# Electro-thermal-mechanical Simulation and Reliability for Plug-in Vehicle Converters and Inverters

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Project ID # APE 026

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# Overview

## Timeline

- June 2011
- December 2013
- 30% Complete

## Budget

- Total project funding
  - $700K
- Funding received FY11
  - $ 200K
- Funding expected FY12
  - $ 300K
- Funding expected FY13
  - $ 200K

## Barriers

Need electro-thermal-mechanical modeling, characterization, and simulation of advanced technologies to:

- Improve electrical efficiency
- Improve package thermal performance and increase reliability
- Reduce converter cost

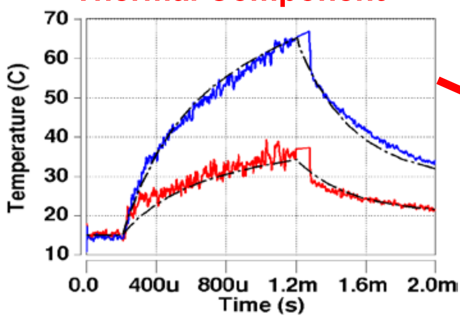
## Partners

- NIST- Electro-thermal modeling
- UMD/CALCE – Reliability modeling
- VTech – Soft switching module
- Delphi – High current density module
- NREL – Cooling technology

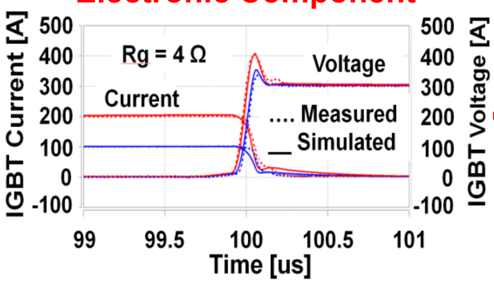
# Goal: Electro-Thermal-Mechanical Simulation

## Models, Parameter Determination

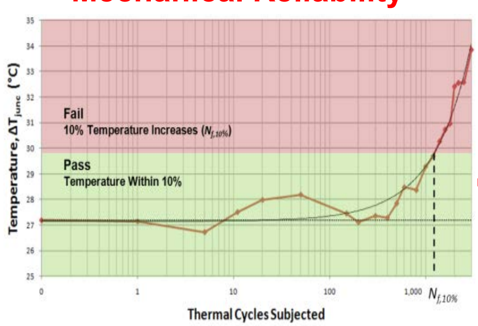
### Thermal Component



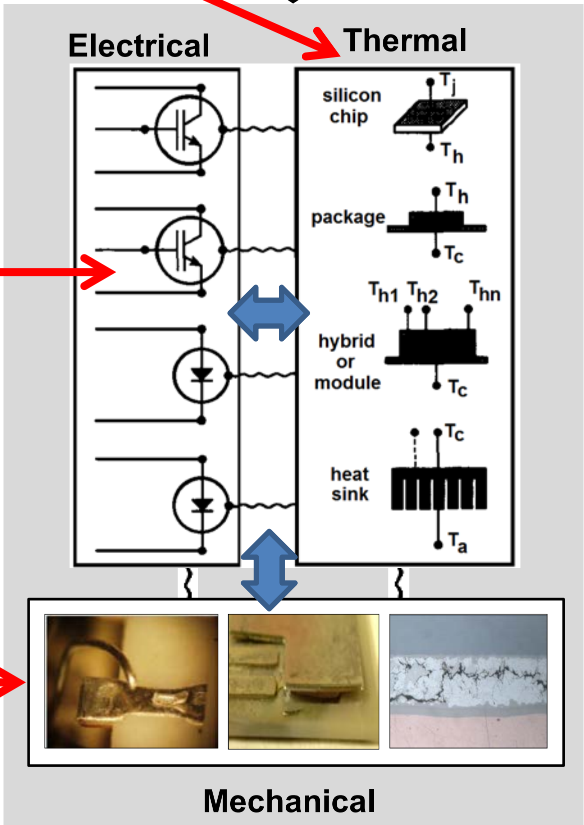

### Electronic Component



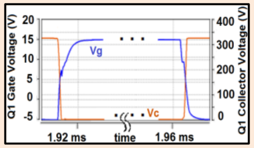

### Mechanical Reliability




## Driving Cycles, Environmental Conditions

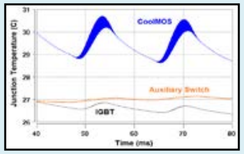



## Simulation Applications




### Electrical

- Inverter performance evaluation
- Advanced topology design
- Advanced device integration



### Electro-Thermal

- Electro-thermal interactions,
- SOA and failure mechanisms,
- Cooling system impacts.

### Reliability

- Reliable integration of advanced technologies
- System reliability evaluation.

- In-Vehicle applications:
  - Maintaining component health,
  - Predicting service needs,
  - Operation with partially degraded capacity near component end-of-life.

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# Relevance

**Objective:** Provide theoretical foundation, measurement methods, data, and simulation models necessary to optimize power module electrical, thermal, and reliability performance for Plug-in Vehicle inverters and converters.

**FY 2012:**

1) Utilize electro-thermal-mechanical models to simulate:
   - VTech soft switching module performance (electrical, thermal, package life)
   - Delphi's Viper module performance (high current IGBT SOA, package life).
2) Develop cooling system thermal network component models for:
   - double-sided liquid cooling fixture (with NREL)
   - air and liquid cooling fixtures for VTech module.
3) Extend thermal cycling and monitoring measurements to include:
   - two different DBC stack types (with Powerex)
   - range of cycling conditions for reliability model parameter determination.
4) Develop electro-thermal models for advanced semiconductor devices e.g., SiC MOSFETs and SiC JFETs and GaN diodes.
5) Perform electro-thermal simulations to determine impact of air cooling and advanced semiconductors on high current density, low thermal resistance, and soft-switching modules.
6) Demonstrate full electro-thermal-mechanical simulations where simulations predict and include damage resulting from system operation.

# Milestones/Decision Points

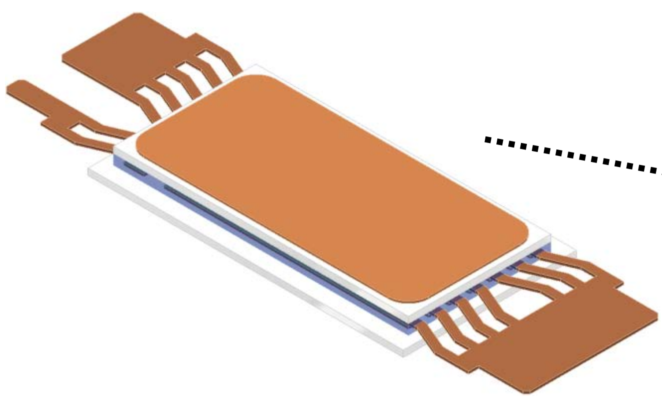
| Month/Yr | Milestone |
|---|---|
| May 12 (ongoing)<br>Aug. 12 | 1a) Simulate fault conditions to determine safe operating area (SOA) of IGBT in high current density Viper module,<br>1b) and evaluate thermal stresses in Viper module for nominal and fault operating conditions. |
| Jun. 12 (ongoing) | 2) Extend thermal cycling degradation and monitoring measurements on two DBC stacks for range of conditions (initial-T, ΔT, T-ramp-rate) necessary for reliability modeling. |
| Jul. 12 | 3) Develop thermal-network-component modes for representative cooling systems. |
| Aug. 12 | 4a) Use simulations to evaluate thermal stresses at module interfaces for VTech module,<br>4b) and use physics-of-failure models to calculate damage and evaluate impact on VTech module life. |
| Oct. 12 | 4c) Calculate increase in thermal resistance at interfaces in VTech module due to thermal cycling damage and use changing resistance in the thermal network during simulations. |
| Nov. 12 | 5) Include liquid- and air-cooling thermal network component models in electro-thermal simulations of vehicle inverters. |
| Feb. 13 | 6) Develop electro-thermal models for advanced semiconductor devices including SiC MOSFETs, SiC JFETs and GaN diodes. |
| Apr. 13 | 7) Include advanced semiconductor device models in simulations to optimize high current density, low thermal resistance, and soft-switching modules. |

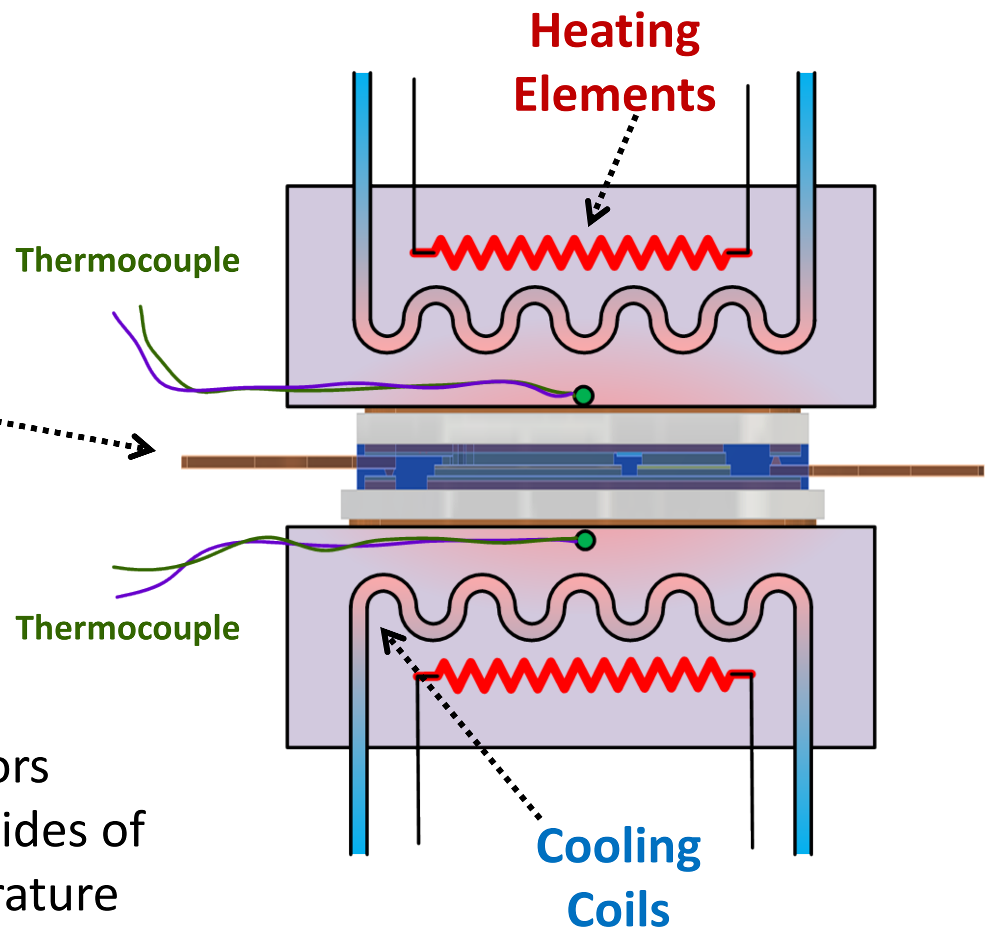
# Approach: Measurement, Modeling, and Simulation

- Develop dynamic electro-thermal Saber models, perform parameter extractions, and demonstrate validity of models for:
  - Silicon IGBTs and PiN Diodes
  - Silicon MOSFETs and CoolMOSFETs
  - SiC Junction Barrier Schottky (JBS) Diodes
- Develop thermal network component models and validate models using transient thermal imaging (TTI) and high speed temperature sensitive parameter (TSP) measurement.
- Develop thermal-mechanical degradation models and extract model parameters using accelerated stress and monitoring:
  - Stress types include thermal cycling, thermal shock, power cycling
  - Degradation monitoring includes TTI, TSP, X-Ray, C-SAM, etc.

# Application: Delphi Viper Module Double-Sided Cooling Model

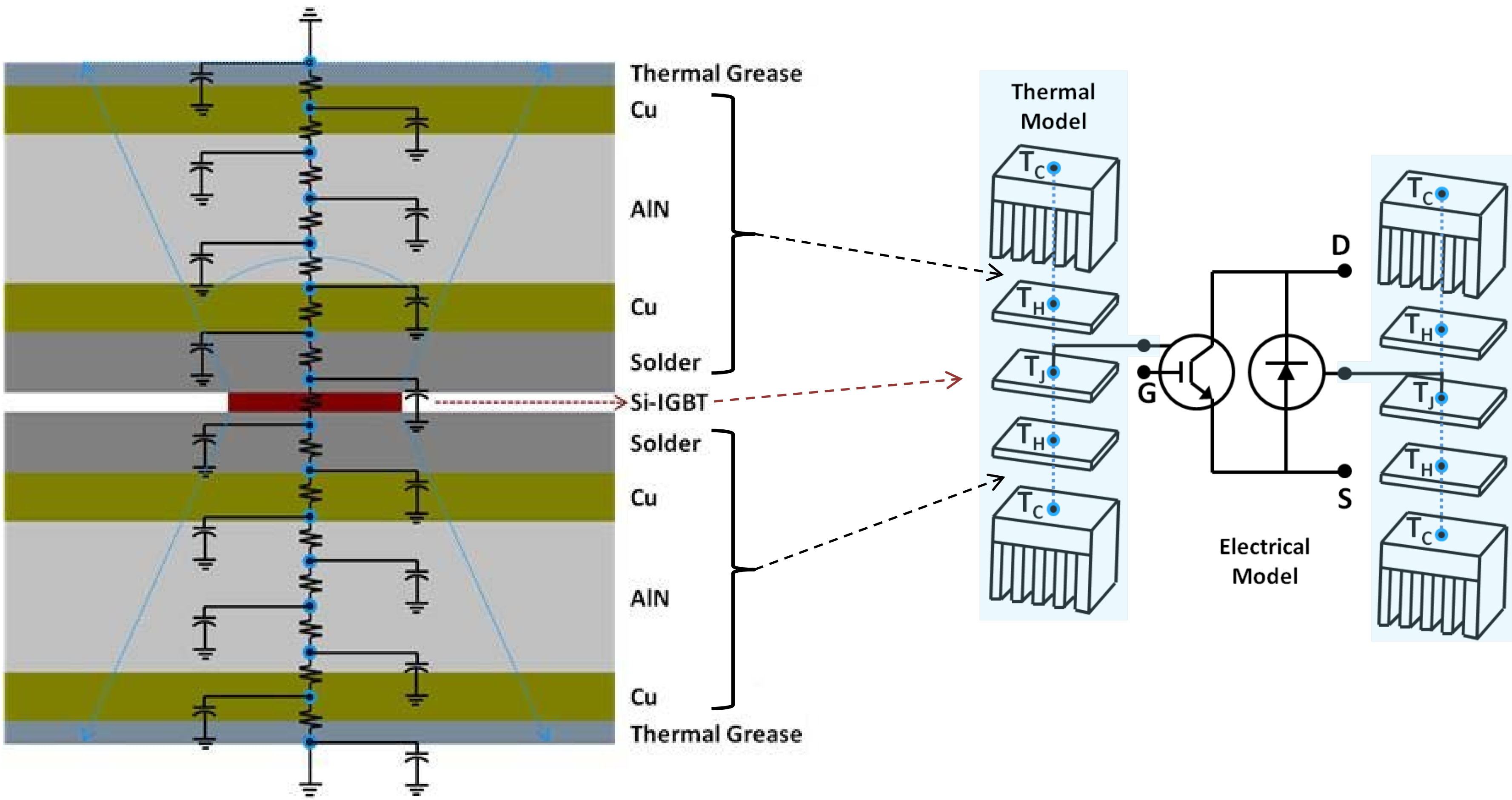
Module
(2.7 mm thick)



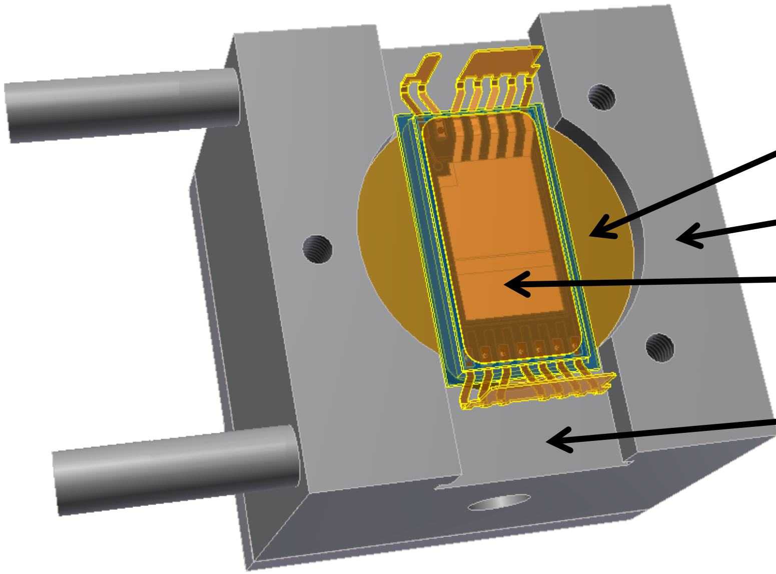



A temperature controller monitors thermocouples to ensure that both sides of the module are at the same temperature before thermal transient.

# Method: Electro-Thermal Model for Double-Sided Cooling Viper Module



# Validation: Thermal Test Fixture Steady State



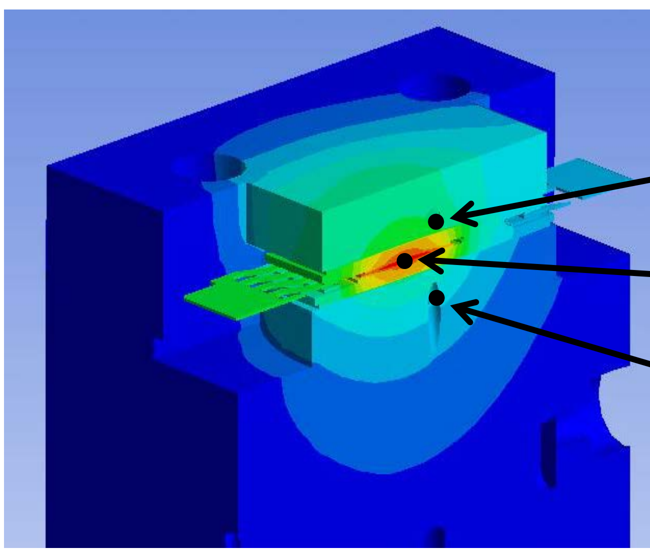
**Viper module thermal test fixture**

Piston

Top Cooling Plate (not shown)

Viper Module

Water Cooling Fixture



**Viper module 262 W steady state ANSYS simulation for double-cooled test fixture**

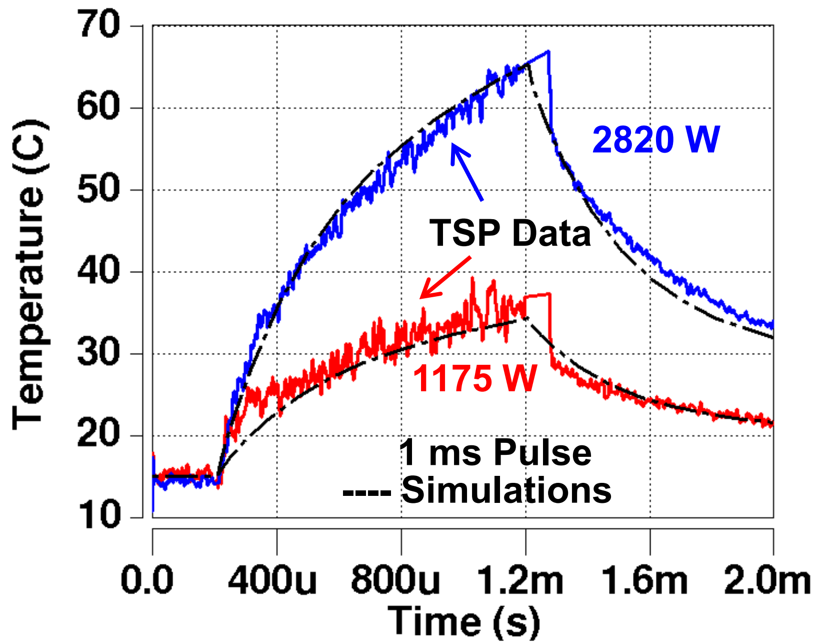
**Top Plate Temperature (0.05" from edge)**
37 °C (ANSYS model)
40.4 °C (Measurement)

**Device Temperature**
69 °C (ANSYS model)

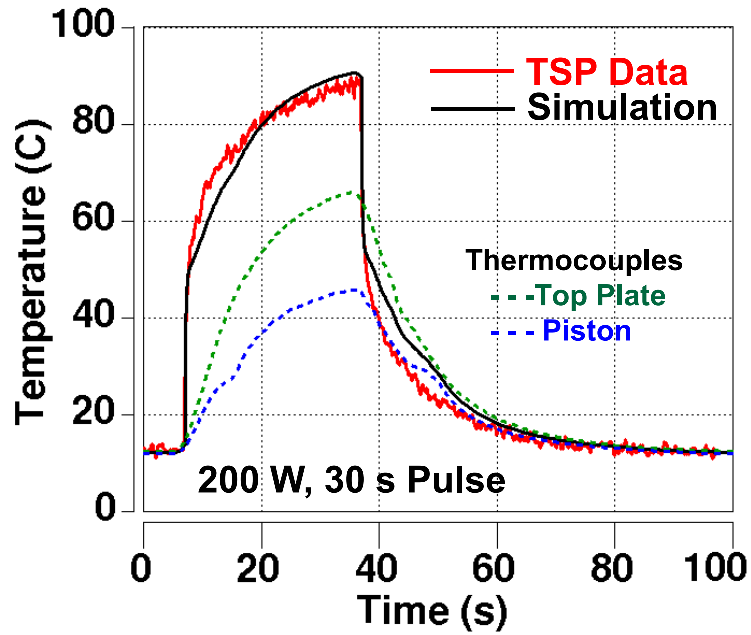
**Piston Temperatures (0.05" from edge)**
28 °C (ANSYS model)
31.7 °C (Measurement)

# Validation: Thermal Network Component Model for Viper Module Package

- Test fixture used to validate thermal model of Viper die, package, and interface to copper plates using TSP measurements.
- Test fixture modeled and compared with ANSYS and TSP.

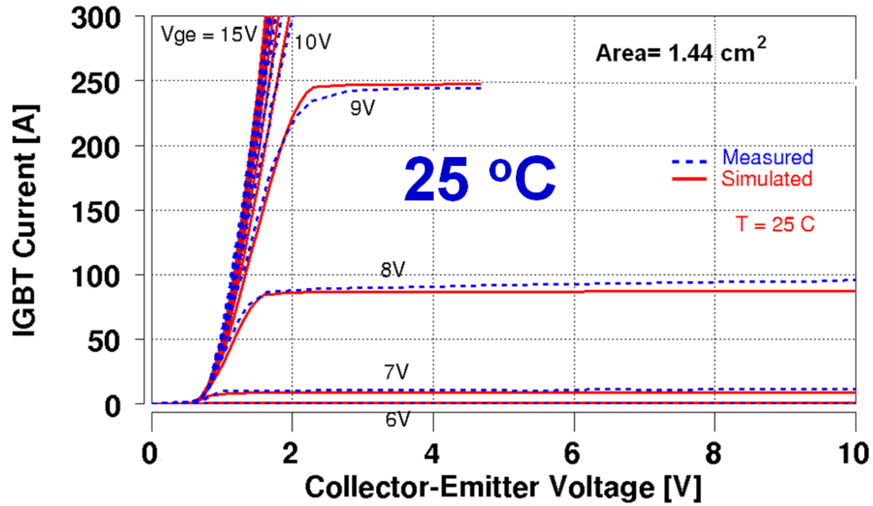


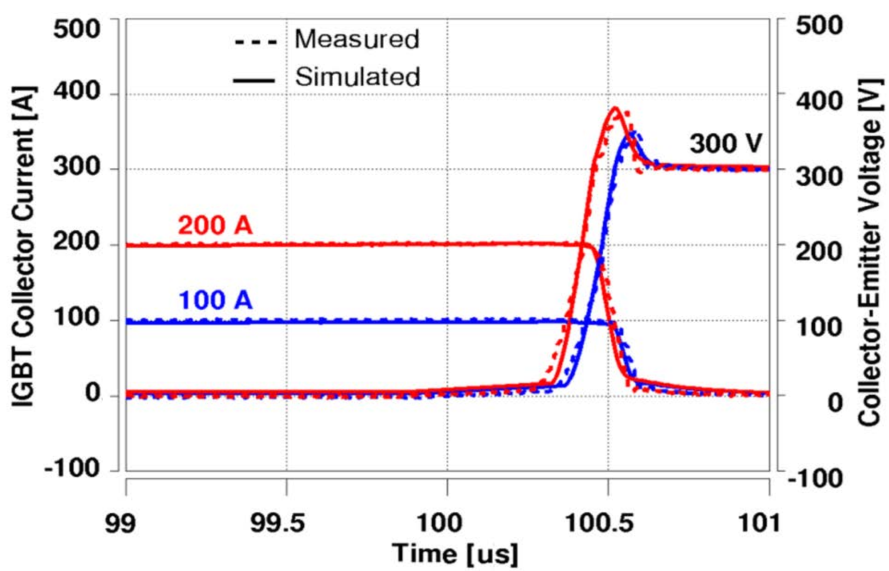

Comparison of simulated and measured Junction Temperature (TSP) for short duration, high power pulses.

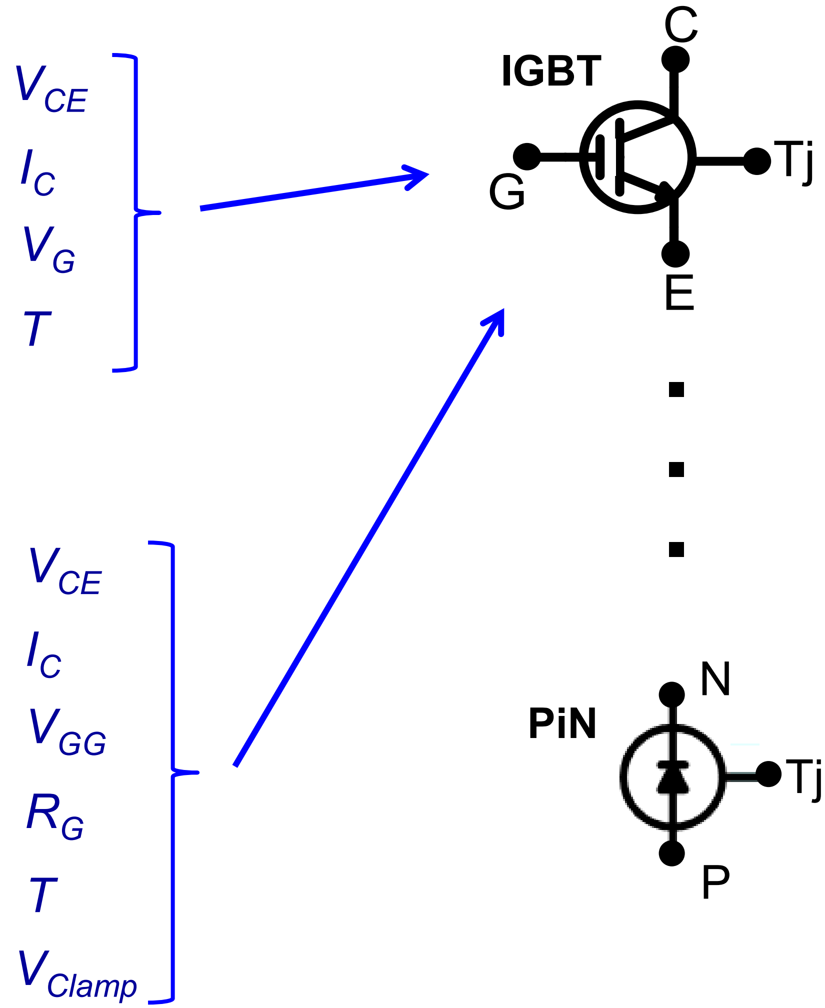



Comparison of simulated and measured Junction Temperature (TSP), and Plate and Piston Temperatures (thermocouples) for a low power, long duration pulse.

# Validation: Delphi-Viper
# Electro-thermal Semiconductor Models



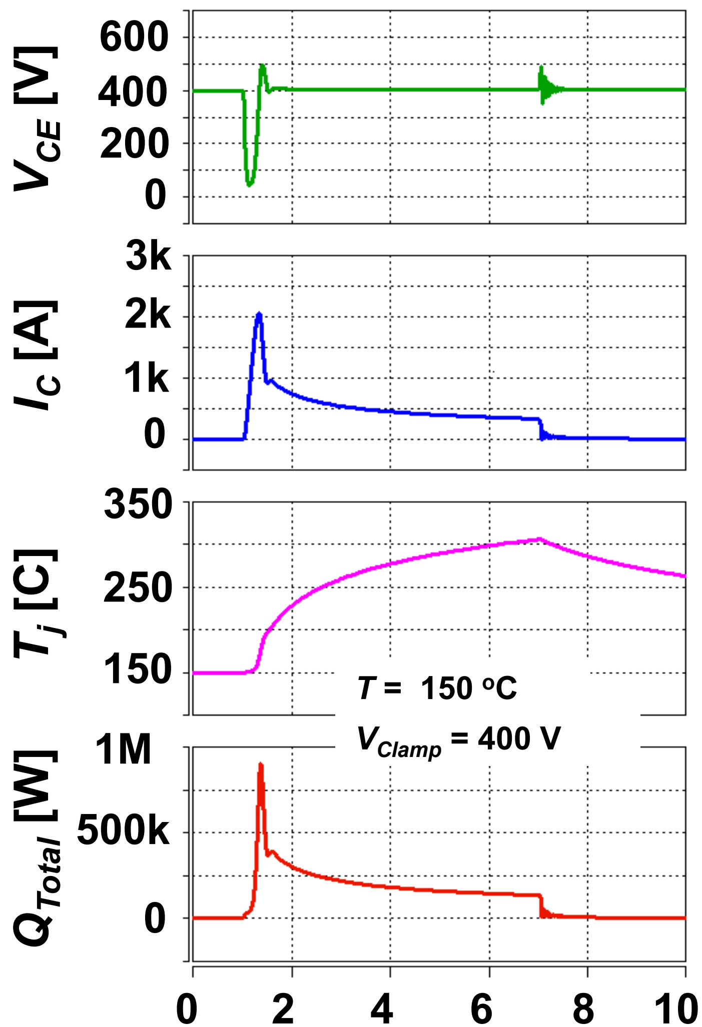



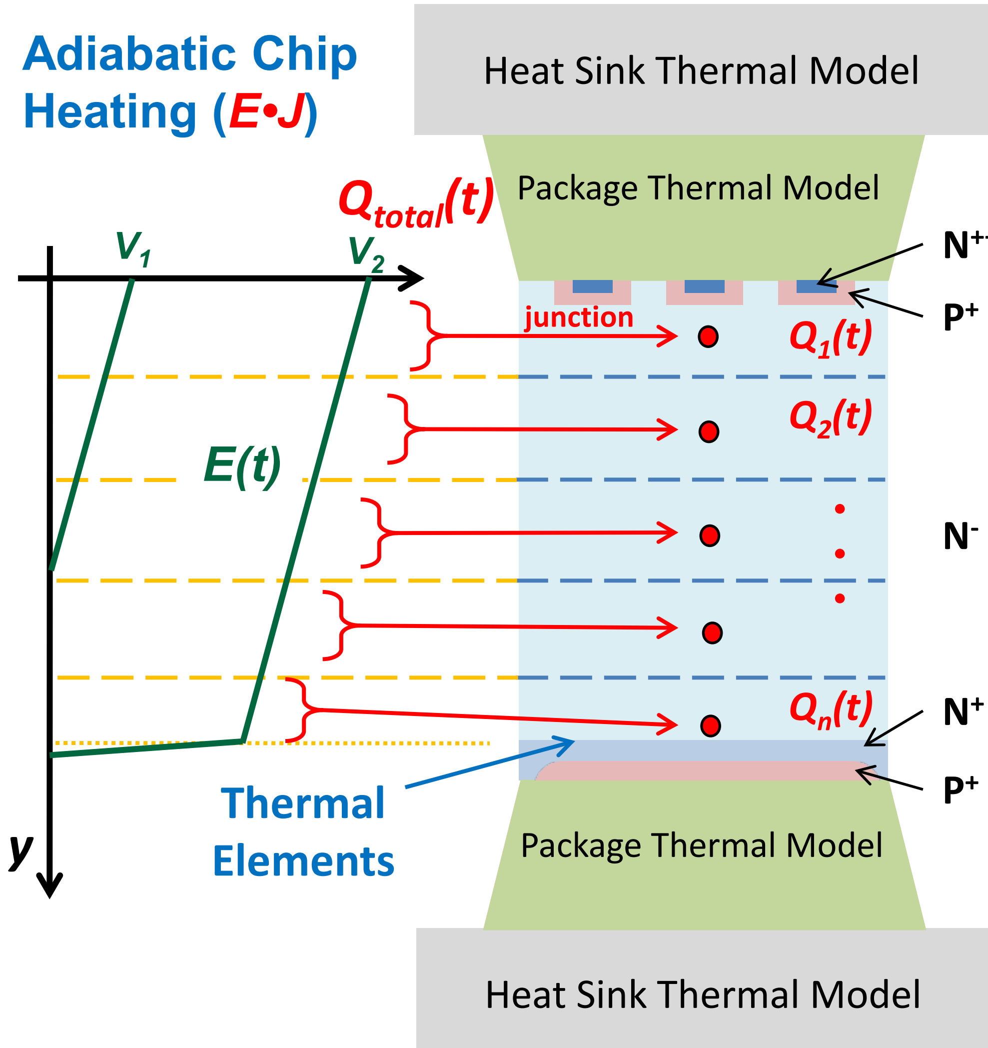

Additional validation results given at 2012 PEEM Kickoff meeting.

# Demonstration: Electro-Thermal Simulation
# Adiabatic Heating for Short Circuit Conditions

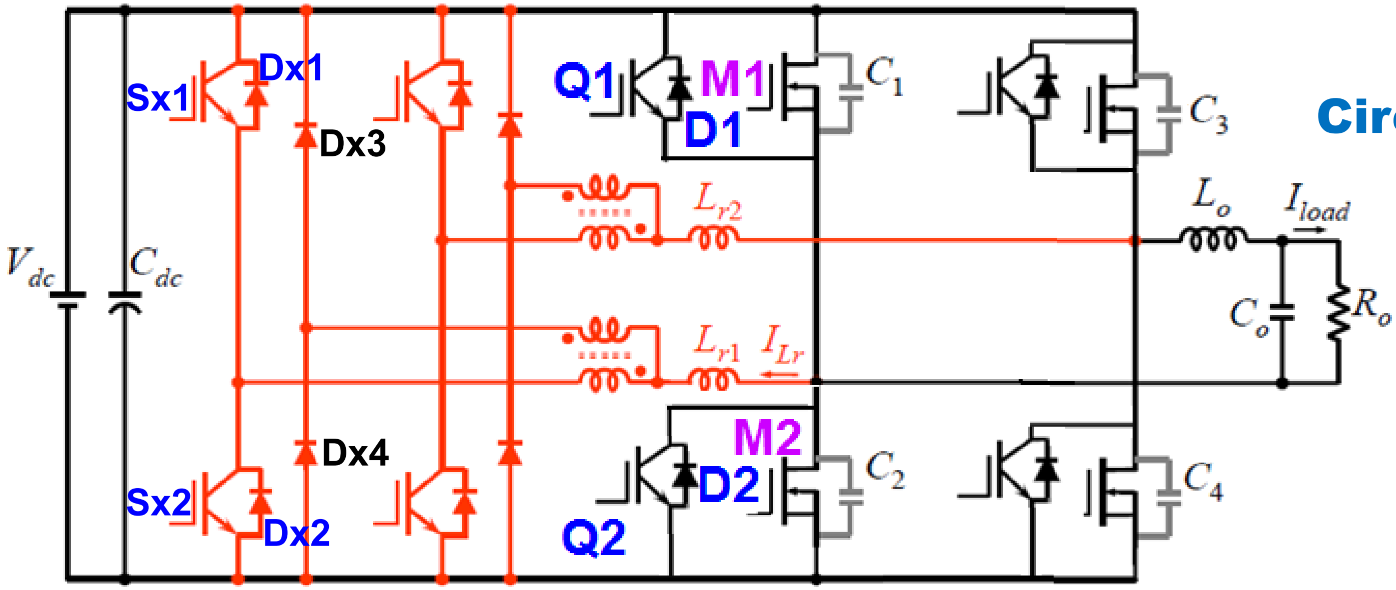
## Short Circuit Simulation




## Adiabatic Chip Heating (*E•J*)

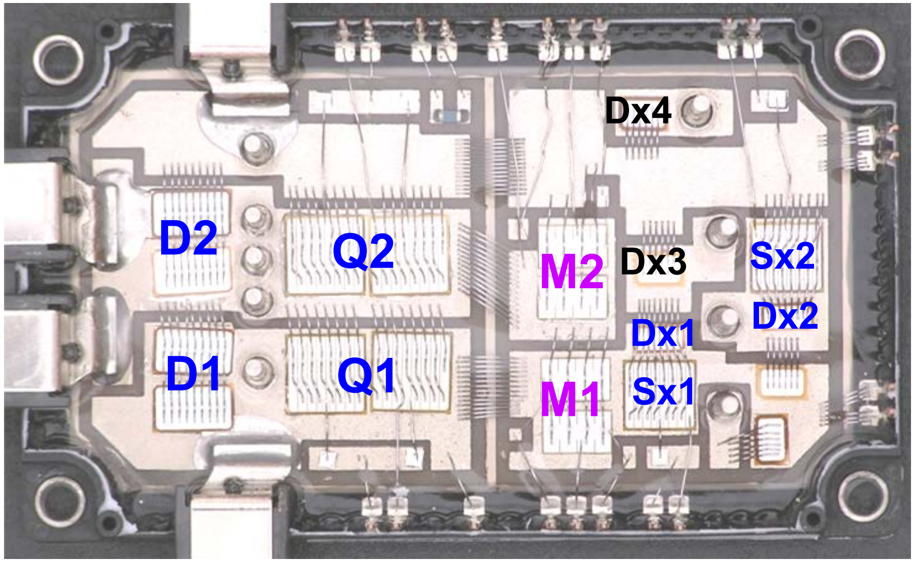


# Application: VTech Soft Switching Module

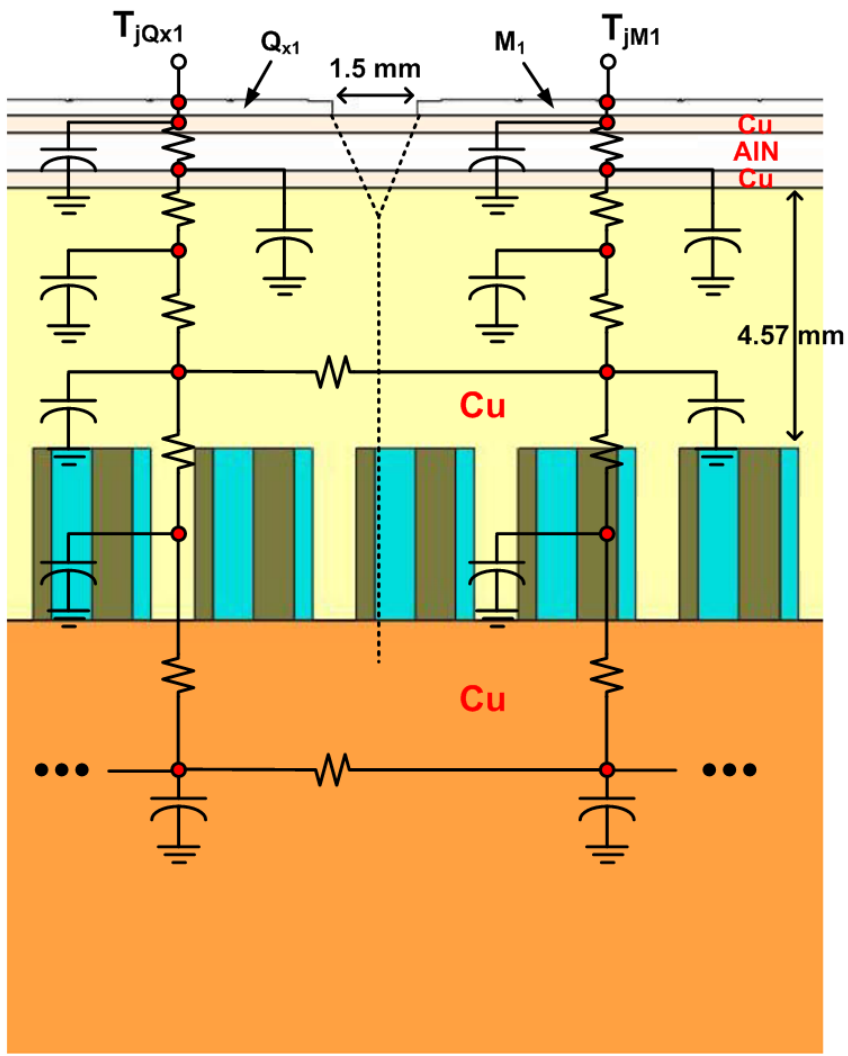


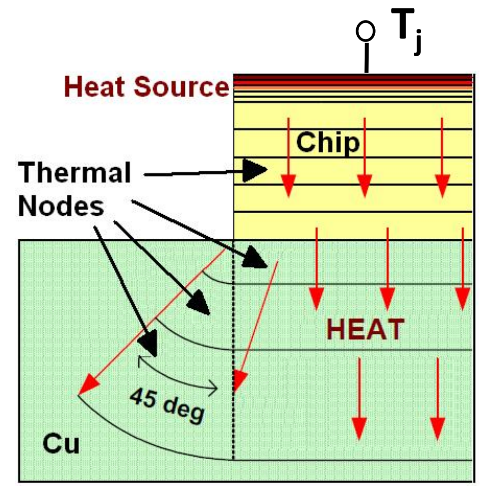

Circuit Diagram

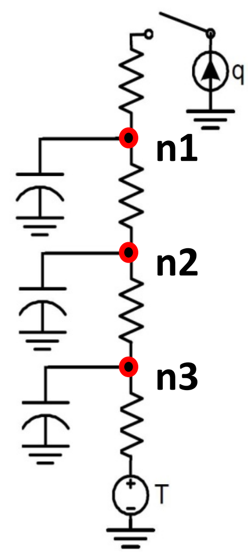
Module Components

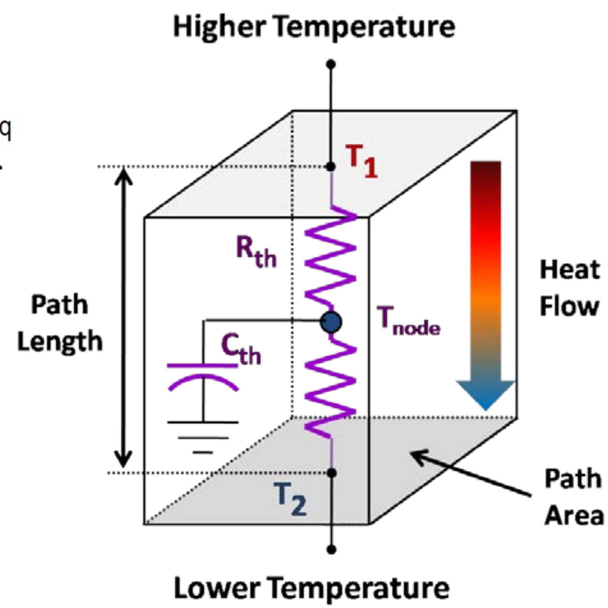


# Method: Thermal Network Component Models

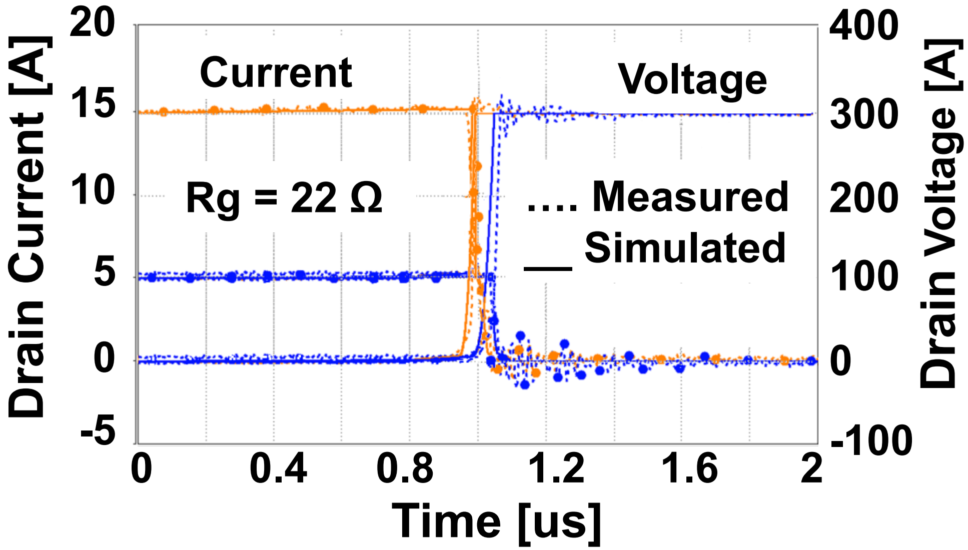


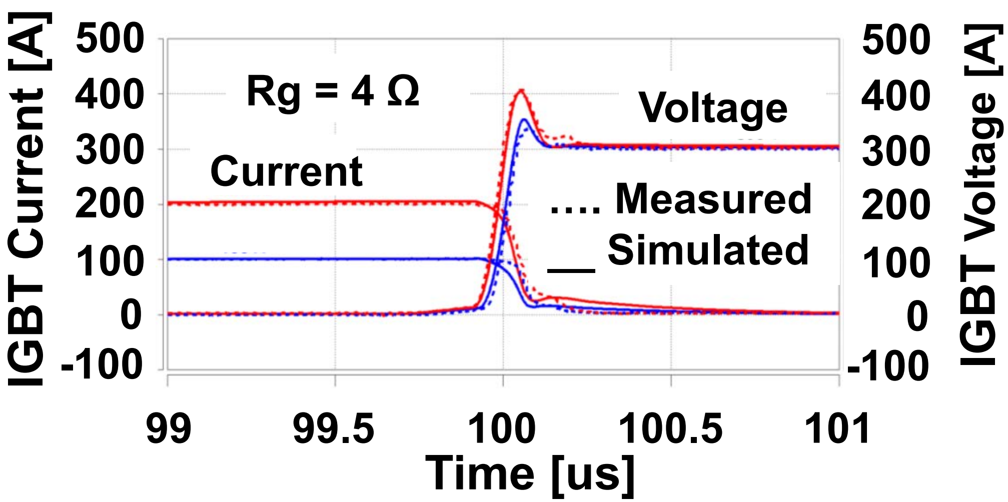



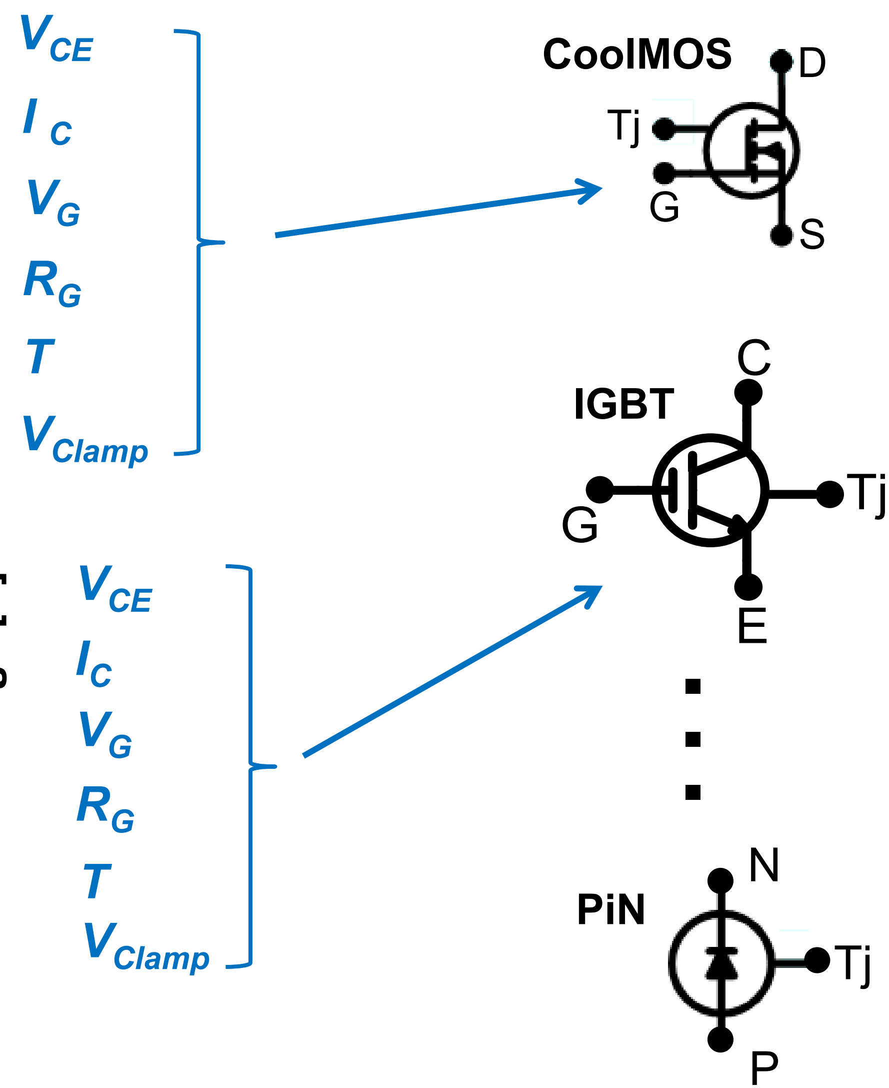



# Validation: VTech Module
# Electro-thermal Semiconductor Models




Additional validation results given at 2012 PEEM Kickoff meeting.

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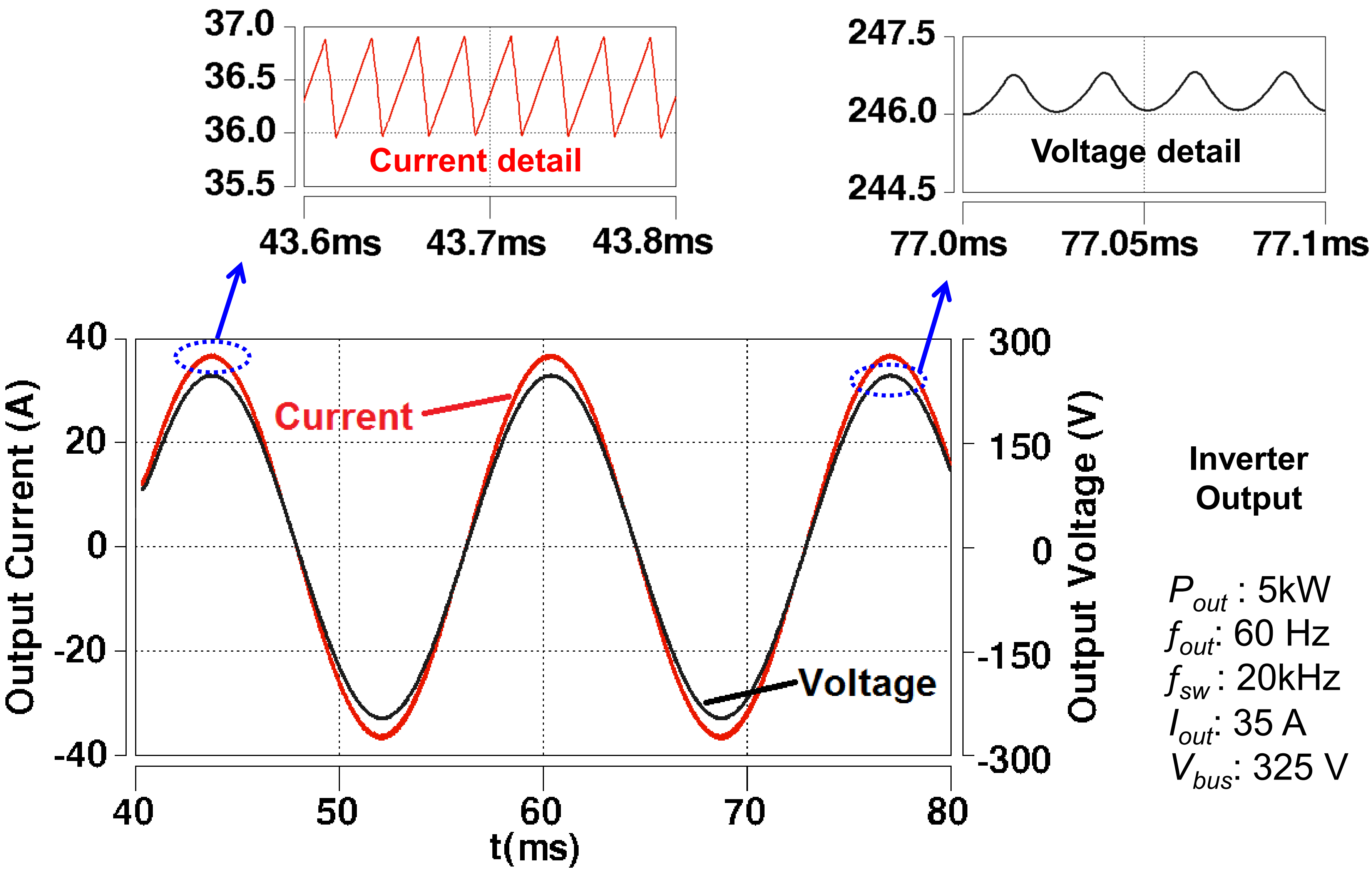
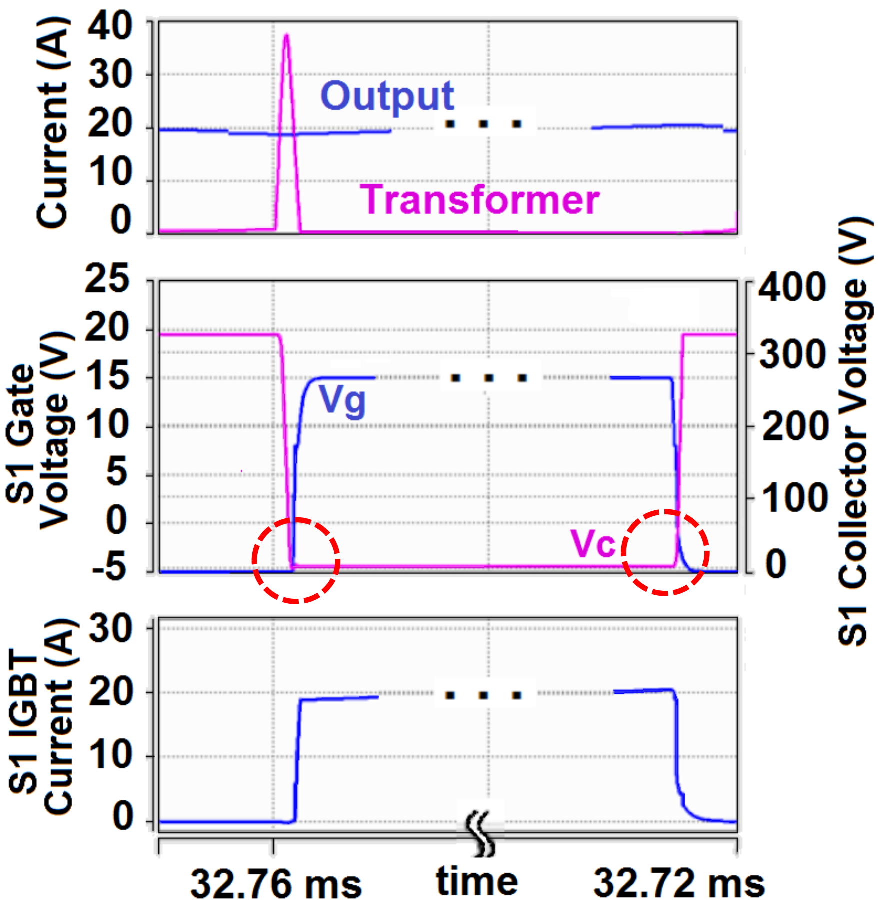
# Demonstration: Full Electro-thermal Simulation of Soft-Switching Vehicle Inverter



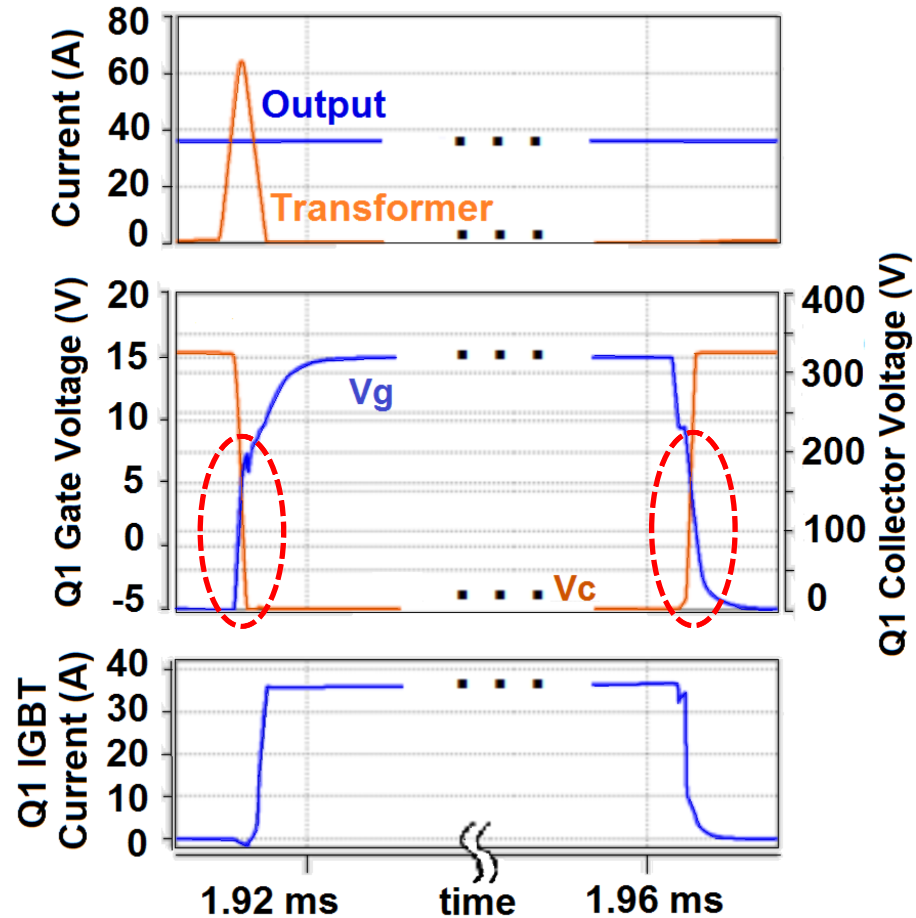

**Inverter Output**

$P_{out}$ : 5kW
$f_{out}$: 60 Hz
$f_{sw}$ : 20kHz
$I_{out}$: 35 A
$V_{bus}$: 325 V

# Analysis: Full Electro-thermal Simulation Optimization of Soft Switching Crossover



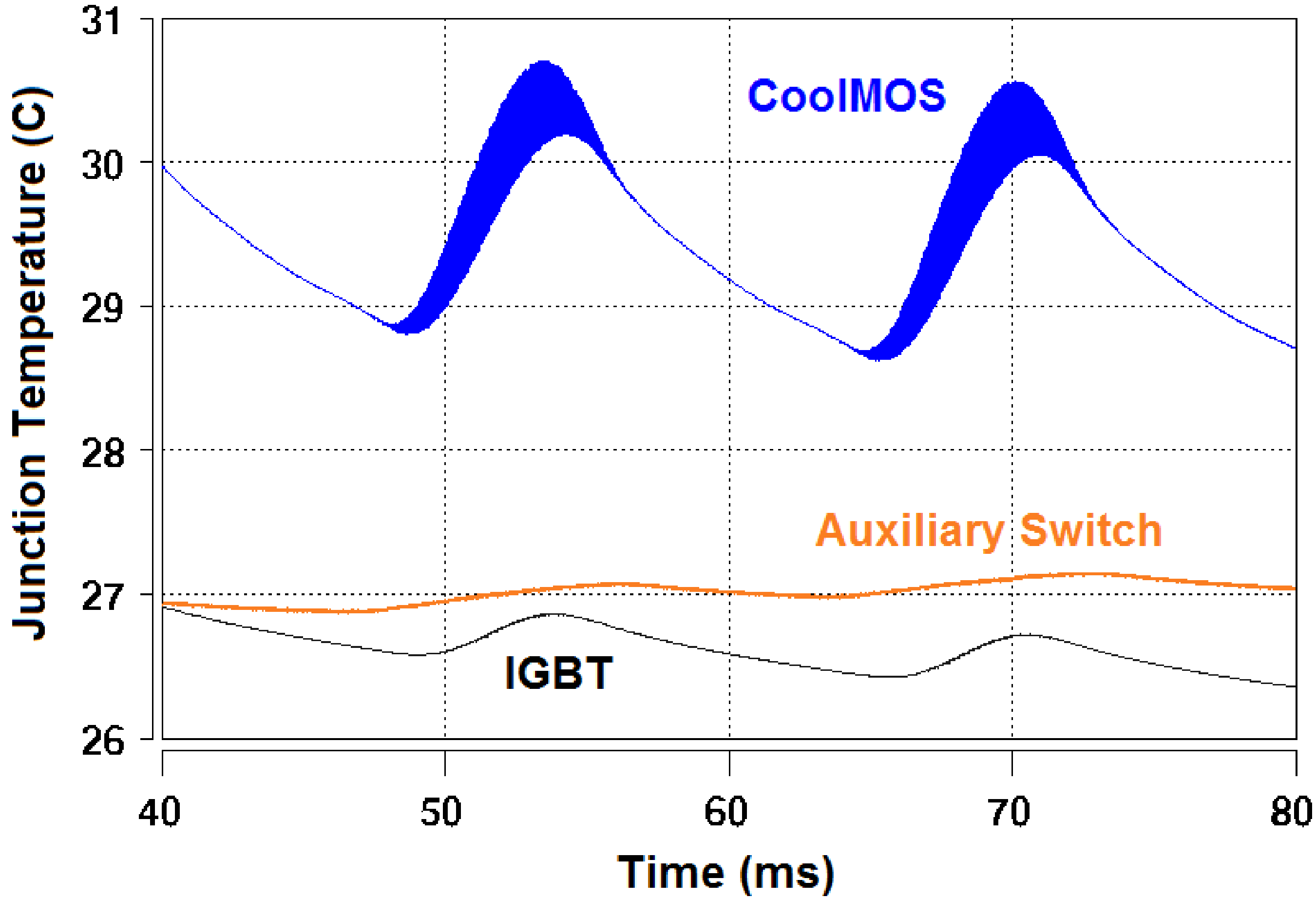

Simulations with generic IGBT model originally used to optimize timing for Zero-voltage switching.




Simulations with physics-based IGBT model indicate that timing is delayed from ideal model prediction.

# Analysis: Full Electro-thermal Simulation

## Operating Temperatures of Hybrid Module Devices




Electro-thermal simulation of junction temperature for switches undergoing half-sine wave power cycle.

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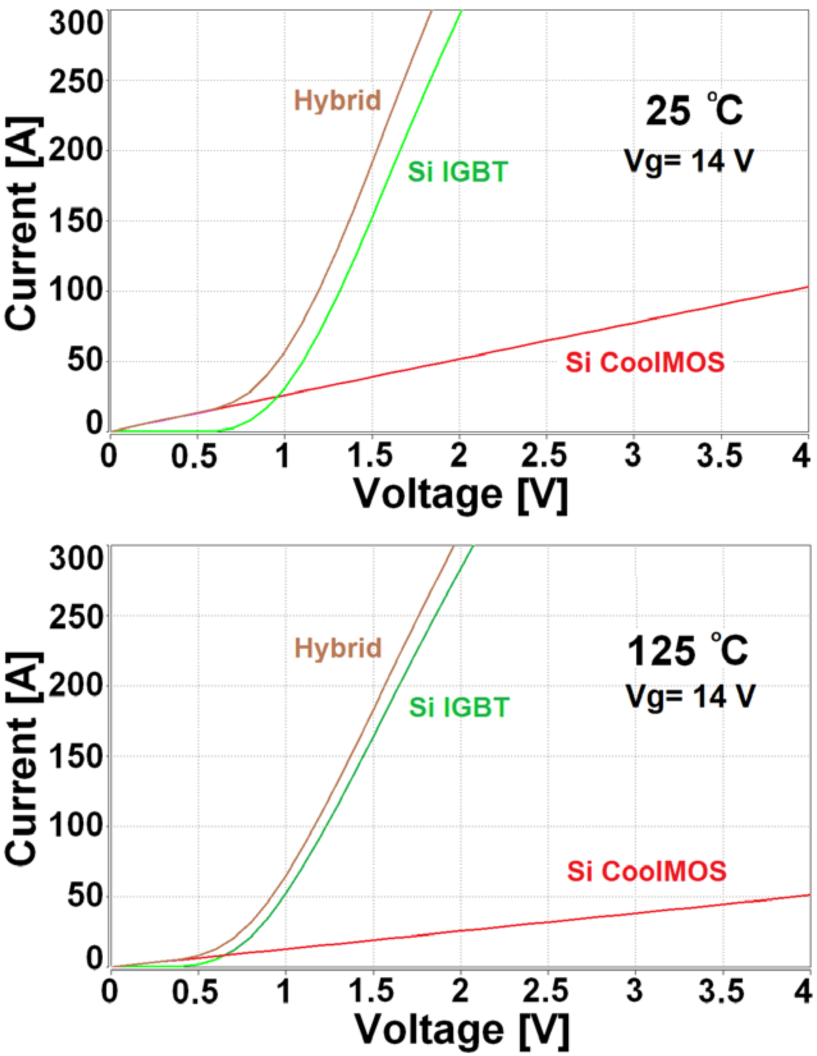
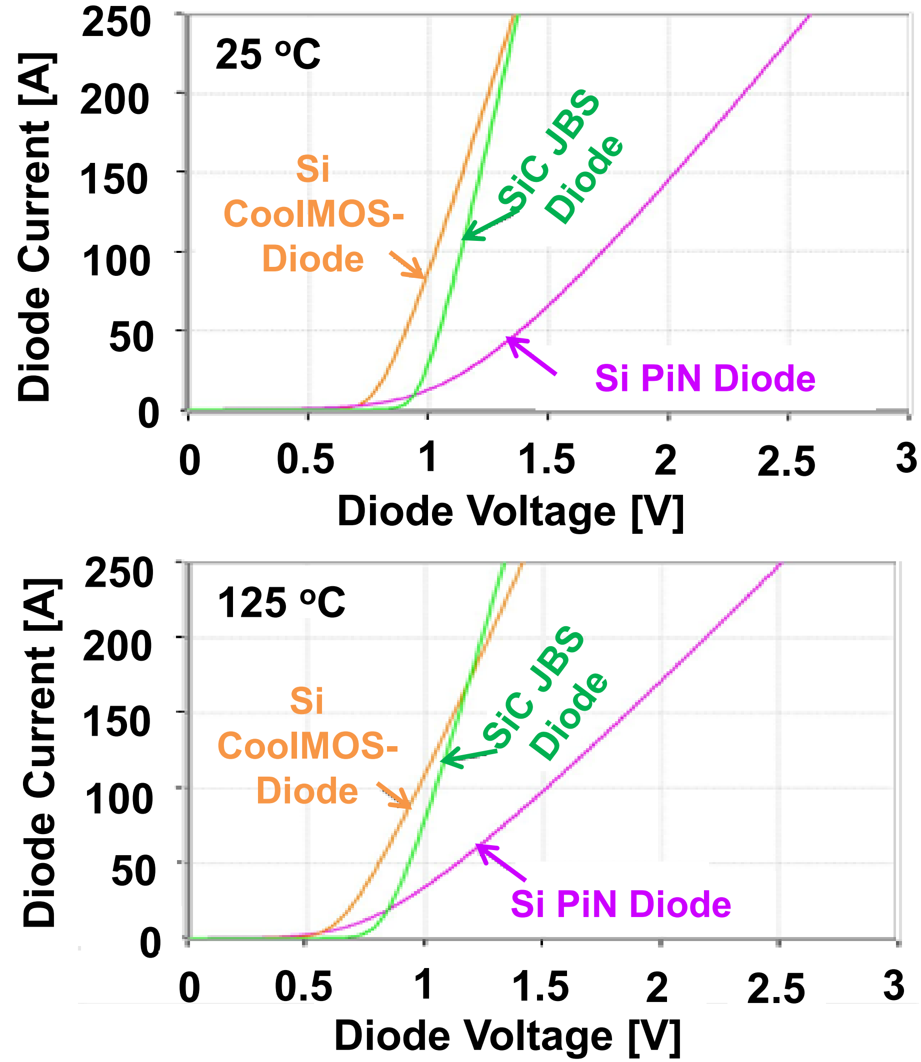
# Analysis: Paralleled Si IGBT, CoolMOS, Diodes




Analysis of current sharing of paralleled Switches (Si IGBT and CoolMOS)




Analysis of current sharing of paralleled Diodes (Si PiN, CoolMOS-body Diode, SiC JBS Diode)

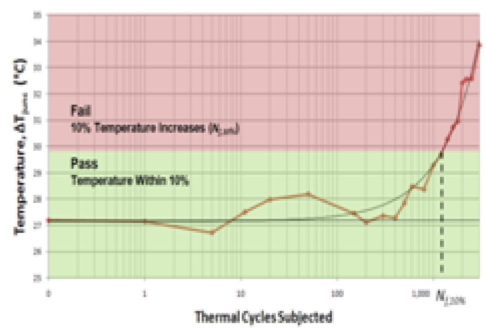
# Application: Package Reliability Simulations

## Physics-of-Failure Models

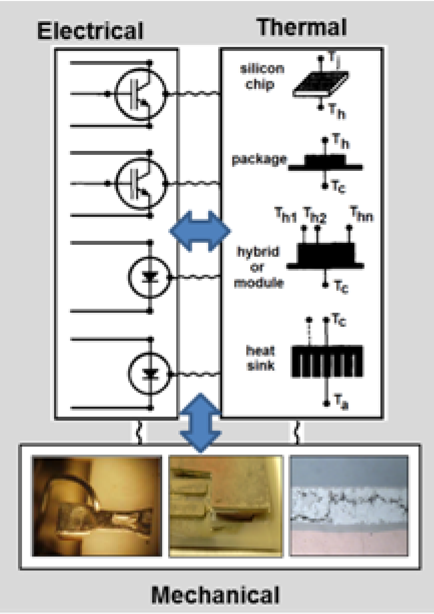
- Coffin-Manson
- Norris-Landzberg
- Energy Partitioning
- Strain-Range Partitioning

## High-speed transient TSP

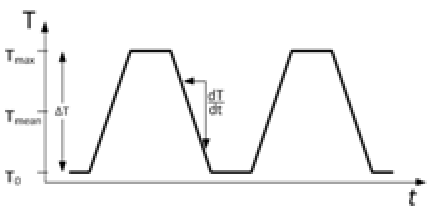
used to detect changes in buried interface thermal resistance caused by thermal cycling damage.




## Reliability Simulations

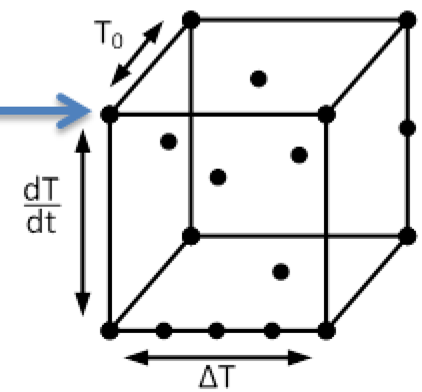



## Variable Ramp-Rate Thermal Cycling




| Initial Temp. | Temp. Swing | Ramp Rate |
|---|---|---|
| $T_{0,1}$ | $\Delta T_1$ | $\left.\frac{dT}{dt}\right\|_1$ |
| $T_{0,2}$ | $\Delta T_1$ | $\left.\frac{dT}{dt}\right\|_2$ |
| … | … | … |
| $T_{0,i}$ | $\Delta T_i$ | $\left.\frac{dT}{dt}\right\|_i$ |

## Degradation and Monitoring Design-of-Experiments




$$N_f\left(T_0, \Delta T, \frac{dT}{dt}\right)$$

Technology Dependent Reliability Models

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# Summary

- Developed electro-thermal semiconductor models and evaluated trade-offs for different semiconductor component selections in VTech soft switching module.
- Developed thermal-network-component model for VTech module and utilized full electro-thermal simulations to determine operating temperature of devices and evaluate impact of IGBT gate drive delay on circuit timing.
- Developed electro-thermal model for Delphi double-sided cooling Viper IGBT module and utilized models to simulate representative short circuit fault condition.
- Developed thermal-network-component model for Viper package, developed double-sided cooling thermal test fixture, and used the fixture to validate the Viper thermal stack model using TSP.
- Developed and demonstrated method for determining parameters for DBC stack physics-of-failure models using variable-ramp-rate thermal cycling with high-speed transient TSP monitoring.

# Future Work

- Develop electro-magnetic package/system interconnect models.
- Perform EMI simulations using electro-magnetic package/system interconnect models, electro-thermal semiconductor models and thermal-network-component models.
- Determine grid applications and develop circuit simulation scripts for bi-directional vehicle charger/grid storage inverters.
- Perform simulations and evaluate impact of advanced technology power semiconductors and module packages in bi-directional vehicle charger inverter applications.