

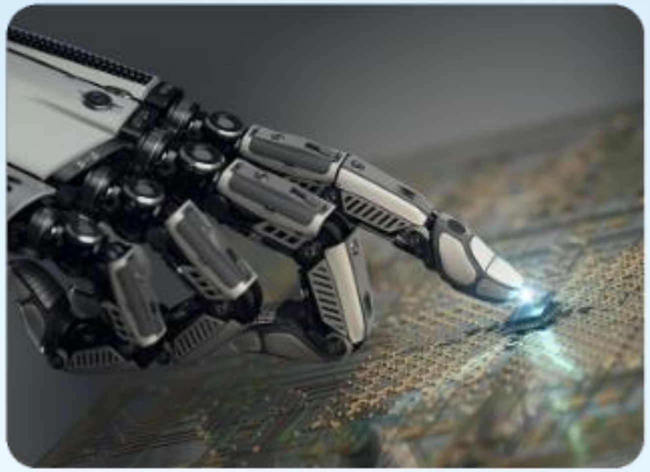

Multiphysics System Co-Design Modeling: State-of-the-Art, Challenges, and Opportunities

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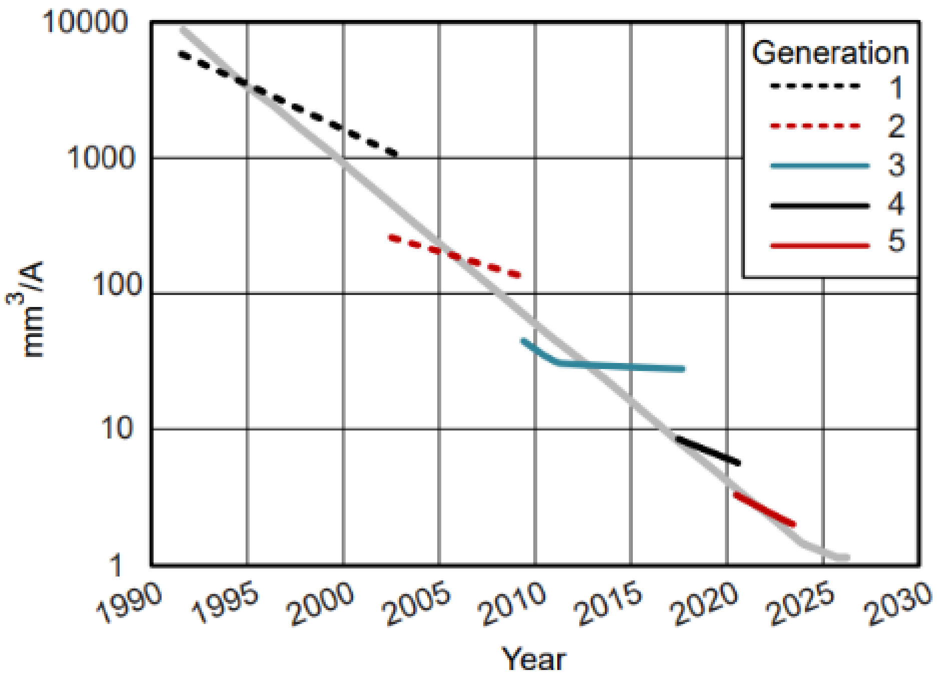
Agenda

- Evolution of Modeling to Address Current Gaps
- Multiphysics System Co-Design (MSC-D) Modeling Methodology
- Implementations of MSC-D Methodology in Automotive:
  - High-Current (40A) Step-Down Converter
  - High-Precision, High-Voltage (±600V) Isolated Hall-Effect Current Sensor
- MSC-D Challenges and Opportunities
- Summary

Gaps in Traditional Modeling Approach

- Power MOSFET is a fast growing market (revenue **US$ 6.17 Bn.** in 2021) and poised to grow at >6.2% CAGR from 2022 to 2029 (reaching **US$ 9.98 Bn**)[1].
- MOSFET scaling, miniaturization, advanced packaging, and passive integration technological development driving cost-effective solutions.
- Power density, power/unit volume, a key FoM[2] of scaling.
- However, complex integration/miniaturization is exacerbating **multiphysics** and **multidomain/multiscale** interactions, ↓performance → business impact ($$$)
- Gaps in traditional modeling approach → paradigm shift[3].



Reduction in converter size over time for 6-A to 10-A power modules with new technology generations.[2] Solid line represents a new generation of technology and demonstrates the associated gains in power density (source Ref [2]).

[1] MMR, "Power MOSFET Market: Global Overview and Forecast (2022-2029)", https://www.maximizemarketresearch.com/market-report/global-power-mosfet-market/35689/

[2] Morroni, J. and Shenoy, P., "Understanding the Trade-offs and Technologies to Increase Power Density", Texas Instruments, Inc., App Note: SLYY193A , October 2022.

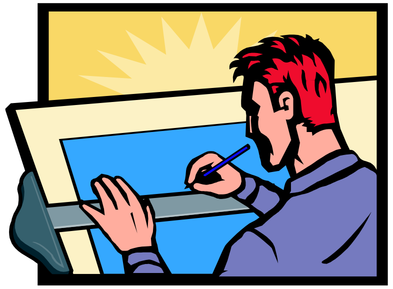
[3] Felton, K., "A new approach to IC packaging design", https://www.ednasia.com/a-new-approach-to-ic-packaging-design/, September 2020.

Evolution of Modeling: System Co-Design (Multidomain)

- “Compartmentalized and throwing-over-the-wall” – doing your part of the design and passing it off to the next team with little/if any communication.

IC Team

Package Team



PCB/System Team

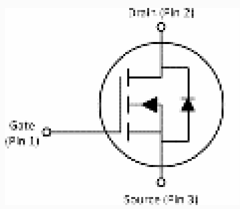
- System Co-Design Concept → ***Breaking the Wall***
  - The teams (viz. IC + Package + PCB) working collaboratively <u>early</u> in the system design phase to deliver an <u>optimized</u>, <u>cost-effective</u> product.
- What does all this mean to IC design?
  - Rethink our modeling scheme ⇒ interactions across domains
  - System Co-Design is critical ⇒ Embrace or be left behind!

Evolution of Modeling: Multiscale Modeling

- Multiscale modeling is the field of solving problems which have important features at multiple **scales of time and/or space**[4].
- It is a technique in which multiple models at different scales are used simultaneously to describe a system. A broad range of scientific and engineering problems involve multiple scales. An example of multiple scale system is a DCDC converter design.

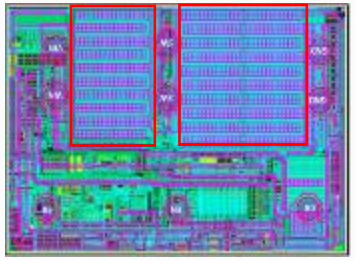
DCDC Converter

Power MOSFET



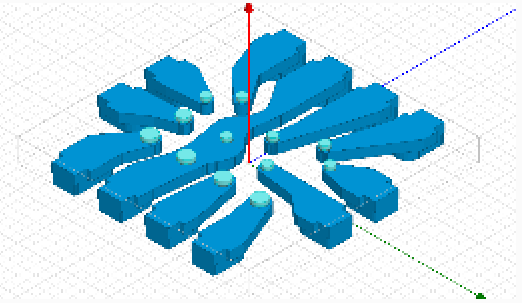
Nanometer

Chip



Micrometer

Package

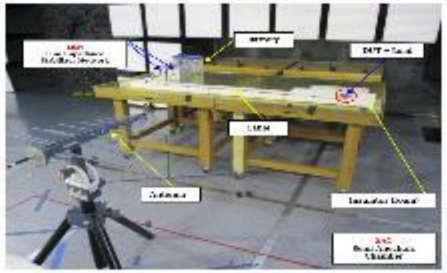


Millimeter

PCB

Centimeter

System

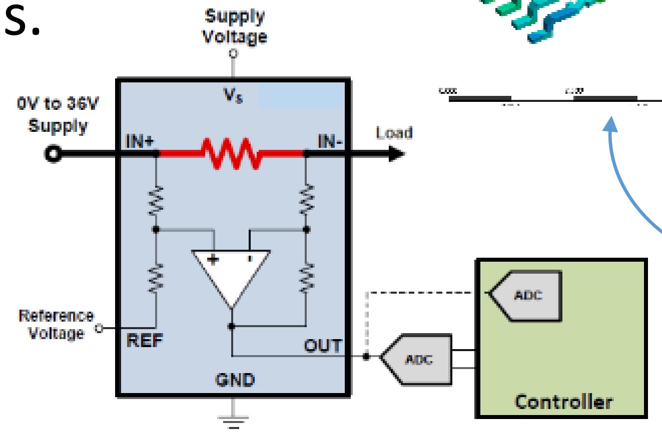


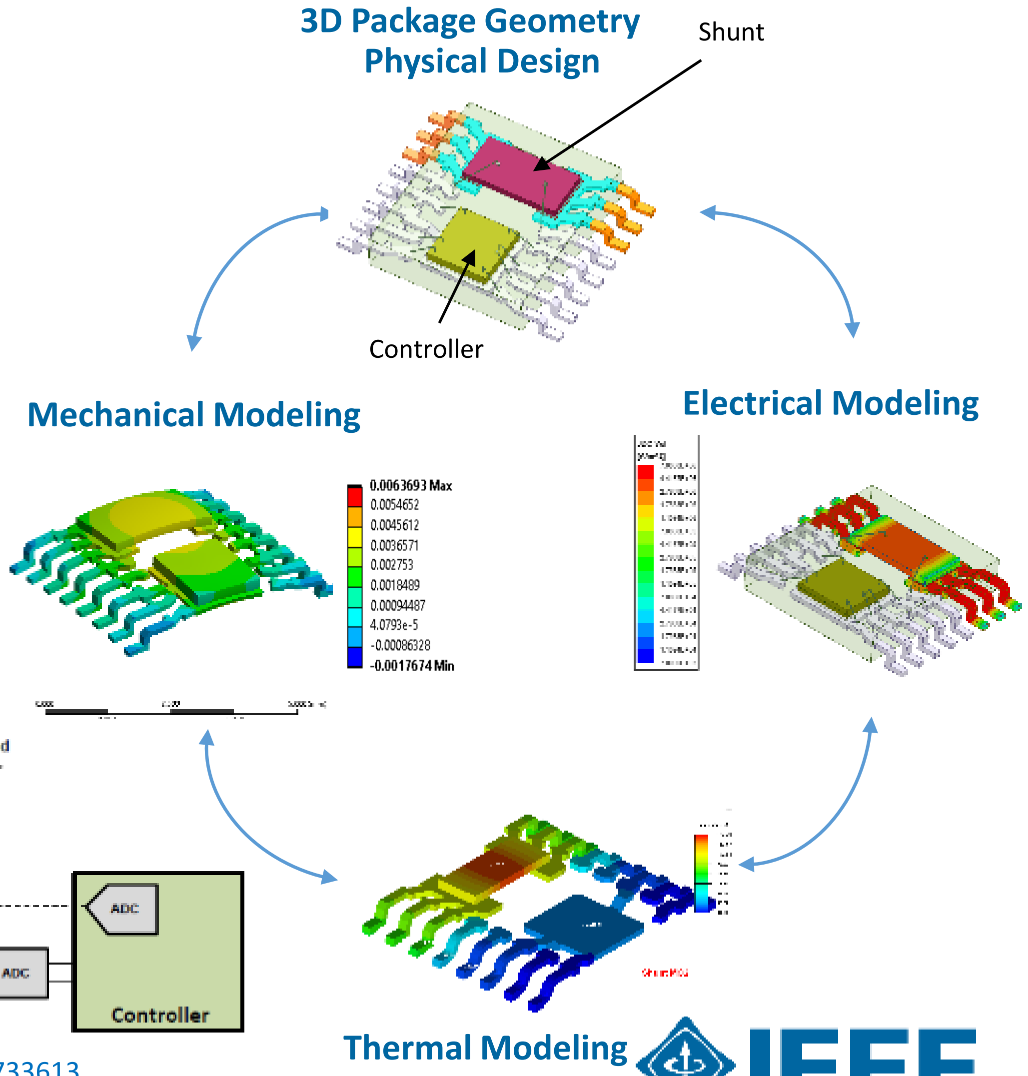
Meter

[4] Zhang Q. and Cen S., "Multiphysics Modeling: Numerical Methods and Engineering Applications", Tsinghua University Press Computational Mechanics Series 1st Edition - December 15, 2015.

Evolution of Modeling: Multiphysics Modeling

- Multiphysics is defined as the simultaneous simulation of different physical aspects of a system and the complex interactions among them[5,6].
- Multiphysics simulation is related to multiscale simulation, which is the simultaneous simulation of a single process on either time and/or distance scales.
- Ex. Shunt resistor current IC sensor.
- Iterate until specifications are met.

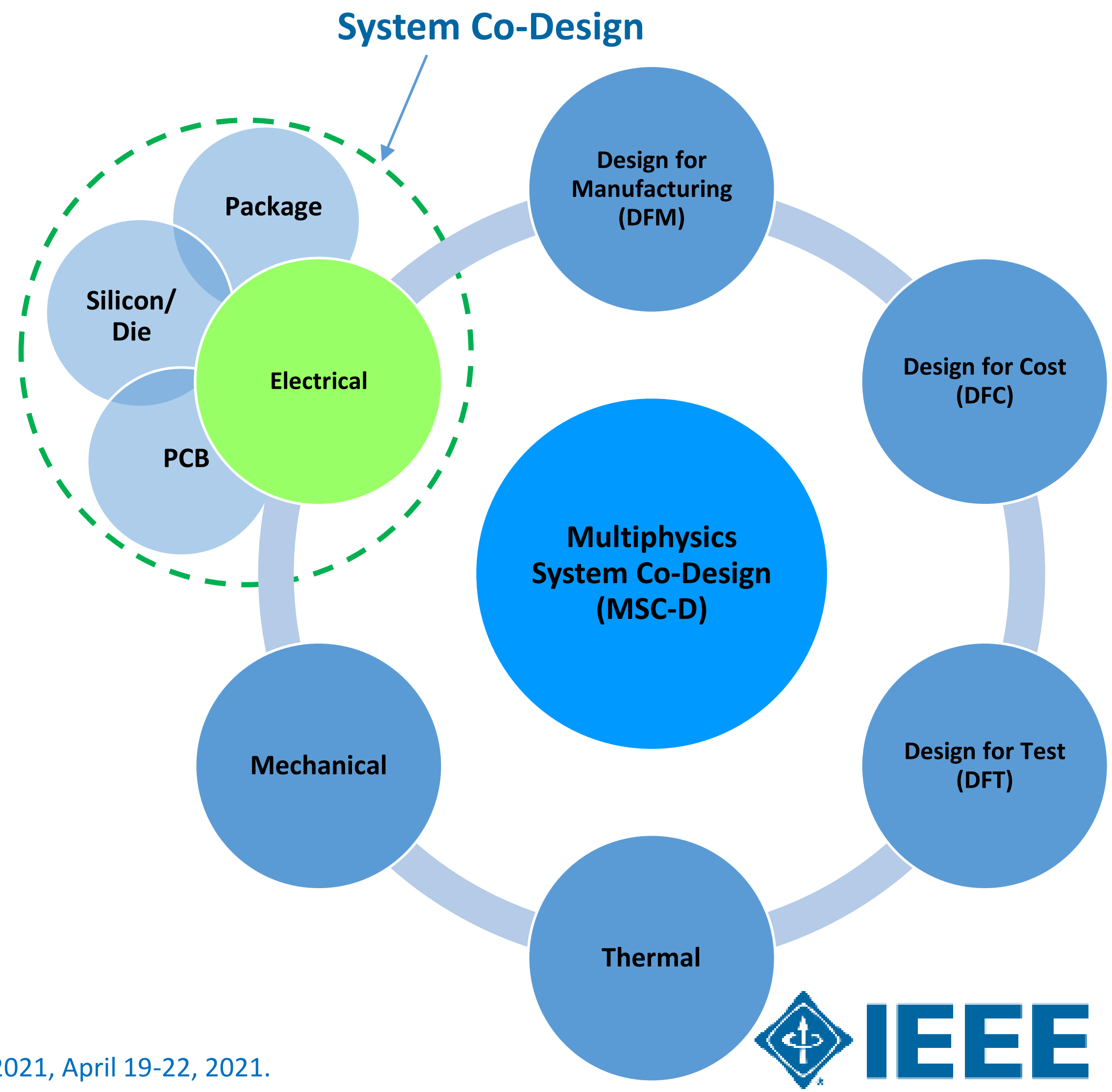




[5] Liu, Zhen (2018). Multiphysics in Porous Materials. Cham, Switzerland: Springer. ISBN 978-3-319-93028-2. OCLC 1044733613.
[6] Kwon, Y. W., (2015). Multiphysics and Multiscale Modeling: Techniques and Applications 1st Edition, CRC Press, October 5, 2015.

State-of-the-Art Modeling Methodology

- Coupled circuit-to-electromagnetic algorithms to handle multidomain (die + package + PCB) → **System Co-Design/Analysis.**
- Emergence and adoption of concurrent system co-design coupled with **multiscale + multiphysics** considerations → a unified approach for modeling (**Multiphysics System Co-Design, MSC-D**).[7]
- Unification enabled through standard file format, interoperability between tools, and global specifications and standardizations.
- Practical for relatively "well-defined" complex system – e.g. power electronics, sensors, among others.

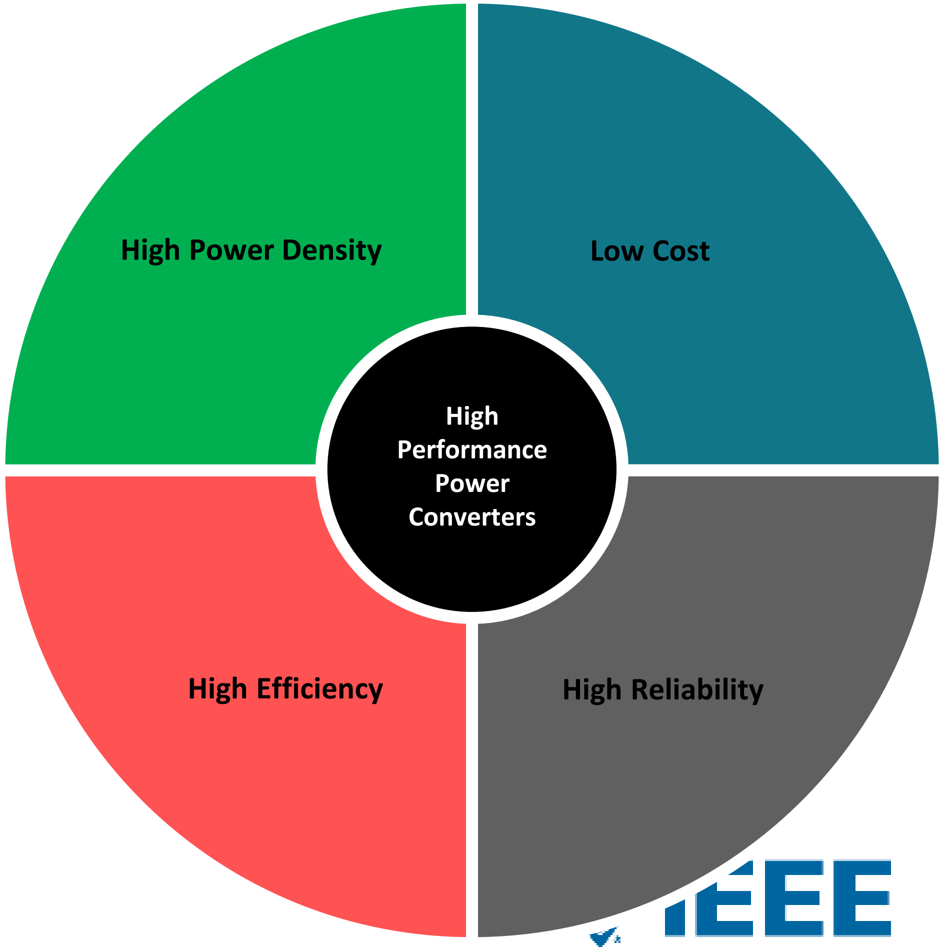


[7] **Rajen Murugan,** "Heterogeneous Integration Roadmap (HIR) Panel - Modeling and Simulation", Eurosime 2021, April 19-22, 2021.

Example: High-Current DCDC Converters

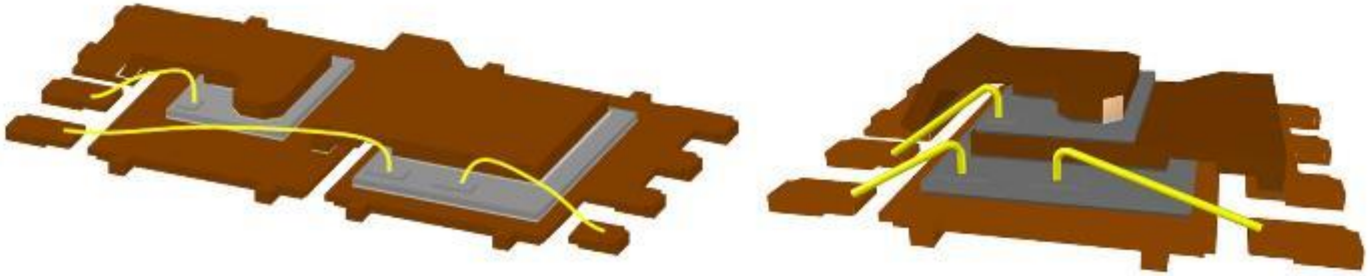
High-Current Step-Down Converter

- Power converters trend → Smaller, Faster, Robust, and Cheaper.
- High power density, efficiency, reliability, and low cost are performance drivers → an **optimization** problem.
- High power density is enabled by:
  - Reduction in power losses (conduction + switching)
  - High-frequency switching
  - 3D Innovative packaging (SiP, MCM, PoP, Stack)
  - Passives integration (die and/or package)
- Power density challenges:
  - Electrical and Thermal → ElectroThermal
  - System (device + package + PCB) impact on thermal



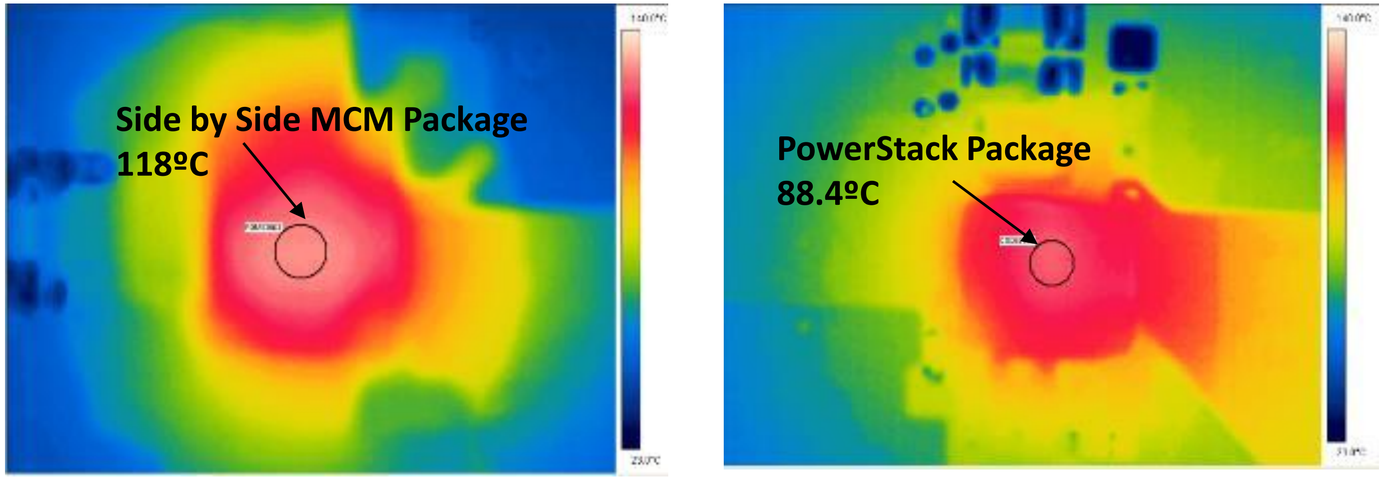
3D Package Innovation

- PowerStack integrate MOSFETs in z-axis → enabled by Cu clip technology
- Side-by-side vs Stack conf.
- Offers many advantages:
  - Higher power efficiency
  - Reduced electrical parasitics
  - Improve thermal
  - Improve reliability
  - PCB real-estate reduction
- PCB thermoelectric/Joule heating effect creeping up!
  - Impact to power density → rising junction temperature
  - An electrothermal coupled problem.



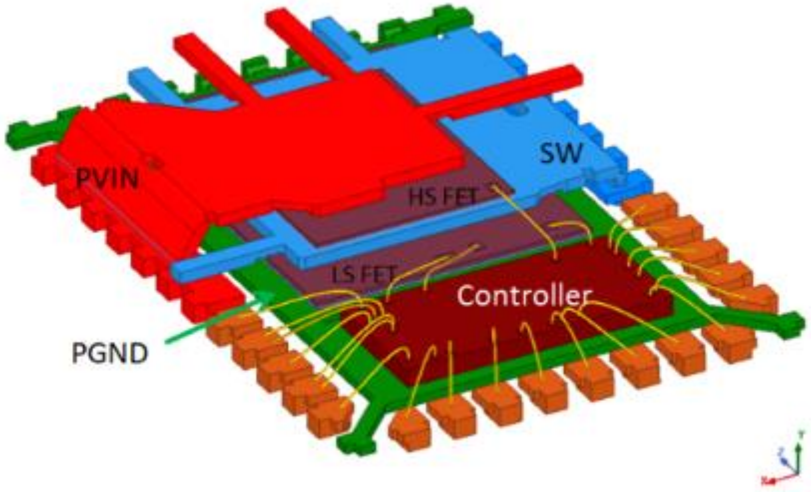
Two MOSFETs in a Side by Side Package

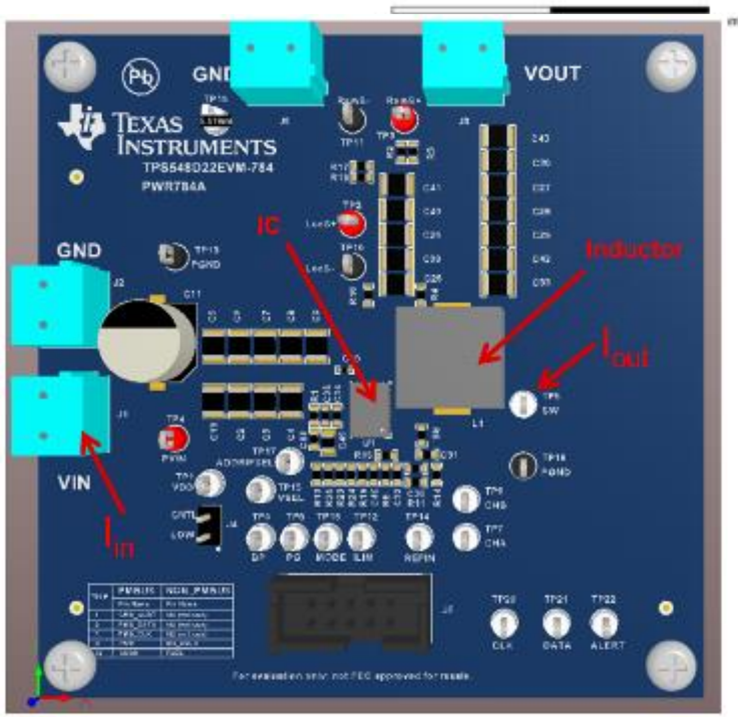
Two MOSFETs in a PowerStack™ Package



DUT: Device, Package, and PCB System

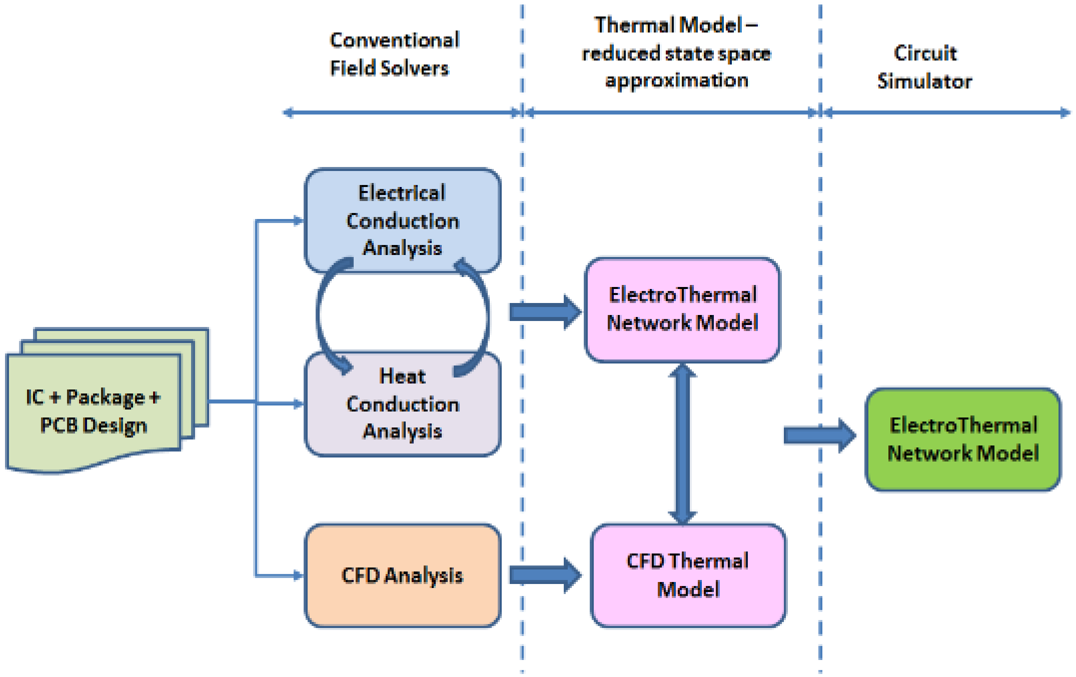
- Highly integrated DC-DC converter capable of 40A output current
- Consists of 3 die in an MCM package:
  - Monolithic Controller IC
  - Sync FET, or Low-Side (LS FET)
  - Control FET, or High-Side (HS FET)
- Input Voltage Range: 1.5 V to 16 V
- Output Voltage Range: 0.6 V to 5.5 V
- Integrated, HS 2.9-mΩ and LS1.2-m Ω power MOSFETs
- Wire-bond and Cu clip connections
- **Package:** 7mm × 5mm, 40-pin, Low Profile LQFN-CLIP (RVF)
- **PCB:** 4ML with 2oz. Cu metal finish with FR-4 dielectrics.





Multiphysics Modeling Methodology

- The coupled electrothermal scheme contains two functional modules[8]:
  - Physical field solvers
  - Circuit/network solver
- The field solvers resolves the electrical and thermal field solutions iteratively via 3D FEM + CFD.
- The integrated equivalent network is solved by a generic circuit solver for steady-state and transient responses.



$$\textit{Electrical equations}: \quad \vec{J} = \overline{\overline{\sigma}} \cdot \vec{E} \qquad [1]$$

$$\overline{\overline{\sigma}} = f(T) \qquad [2]$$

$$\vec{J} \cdot \vec{E} = \frac{J^2}{\sigma} \qquad [3]$$

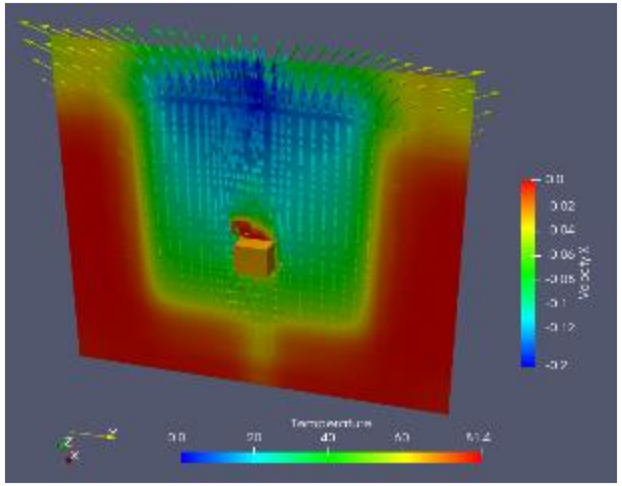
$$\textit{Thermal equation}: \quad \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + Q = \rho c \frac{\partial T}{\partial t} \qquad [4]$$

[8] **Murugan R.,** Chen J., Harrison T., Kao CT., & Ai N., "System Electrothermal Transient Analysis of a High Current (40A) Synchronous Step Down Converter“, Proceedings of the ASME 2019 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems. ASME 2019, California, USA. October 7–9, 2019.

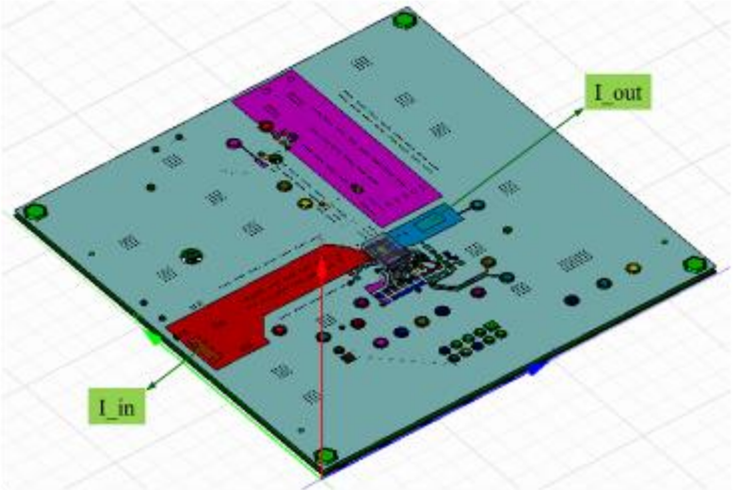
Static Thermal & Static Electrothermal Analysis

Methods:

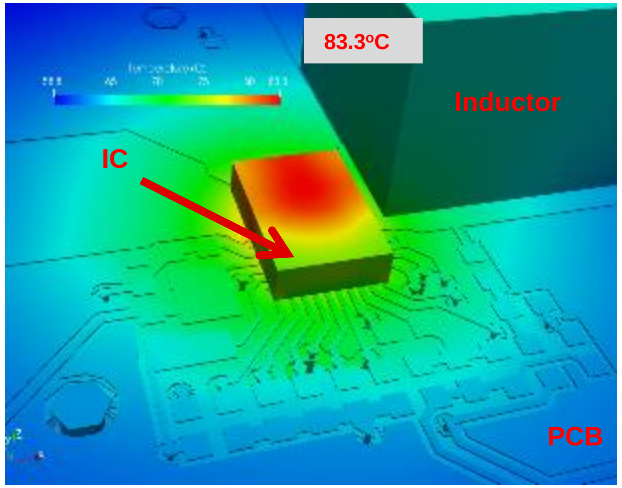
- MOSFETs Power map/heat sources are assigned along with appropriate boundary conditions.
- CFD analyses are performed. Heat transfer coefficients (HTCs) are extracted.
- At high currents the power generation due to Joule heating within the PCB can be significant in real applications.
- An increase of **5.5°C** is observed for the natural convection (still air) case.



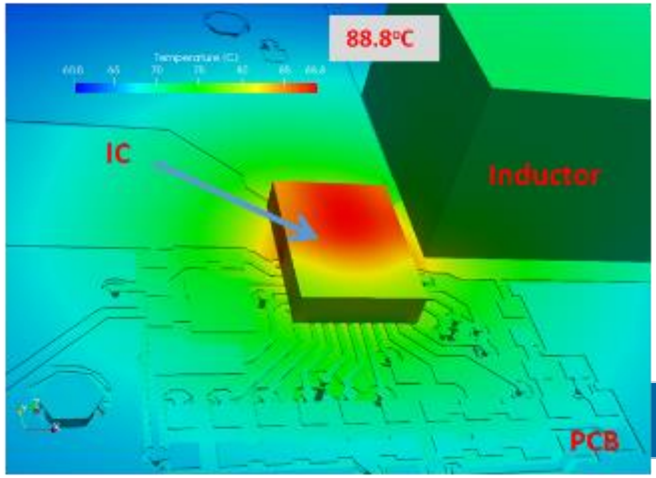
CFD analysis under natural convection



Current injection and extraction sites



Static thermal analysis under natural convection



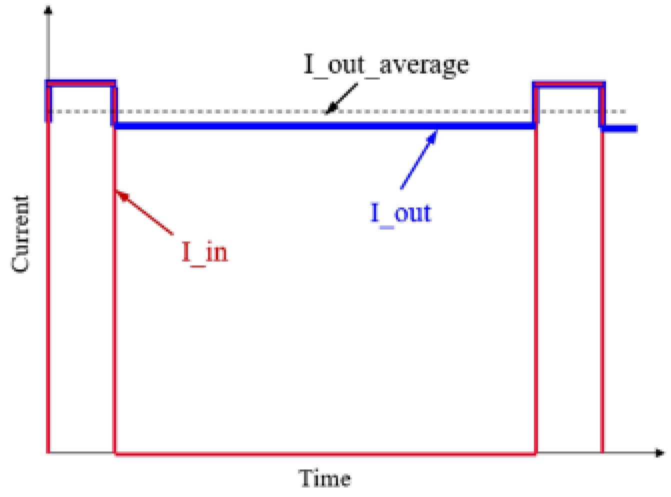
Static Electrothermal analysis under natural convection

Transient Electrothermal Analysis

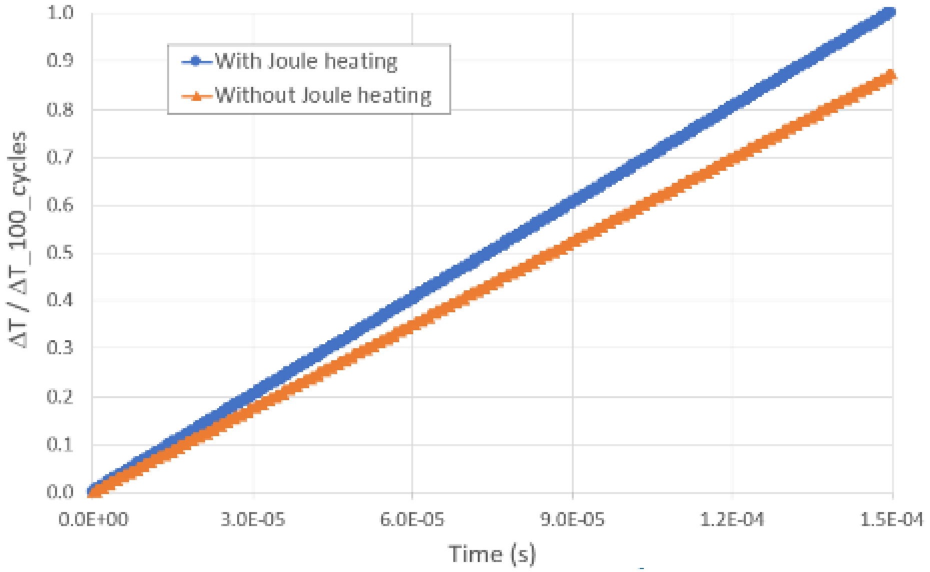
- Transient behavior analyze under realistic switching conditions (current stimulus).
- Duty cycle of I_in derive based on the voltage ratio, i.e., V_out / V_in.
- I_out is a superposition of I_in and inductor ripple current, I_R

$$I_R = \frac{V_{IN} - V_{OUT}}{L_{ind} \cdot f_{SW} \cdot {V_{IN}}/{V_{OUT}}} \qquad [5]$$

- Plot shows temperature increase during the first 100 current cycles, with and without Joule heating (period of each cycle ~ 1.5 us).



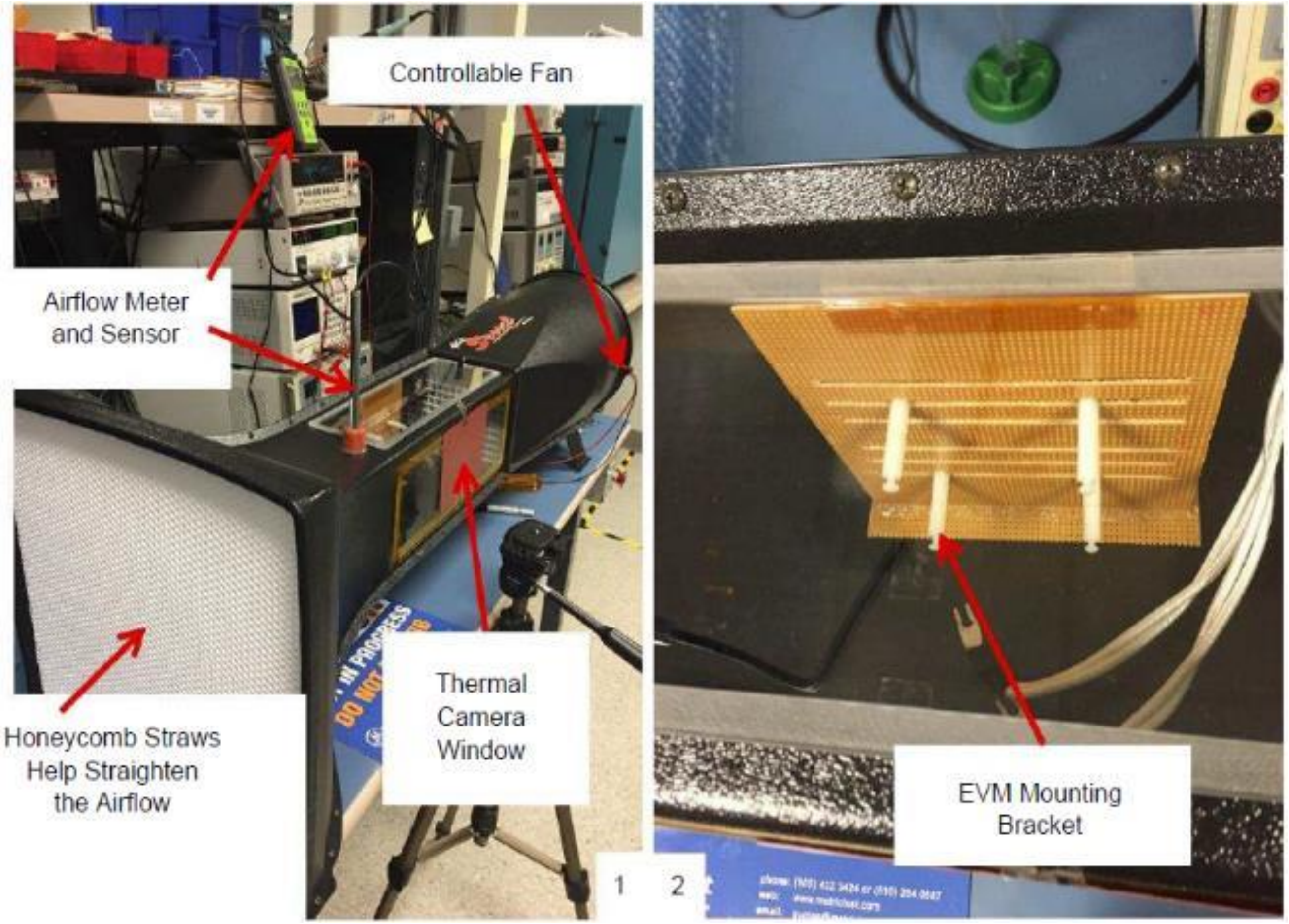
Sample of transient current stimulus



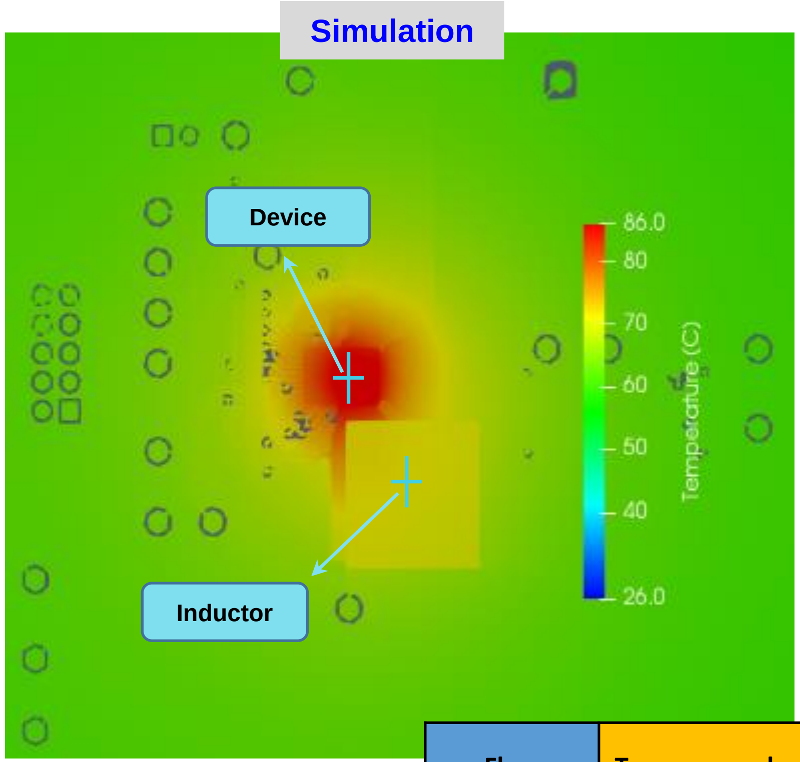
Temperature increase with and without Joule Heating

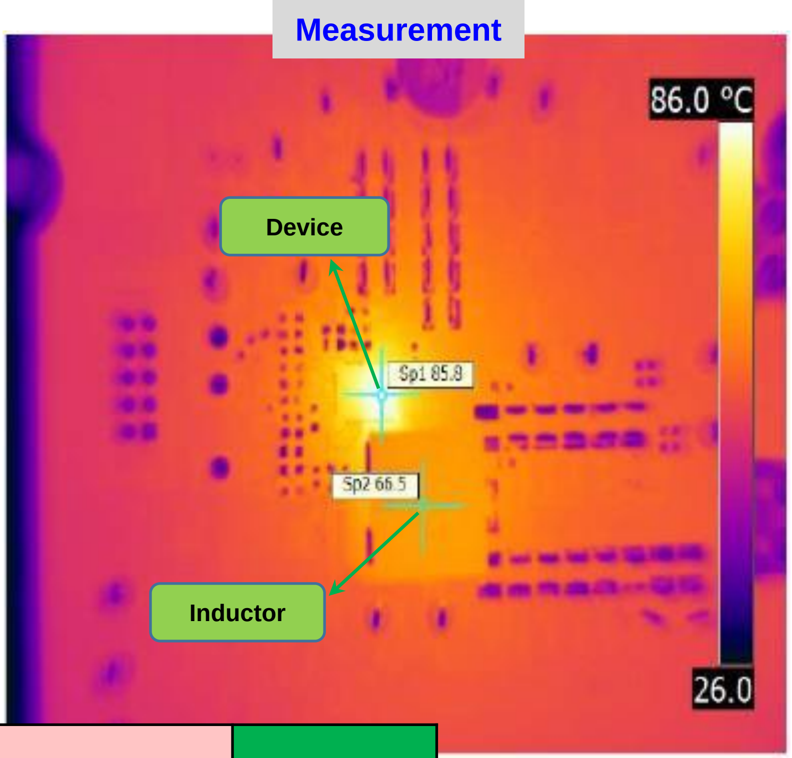
Thermal Measurements

- System-level thermal measurements were performed on the evaluation module (EVM).
- The EVM module was mounted inside a Venturi tunnel in order to provide a well-controlled environment for airflow and temperature measurements.
- Figure shows the Venturi tunnel, anemometer (airflow meter) and sensor, thermal camera placement and EVM mounting bracket.
- Camera is positioned about 1 foot from the EVM mounted inside the chamber.



Simulation to Measurement Correlation



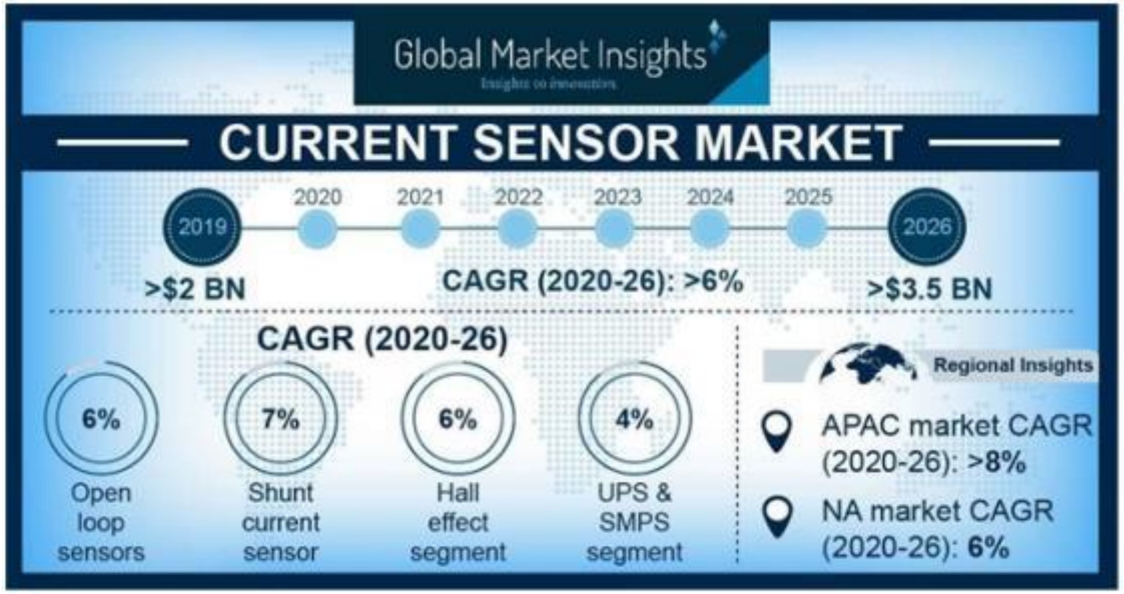


Flow condition	T_ave on package (°C) without Joule heating	T_ave on package (°C) with Joule heating	T_reading (°C) IR Measured
Natural convection	79.3	84.6	85.8
Airflow (400 LFM)	58.0	59.2	59.8

Example: Magnetic IC Current Sensors

Current Sensor Market

- A fast growing market (revenue **US$ 2B+** in 2019 and poised to grow at >6% CAGR between 2020 and 2026)
- Market is segmented based on:
  - **Type 1:** Open loop and Closed loop
  - **Type 2:** Isolated and non-isolated
  - **Sensing Technology: Hall-Effect**, current transformer, flux gate, and Rogowski coil.
  - **End Application:** Automotive, Consumer Electronics, Healthcare, Industrial, others.

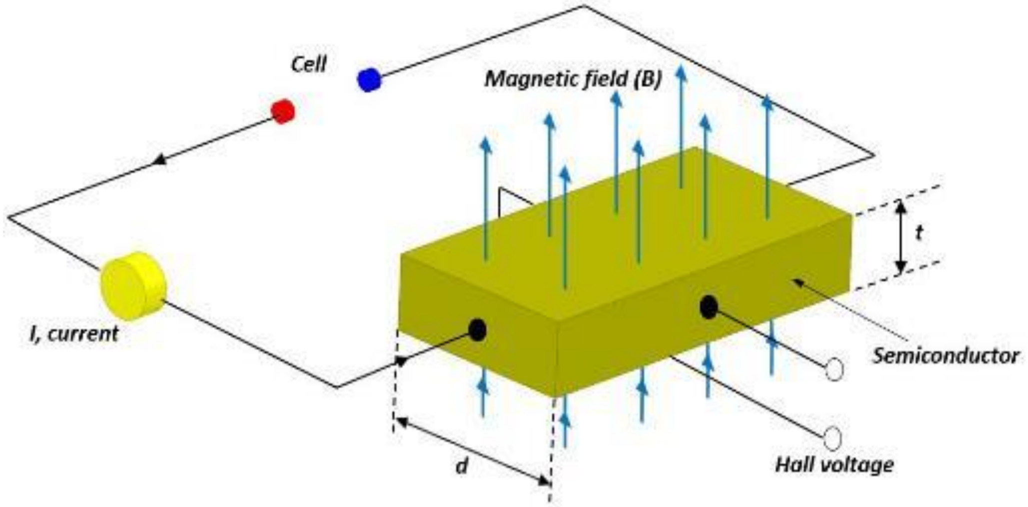


Source: *https://www.gminsights.com/industry-analysis/current-sensor-market*

- Types of sensors:
  - Isolated: **magnetic current sensors**, opto-Isolated op amp, and shunt-isolated op amp.
  - Non-isolated: current sensing amplifiers and analog-to-digital converters.
- An example of current sensor based on Hall-Effect is demonstrated here.

Physics of Hall-Effect Current Sensor

- The classical Hall effect is the production of a voltage difference transverse to an electric current in a conductor with an orthogonal magnetic field (B) to the current.
- According to classical electromagnetic theory, electric charges (i.e., electrons) moving through the magnetic field experience a magnetic force.
- This magnetic force sets a differential voltage across the conductor width (d) due to separation of electrons.
- This separation of charge creates a voltage difference known as the Hall voltage (V_H).
- The voltage builds up until the electric field produces an electric force equal in magnitude and opposite to the magnetic force → Lorentz Force [eqt. 6].
- The Hall voltage (V_H) is dependent on the Hall sensitivity (K_H), Hall current (I_H), and applied transverse magnetic field [eqt. 7].

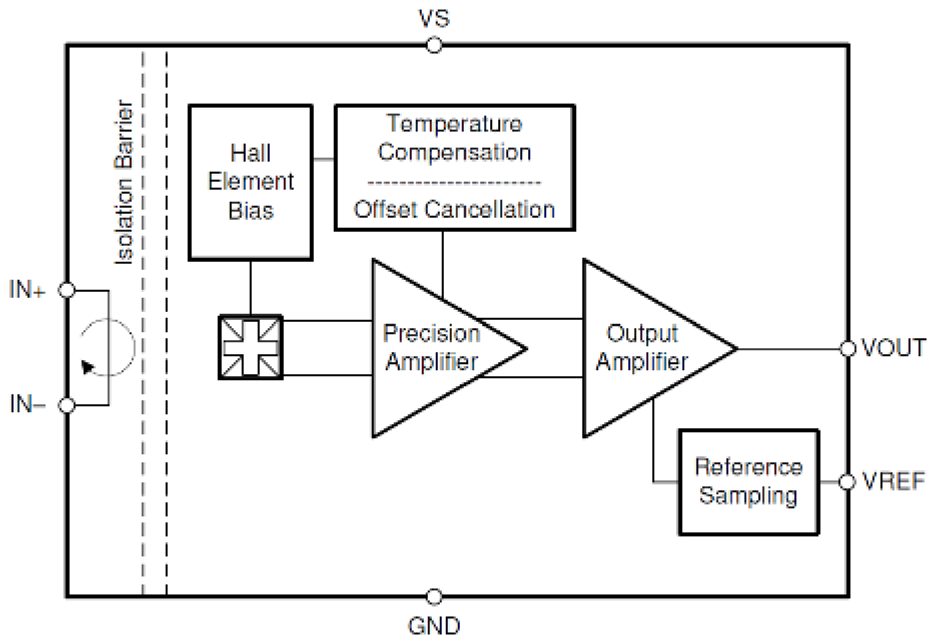


$$\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B}) \quad [6]$$

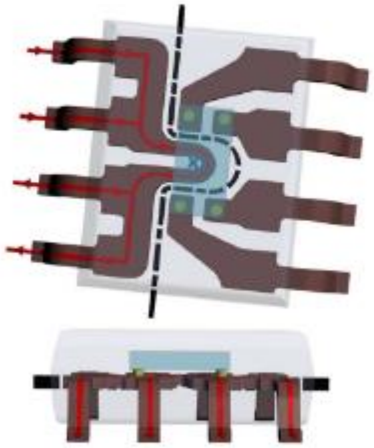
$$V_H = K_H I_H B \quad [7]$$

Example: Current Sensor IC Detail

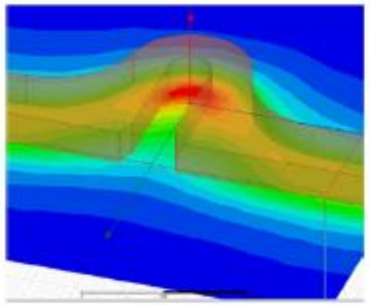
- Galvanically isolated, integrated in-package, Hall-effect current sensor capable of dc or ac current measurement.
- Industry's first zero-drift Hall-Effect current sensors with high accuracy, excellent linearity, and temperature stability, while providing reliable 3-kVrms isolation.
- Typical applications include overcurrent protection, monitoring and diagnostics, and closed-loop control in high-voltage, high-current systems.
- The in-package Hall-Effect current sensor technology is preferred as market needs drive highly-integrated, high-performance, and cost-effective solutions.



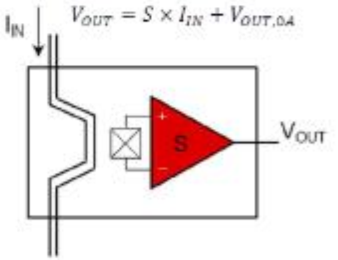
Current flows through lead frame, electrically isolated from die



Lead frame loop generates magnetic field proportional to current

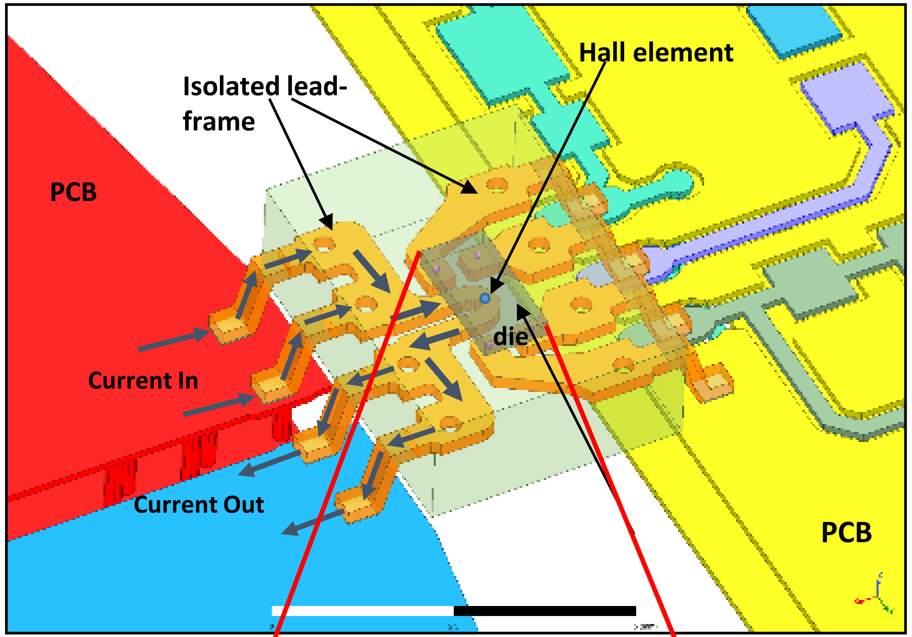


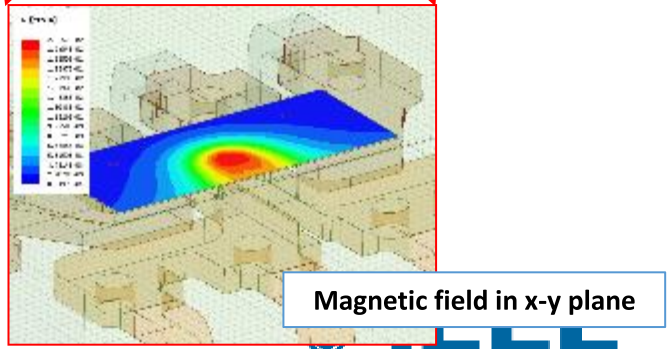
Precision Hall effect sensor converts magnetic field to voltage signal



Hall-Effect Sensor IC Design Challenges

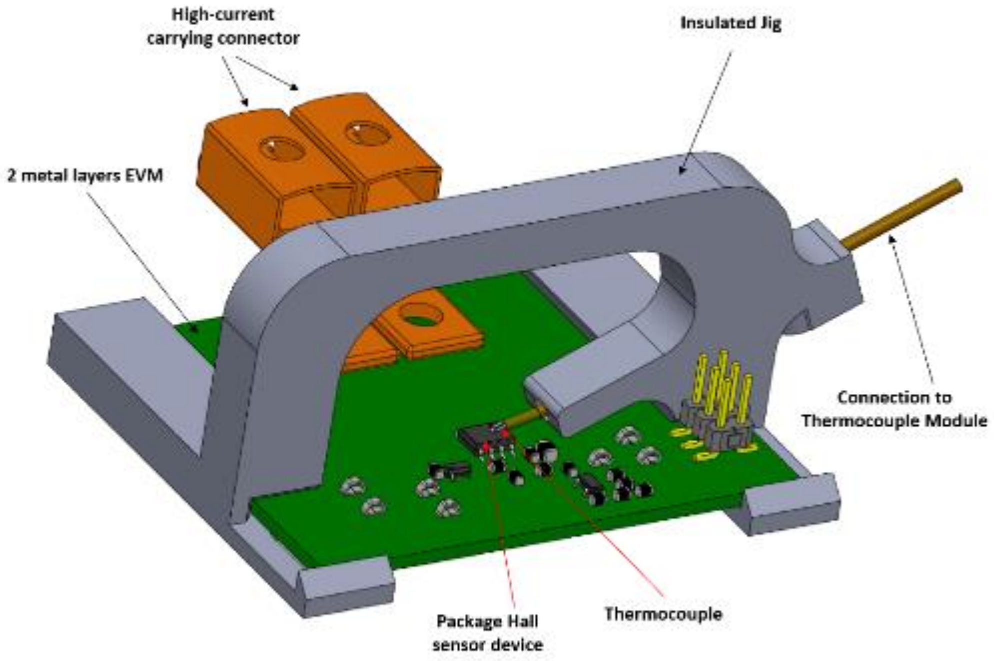
- Magnetic current sensor IC based on Hall-Effect principles are quite popular and can be relatively cost-effective.
- However, performance depends on Piezoresistance effect, non-uniformity of the magnetic field, **thermal and temporal drift offset** and sensitivity.
- Measured input current safe operating area (SOA) is dependent on maximum junction temperature excursion and Joule heating in the whole system.
- Temperature drift compensation, to-date, has been mostly at the IC-level, with little to no considerations of the multiphysics **system-level** (package and PCB) impacts.
- In this example, multiphysics system co-design is employed to accurately predict system temperature in order to improve thermal drift offset cancellation accuracy.

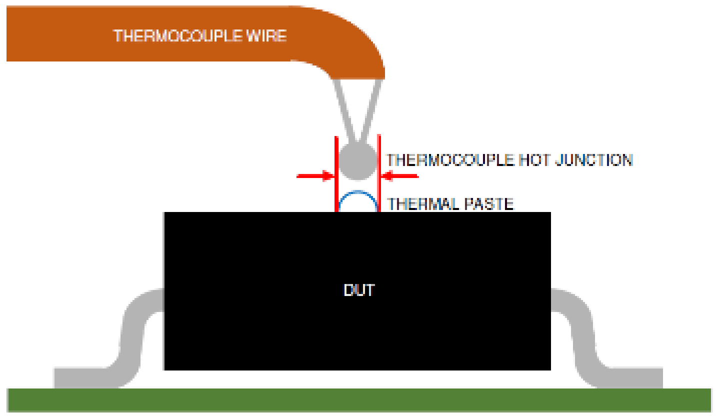




Temperature Measurements Set-up

- Current is introduced into the system through the orange-brown connector which is secured to the PCB by plated steel screw.
- The gray structure is a jig, made of plastic nylon, that was designed specifically to hold the thermocouple probe.
- By biasing an internal ESD diode, junction temperatures (T_J) can be made accurately.
- K-type thermocouples are used for measuring Case (T_C) temperatures up to 150°C.
- For accurate measurement, a thermal paste was employed to provide a good thermal conductive bridge between the surface of the thermocouple and the surface.





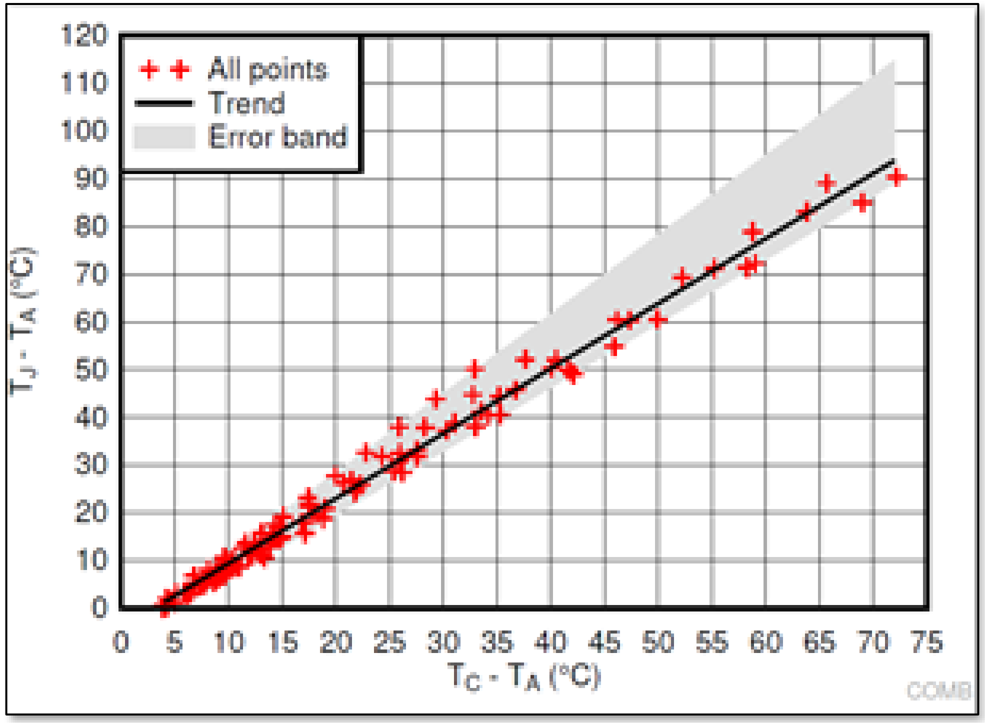
DUT = Device Under Test

(T_J) *and* (T_C) Empirical Relationship

- Practically, validation through junction temperature measurement is quite challenging.
- A relatively linear relationship can be observed by plotting junction temperature versus case temperature with the ambient offset removed ($T_J - T_A$ versus $T_C - T_A$).
- Best-fit analysis (a least sum squares approximation). For this device and system under investigation, the empirical fit was derived and shown to be:

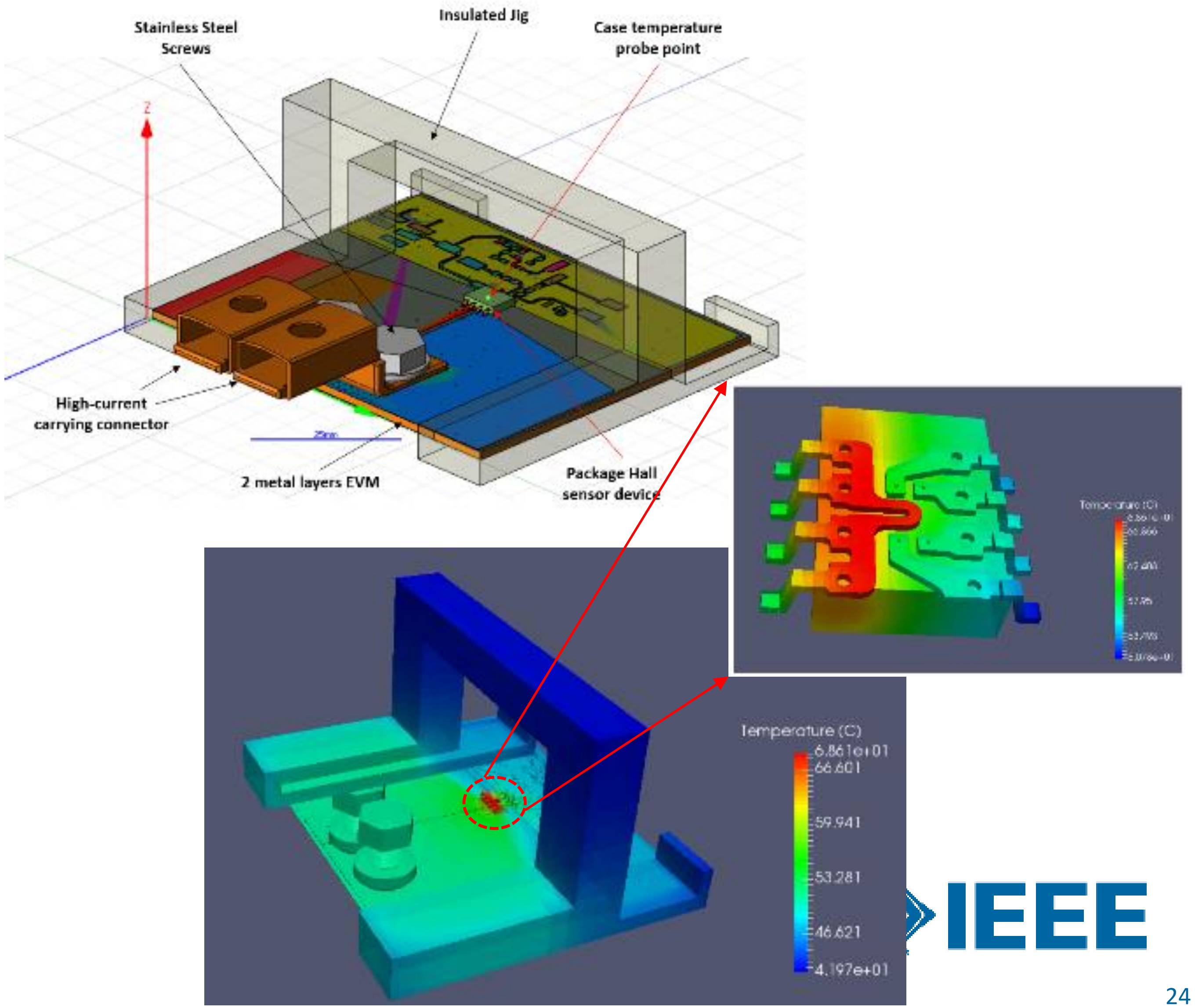
$$T_J - T_A = 1.31 \times (T_C - T_A) - 2.8 \qquad [8]$$

- Using the above derived empirical equation, the junction temperature can now be estimated based upon a case measurement and an ambient temperature (preferably taken near the device case).



Multiphysics Simulation Results

- Simulation performed using MSC-D methodology.
- Top right picture shows measurement set-up and configuration.
- Bottom picture shows simulation set-up. Components were imported as physical three-dimensional geometries and assembled to emulate the measurement set-up.
- Appropriate materials properties were employed along with boundary conditions for the multiphysics analysis.



Simulation vs. Measurement Correlation

- Table shows the comparative results.
- Overall good correlation observed across current and temperature range.[9]
- The relatively good correlation validates the multiphysics co-design modeling flow.
- For improved correlation, possible improvements areas are – inclusion of package and PCB manufacturing process variations, accurate thermal and electrical material properties, and controlled oven chamber thermal measurements.

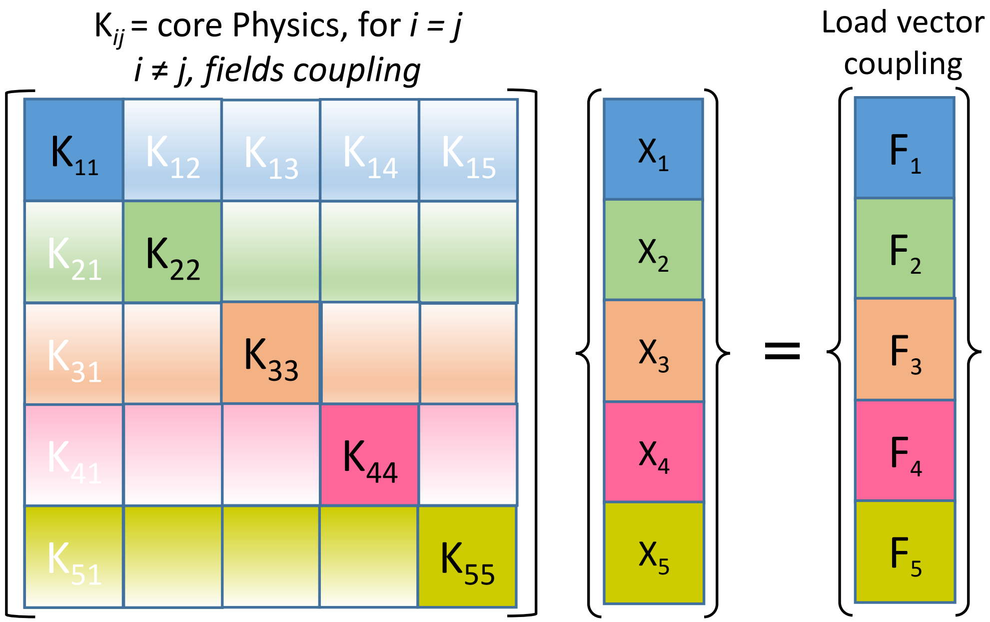
Case Temperature (T_C) Comparison			
Current (A), Ambient (40 ºC)	**Simulation, ºC**	**Measurement, ºC**	**Delta (%)**
10A	46.60	47.28	1.44
Current (A), Ambient (85 ºC)	**Simulation, ºC**	**Measurement, ºC**	**Delta (%)**
14A	96.64	91.74	5.34
30A	119.80	113.53	5.52
Current (A), Ambient (125 ºC)	**Simulation, ºC**	**Measurement, ºC**	**Delta (%)**
10A	130.90	129.07	1.42
12A	133.60	130.22	2.60
14A	136.73	132.06	3.54

[9] **R. Murugan** et al., "Multiphysics System Co-Design of a High-Precision, High-Voltage (±600V) Isolated Hall-Effect Current Sensor," 2021 IEEE 71st Electronic Components and Technology Conference (ECTC), San Diego, CA, USA, 2021, pp. 1226-1233.

MSC-D Challenges and Opportunities

Electromigration: Coupled Fields Solution Problem

- Electromigration (EM) is an enhanced diffusion-controlled mass transport process in metallic interconnects that poses severe reliability concerns.[10]
- EM is characterized via the mass transport equation and the coupling of fluxes (atomic diffusion, electromigration, stress migration, and thermomigration.
- Requires a **fully-coupled, non-linear** fields numerical analysis solutions.[11]
- A non-trivial multiscale/multiphysics problem.



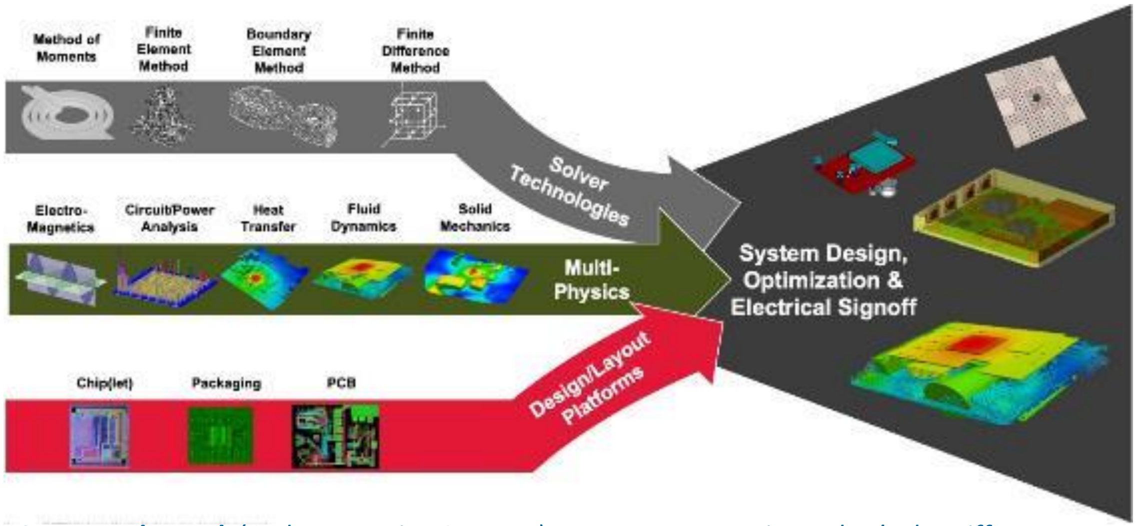
$$\frac{\partial \theta}{\partial t} = -\Omega \nabla \cdot \boldsymbol{J}_a \qquad [9]$$

$$\boldsymbol{J}_a = D_a\left(-\nabla C_a - C_a \frac{Z^* e \rho j}{k_B T} + C_a \frac{\Omega \nabla \sigma}{k_B T} - C_a \frac{Q^* \nabla T}{k_B T^2}\right) \qquad [10]$$

[10] S. Ankamah-Kusi, K. Sreenivasan and **R. Murugan**, "A New Current Crowding Phenomenon for Flip-Chip-on-Leadframe (FCOL) Package and its Impact on Electromigration Reliability," 2022 IEEE Electrical Design of Advanced Packaging and Systems (EDAPS), 2022, pp. 1-3.
[11] Z. Cui, X. Fan and G. Zhang, "Implementation of Fully Coupled Electromigration Theory in COMSOL," 2022 IEEE 72nd Electronic Components and Technology Conference (ECTC), San Diego, CA, USA, 2022, pp. 233-238.

Multiphysics System Co-Design Challenges

- Seamless **physical** (entire layout chain) **co-design**, optimization, and visualization + **multiphysics** modeling and analysis capabilities (a single tool).
- Coupled circuit-to-electromagnetic algorithms are not computationally rigorous/efficient to handle complex advanced packaging platforms yet.
- Issues with **stability**, **accuracy**, and **convergence** in transient circuit-level analysis.[12]



- ***Source: John Park*** *(Cadence Design Systems) - An EDA Perspective: What's the Difference Between Heterogenous Integration and System in Package (SiP), MEPTEC, March 2021.*

- Continuum-continuum coupling (space and/or time scale difference), Floating Point Overflow/Underflow, and accurate[13], compact Spice-based models are practical challenges.
- Managing complexity of advanced packaging in a coherent model/tool is a challenge to current computational capabilities and is likely to drive significant conceptual and algorithmic innovations.

[12] S Senecal, J. & Ji, W. (2017). Approaches for Mitigating Over-Solving in Multiphysics Simulations. International Journal for Numerical Methods in Engineering. 112. 10.1002/nme.5516.
[13] Sha, Wei. (2016). The Challenges and Remedies of Multiphysics Modeling — A Personal View.

Multiphysics System Co-Design Opportunities

- Innovations to address real-world challenges:
  - Advanced adaptive meshing algorithms to speed up computational analysis.
  - Massive parallelization for direct and iterative solvers (CPU, CPU-GPU, Cloud AWS/DSA).
  - AI/ML/Domain decomposition for multiscale.
  - EDA suppliers enabling multiphysics and system co-design solutions through on-going developments:

__Source__: IEEE EPS Heterogeneous Integration Roadmap 2021 Edition – Chapter 14: Modeling and Simulation, https://eps.ieee.org/images/files/HIR_2021/ch14_sim.pdf

Summary

- Continued miniaturization/integration is exacerbating multiphysics and multidomain interactions that are impacting performance, time-to-market, and cost.
- Evolving modeling schemes (compartmentalized → system co-design/multidomain → multiscale → multiphysics).
- Multiphysics modeling and simulations are increasingly becoming an essential part of semiconductor CAE/D, virtual prototyping, research and development (R&D), and product design.
- MSC-D modeling and analysis methodology is helping to secure first-pass design success for current traditional power electronics products.
- However, these interactions will worsen when we transition to AP/HI technologies.
- Opportunities for disruptive innovations exist in many areas – multiphysics numerical computation algorithms, fast and parallel solvers, meshing schemes, model order reduction, among others.