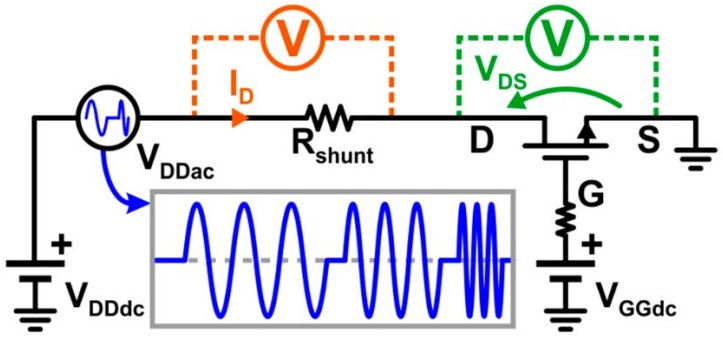

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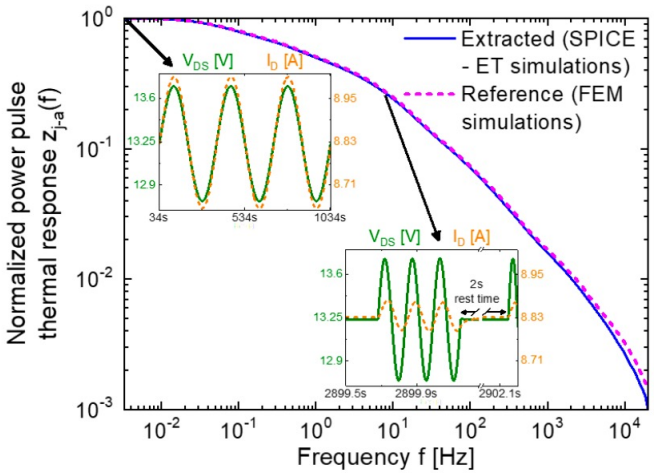
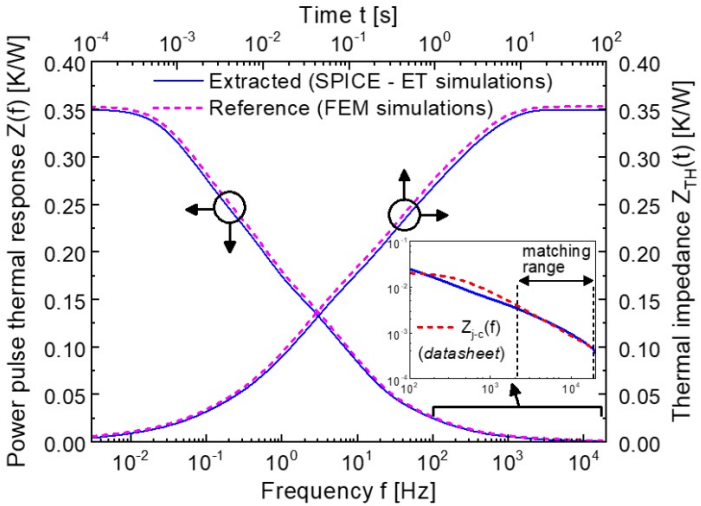
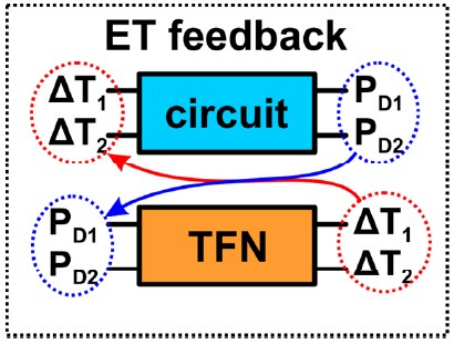
Validation through '*simulated experiments*' on **SiC-** and **GaN-based power devices**





PhD thesis



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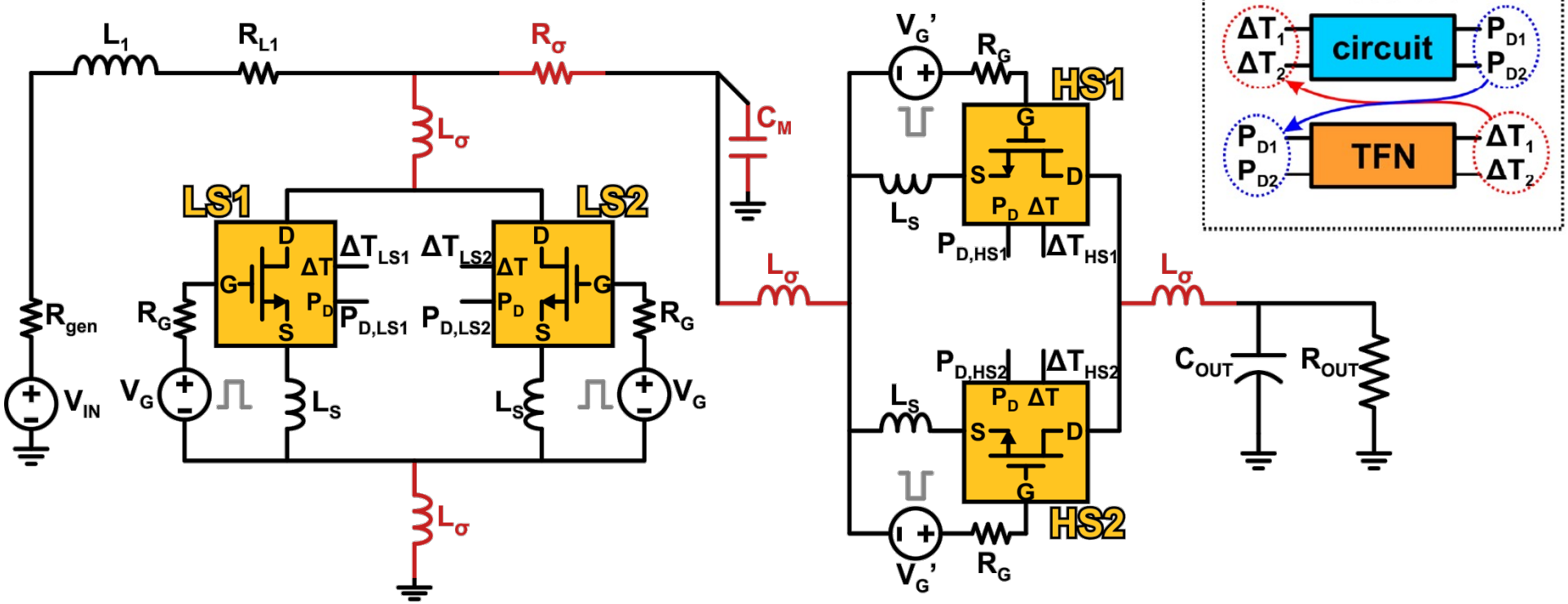
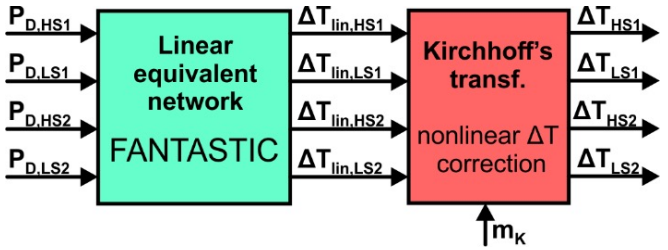


R_σ	4 mΩ
L_σ	30 nH
C_M	118 pF

Step-up configuration
with parasitics



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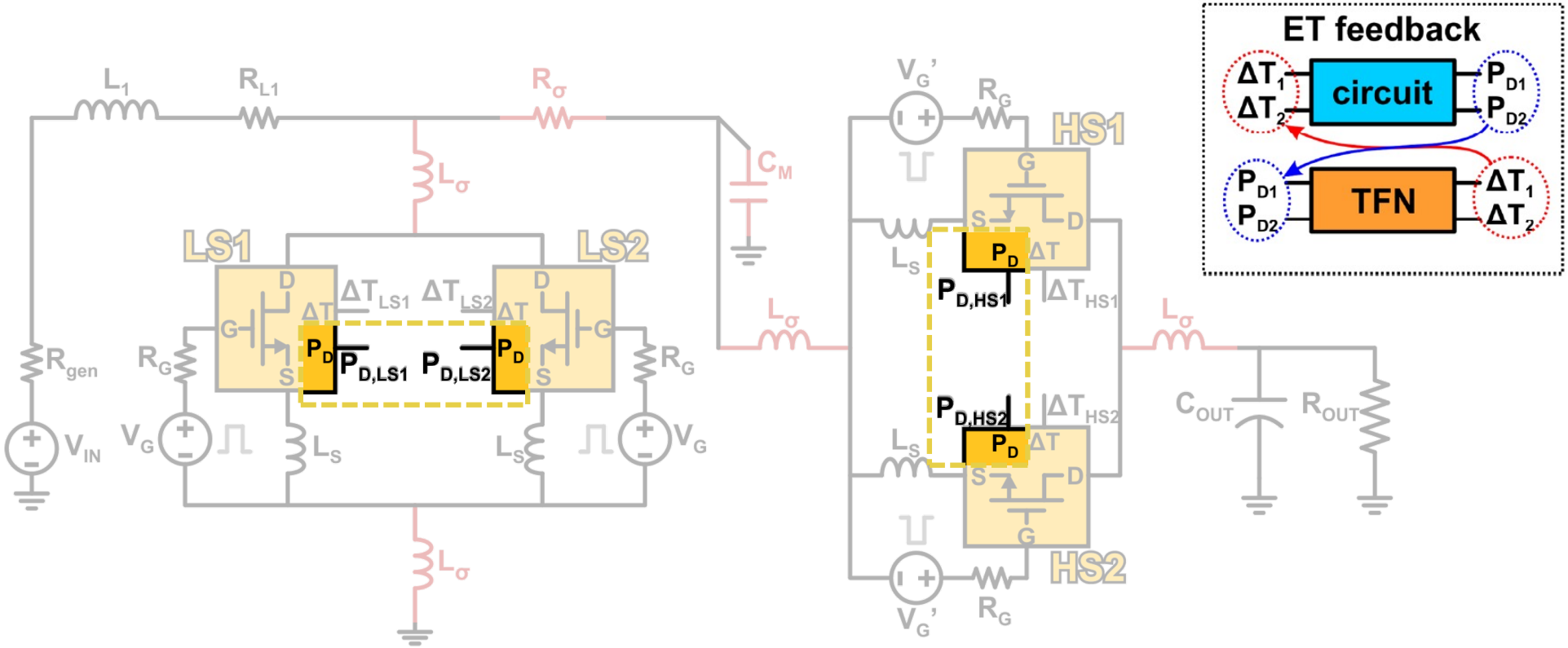

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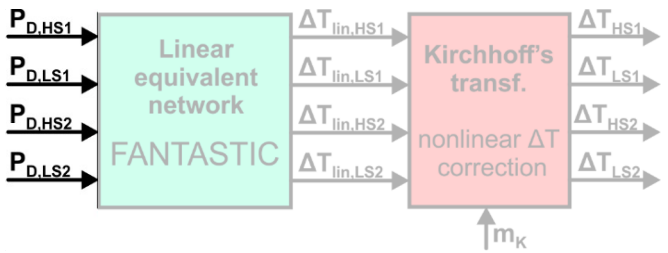

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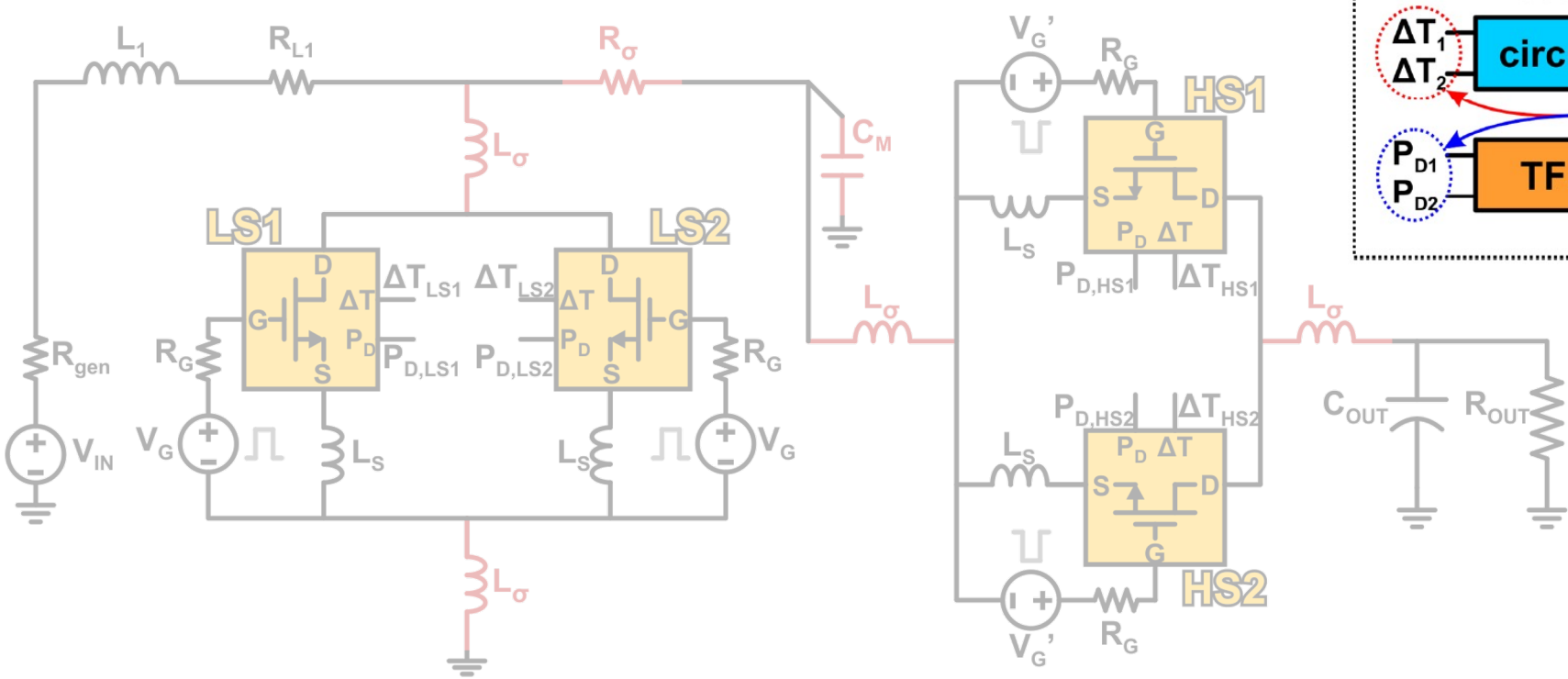

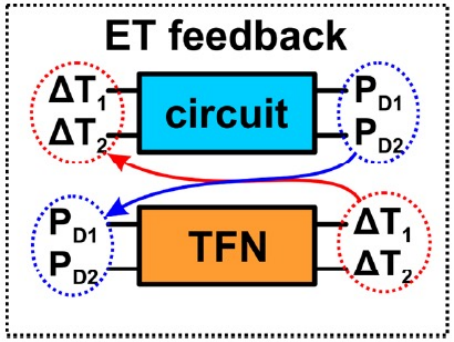

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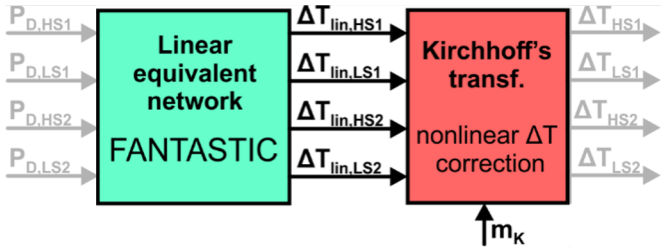
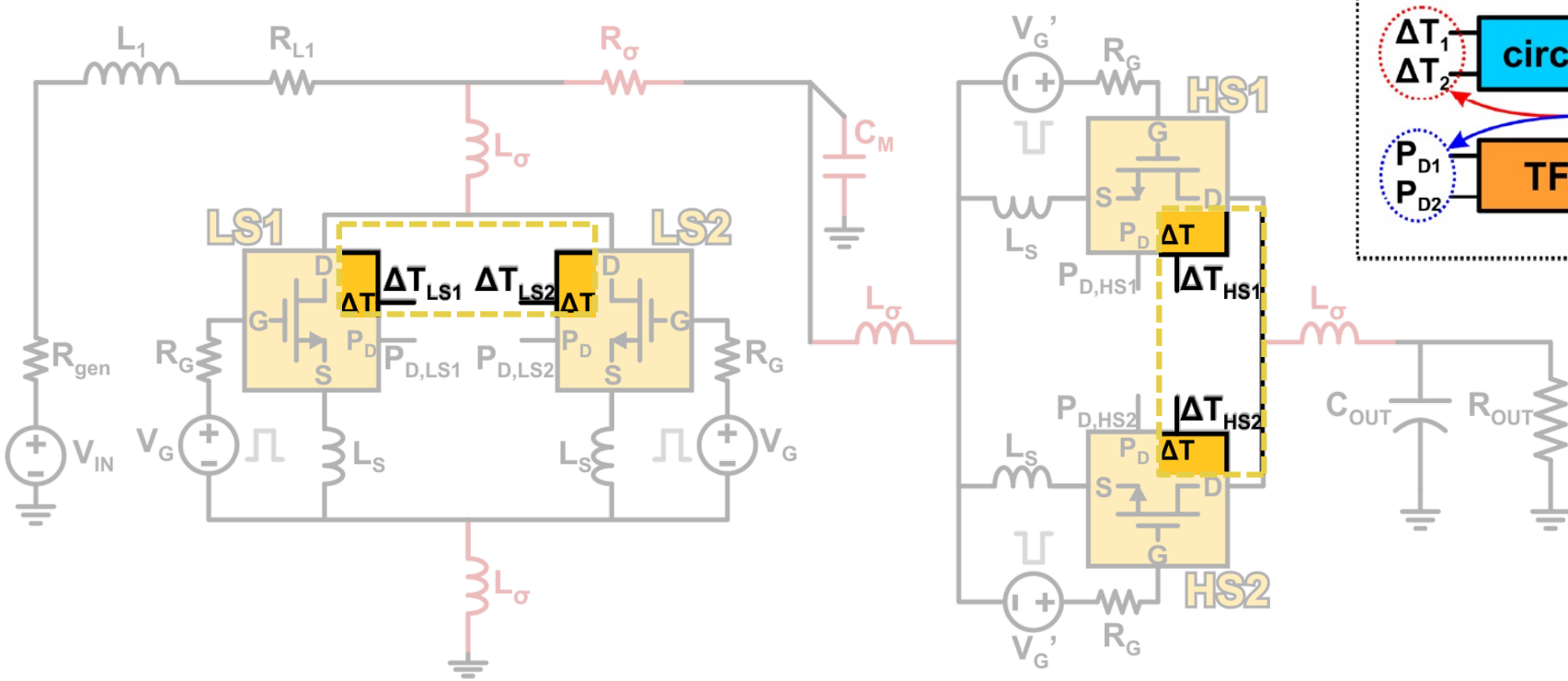
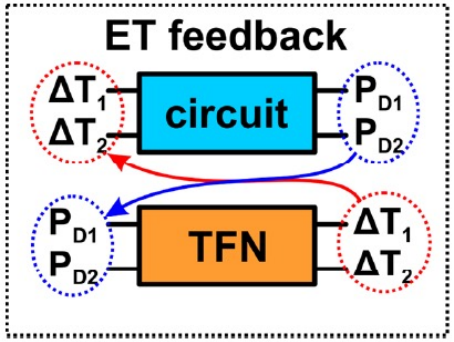


PhD thesis





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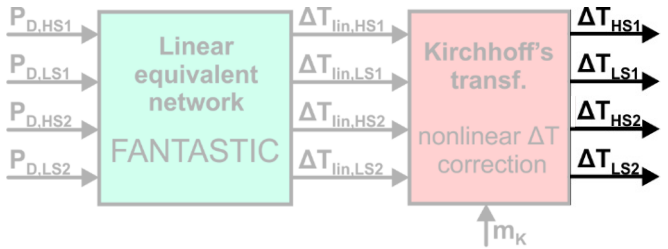

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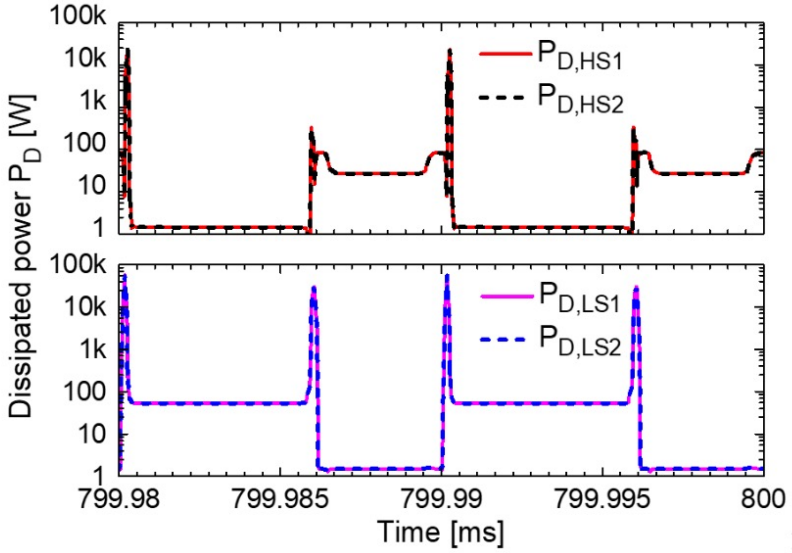


R_G	2 Ω	4 Ω	6 Ω
η	95.17%	94.35%	93.55%

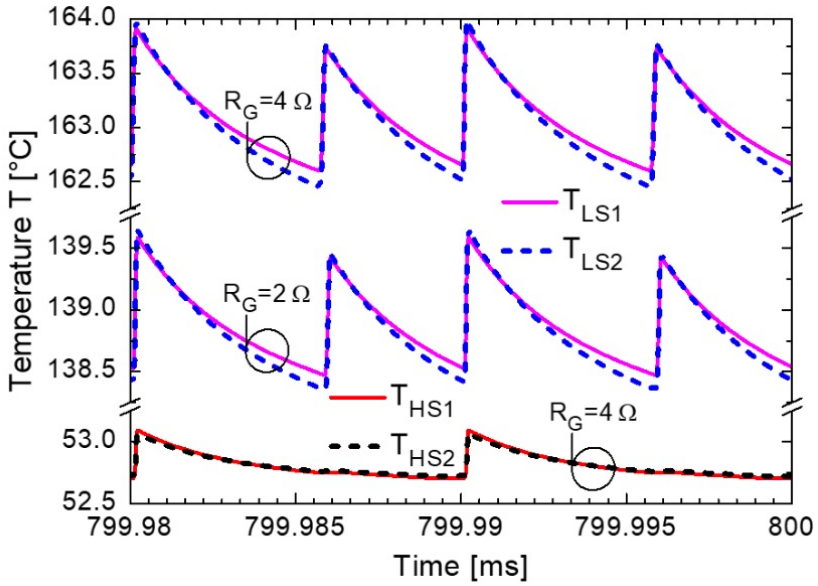
f_{SW}	105 kHz	100 kHz	90 kHz
η	93.49%	94.35%	95.59%

☺ Robust (**no convergence issues**) and fast electrothermal simulation:

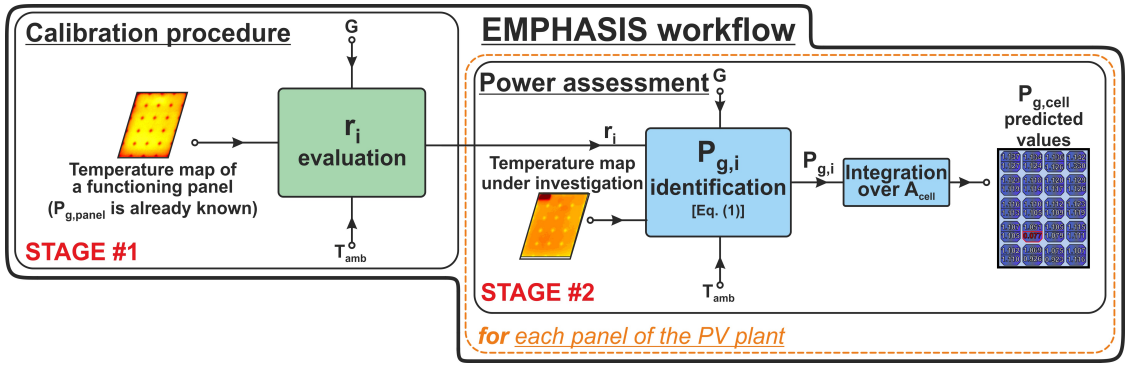
proposed tool: 0.4 s/h_{CPU}

FEM + SPICE: 0.8 μs/h_{CPU}

☺ Extremely **beneficial for designers** – no need for expensive and time-consuming prototyping stages

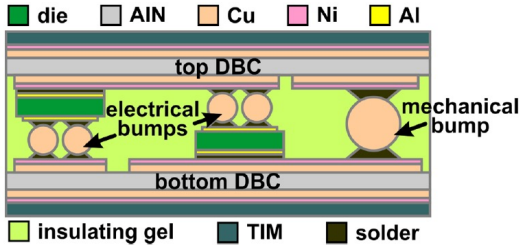


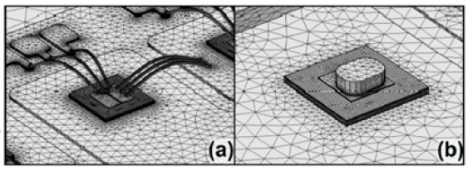
Research results

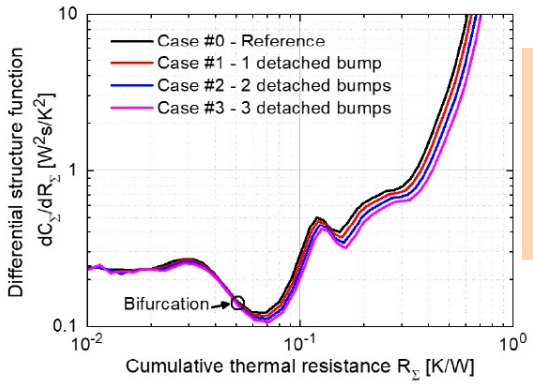


EMPHASIS

- Analytical method for fast and non-invasive fault detection in PV panels
- Tested under nonuniform environmental conditions

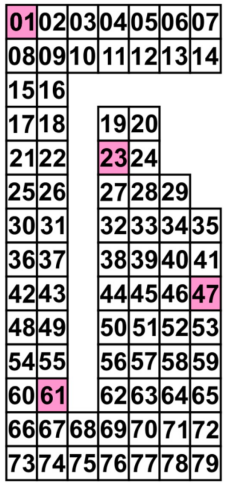


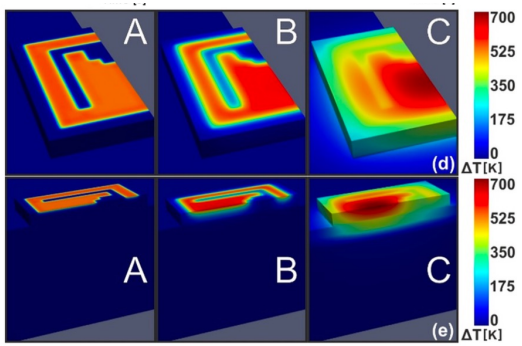




***Multicellular* ET modeling**

- Thermal and electrical interaction between cells
- Model-order reduction approach (FANTASTIC)





Power modules investigation

- Structure functions for defect detection in DSC PMs
- Pushout effect

Research products

A. P. Catalano et al., “Numerical analysis and analytical modeling of the thermal behavior of single- and double-sided cooled power modules,” IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 10, no. 9, pp. 1446–1453, Sep. 2020.
C. Scognamillo et al., “Combined experimental-FEM investigation of electrical ruggedness in double-sided cooled power modules,” Microelectronics Reliability, 113742, 2020.
V. d’Alessandro et al., “Circuit-based electrothermal simulation of multicellular SiC power MOSFETs using FANTASTIC,” Energies, vol. 13, no. 17, 4563, 2020.
A. P. Catalano et al., “Using EMPHASIS for the thermography-based fault detection in photovoltaic plants,” Energies, vol. 14, no. 16, 1559, 2021.
V. d’Alessandro et al., “Analysis of electrothermal effects in devices and arrays in InGaP/GaAs HBT technology,” Electronics, vol. 10, no. 6, 757, 2021.
L. Codecasa et al., “Accurate and efficient algorithm for computing structure functions from the spatial distribution of thermal properties in electronic devices,” IEEE Transactions on Electron Devices, vol. 68, no. 11, pp. 5386–5393, 2021.
C. Scognamillo et al., “Compact modeling of a 3.3 kV SiC MOSFET power module for detailed circuit-level electrothermal simulations including parasitics,” Energies, vol. 14, no. 15, 4683, 2021.
V. d’Alessandro et al., “Experimental Determination, Modeling, and Simulation of Nonlinear Thermal Effects in Bipolar Transistors under Static Conditions: A Critical Review and Update,” Energies, vol. 15, no. 15, 5457, 2022.
C. Scognamillo et al., “A Technique for the In-Situ Experimental Extraction of the Thermal Impedance of Power Devices,” IEEE Transactions on Power Electronics Letters, vol. 37, no. 10, Oct. 2022.
A. P. Catalano et al., “Optimum module design I: Electrothermal,” in SiC Power Module Design: Performance, robustness and reliability, A. Castellazzi and A. Irace, IET, ch. 5. ISBN: 978-1-78561-907-6.
A. P. Catalano et al., “Optimum thermal design of high-voltage double-sided cooled multi-chip SiC power modules,” Proc. IEEE International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), Sep. 2019.
A. P. Catalano et al., “Stress-induced vertical deformations in state-of-the-art power modules: an improved electro-thermo-mechanical approach,” Proc. IEEE International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Jul. 2020.
A. P. Catalano et al., “Optimization of thermal vias design in PCB-based power circuits,” Proc. IEEE International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Jul. 2020.

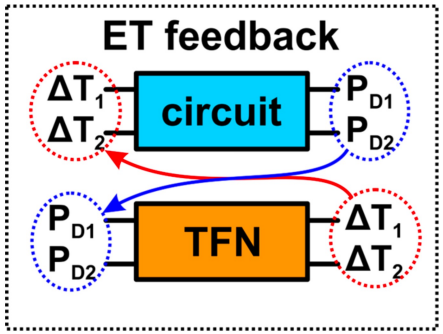
Research products

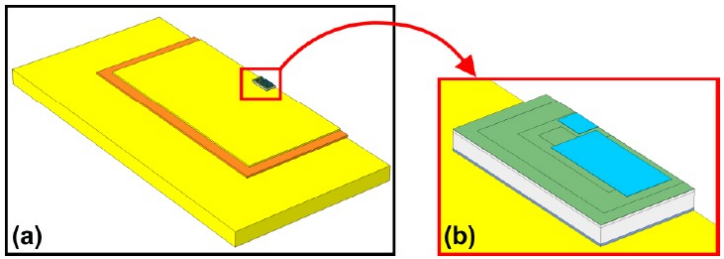
C. Scognamillo et al., “3-D FEM investigation on electrical ruggedness of double-sided cooling power modules,” Proc. IEEE International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Jul. 2020.
C. Scognamillo et al., “Numerical analysis of the thermal impact of ceramic materials in double-sided cooled power modules,” Proc. International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), Sep. 2020.
A. P. Catalano et al., “Experimental validation of analytical models for through-PCB thermal vias,” Proc. International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), Sep. 2020.
C. Scognamillo et al., “Electrothermal modeling, simulation, and electromagnetic characterization of a 3.3 kV SiC MOSFET power module,” Proc. International Symposium on Power Semiconductor Devices and ICs (ISPSD), Jun. 2021.
A. P. Catalano et al., “Study of the thermal behavior of double-sided cooled power modules,” Proc. IEEE International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), 2021.
C. Scognamillo et al., “PV fault detection through IR thermography: using EMPHASIS under uneven environmental conditions,” Proc. IEEE International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), 2021.
C. Scognamillo et al., “Defect Detection in Double-Sided Cooled Power Modules by Structure Functions,” 17th International Conference on PhD Research in Microelectronics and Electronics (PRIME), Jun. 2022.
C. Scognamillo et al., “In-Situ Thermal Impedance Extraction Technique applied to a PCB-integrated Power Device, Lecture Notes in Electrical Engineering (in press),
A. P. Catalano et al., “SPICE Modeling of Li-Ion Pouch Battery Cell Including Thermo-Electrochemical Effects”, Lecture Notes in Electrical Engineering (in press)
L. Codecasa et al., “Determining the Contribution of Spatial Sub-Regions to Structure Functions”, Proc. IEEE International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), 2022.
V. d'Alessandro et al., “Analytical Modeling and Numerical Simulation of Nonlinear Thermal Effects in Bipolar Transistors,” Proc. IEEE International Workshop on Thermal Investigations of ICs and Systems (THERMINIC), 2022.

In 2021, I received the **Borsa Califano** award from Fondazione Roma Sapienza for my activity in the field of *fault-detection and diagnostics in PV panels and strings*.

Thank you for your kind attention!

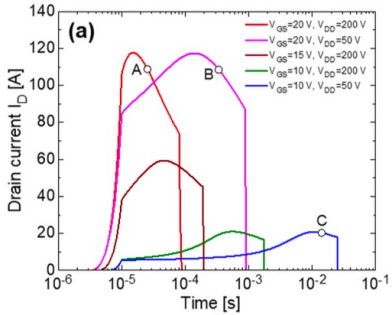
Backup #1: multicellular ET modeling

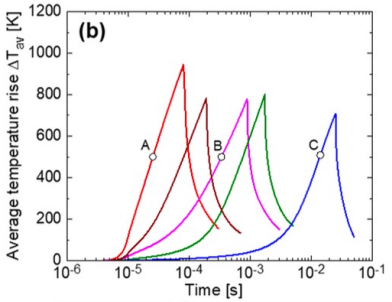


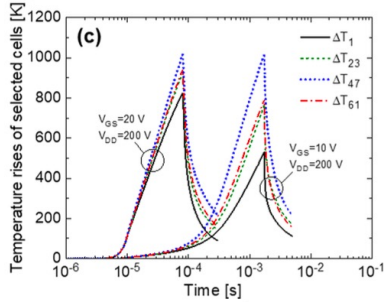


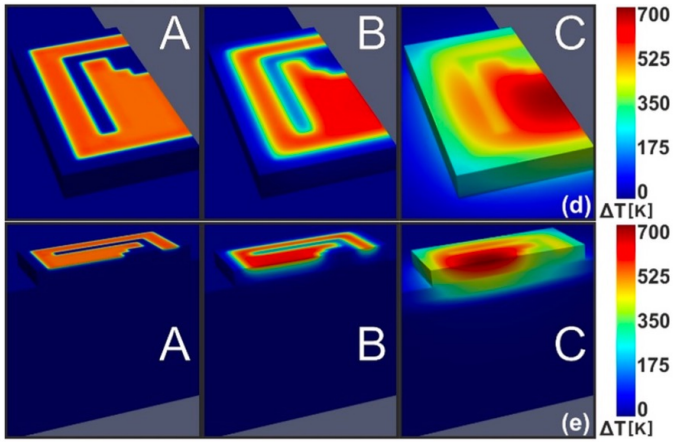
multicellular approach

01	02	03	04	05	06	07
08	09	10	11	12	13	14
15	16					
17	18		19	20		
21	22		23	24		
25	26		27	28	29	
30	31		32	33	34	35
36	37		38	39	40	41
42	43		44	45	46	47
48	49		50	51	52	53
54	55		56	57	58	59
60	61		62	63	64	65
66	67	68	69	70	71	72
73	74	75	76	77	78	79

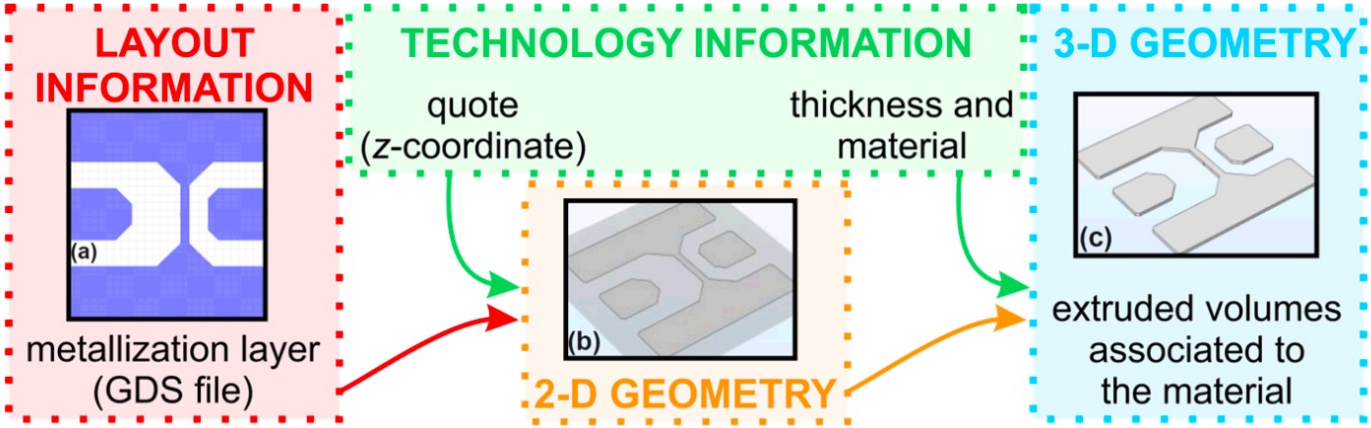


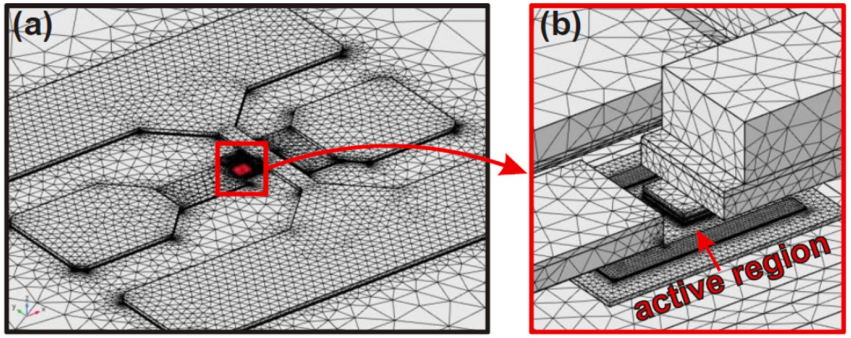


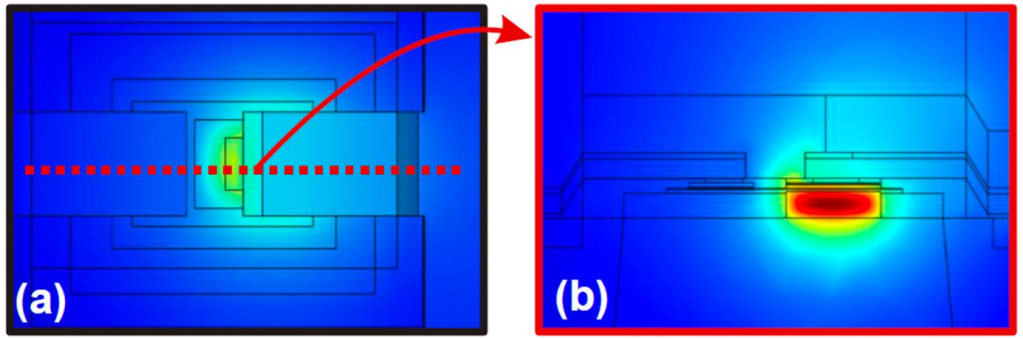




Backup #2: in-house routine

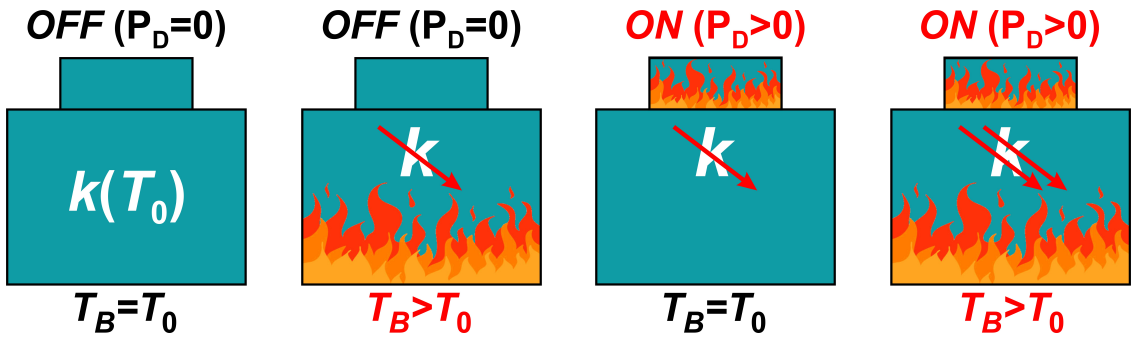


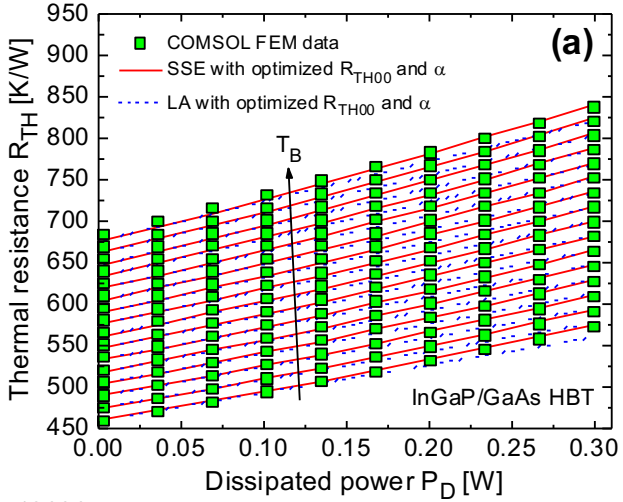


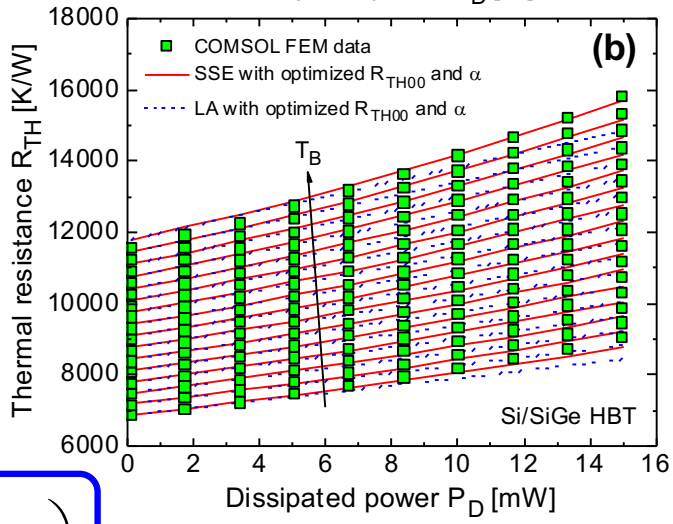


Backup #3: nonlinear thermal effects

two mechanisms concur to the ***reduction in thermal conductivities***







SSE

$$R_{TH}(T_B,P_D)=\frac{T_B}{P_D}\cdot\left\{\left[1-(\alpha-1)\cdot\frac{R_{THB0}(\alpha,R_{TH00})\cdot P_D}{T_B}\right]^{\frac{-1}{\alpha-1}}-1\right\}$$

LA

$$R_{TH}\left(T_B,P_D\right)\approx R_{THB0}(\alpha,R_{TH00})\cdot\left(1+\alpha\frac{R_{THB0}(\alpha,R_{TH00})}{2T_B}\cdot P_D\right)$$

Backup #4: EMPHASIS

Pixel area (of any size)

Temperature increment

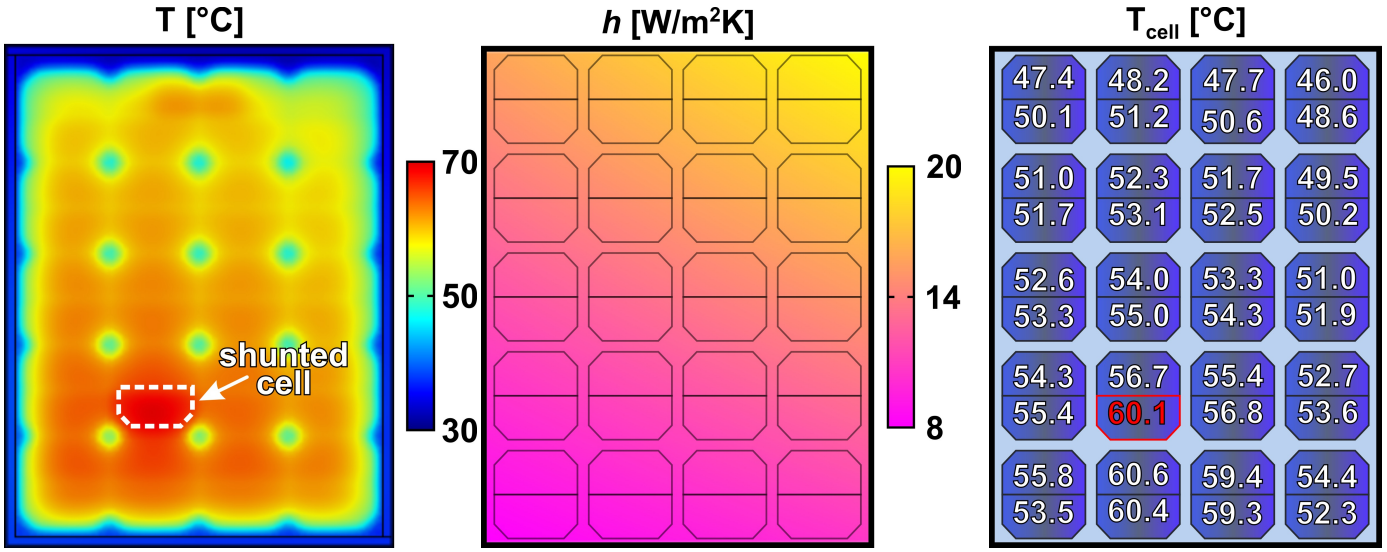
$$0.95 \cdot G \cdot A_{pixel} = P_{g,i} + \frac{(T_i - T_{amb})}{r_i} + P_{out,i}$$

Solar irradiance (reduced due to reflection)

Generated electrical power

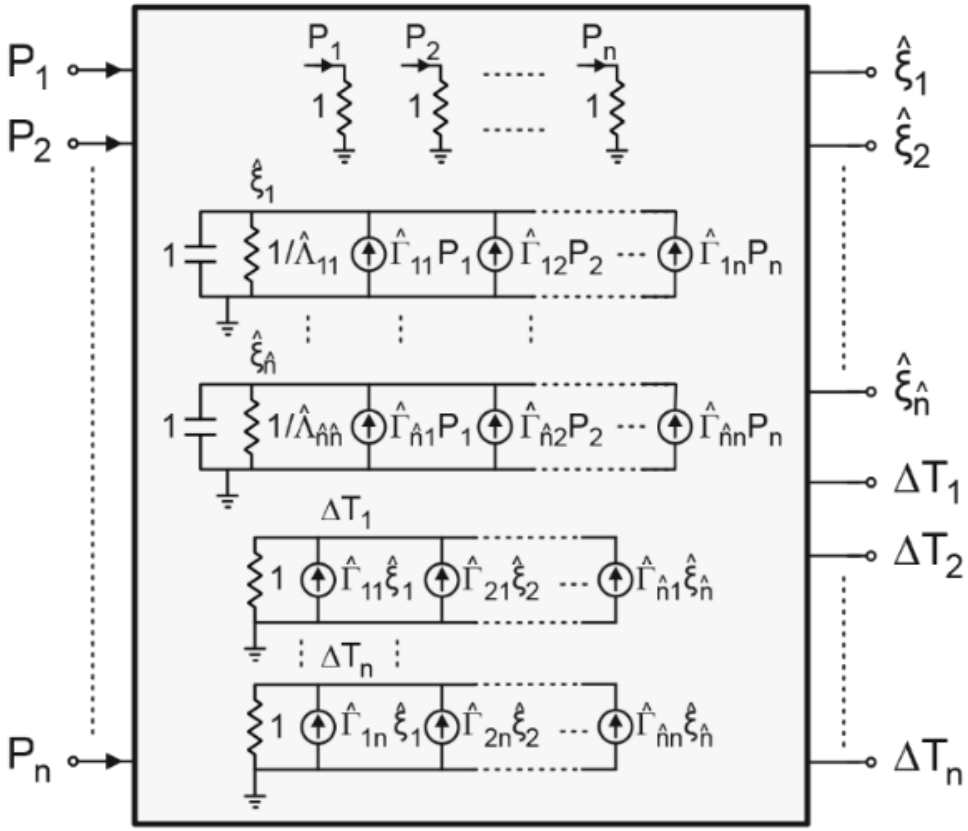
Tuning parameter

Outgoing thermal power



Efficient
Method
for **PH**otovoltaic
Arrays
Study
through **I**nfrared
Scanning

Backup #5: FANTASTIC



- ☺ Extracted **with no simulations**
- ☺ Enables the **dynamic ET feedback**
- ☺ Evaluates **self- and mutual-heating phenomena**
- ☺ Besides **input (P_i)** and **output (ΔT_i) quantities**, **state variables ($\hat{\xi}_i$)**!

Reconstruction of **space-time temperature rise distribution** at each time instant t*