A Simulation Platform for Electrothermal Design/Verification of IGBT Modules

2019.6

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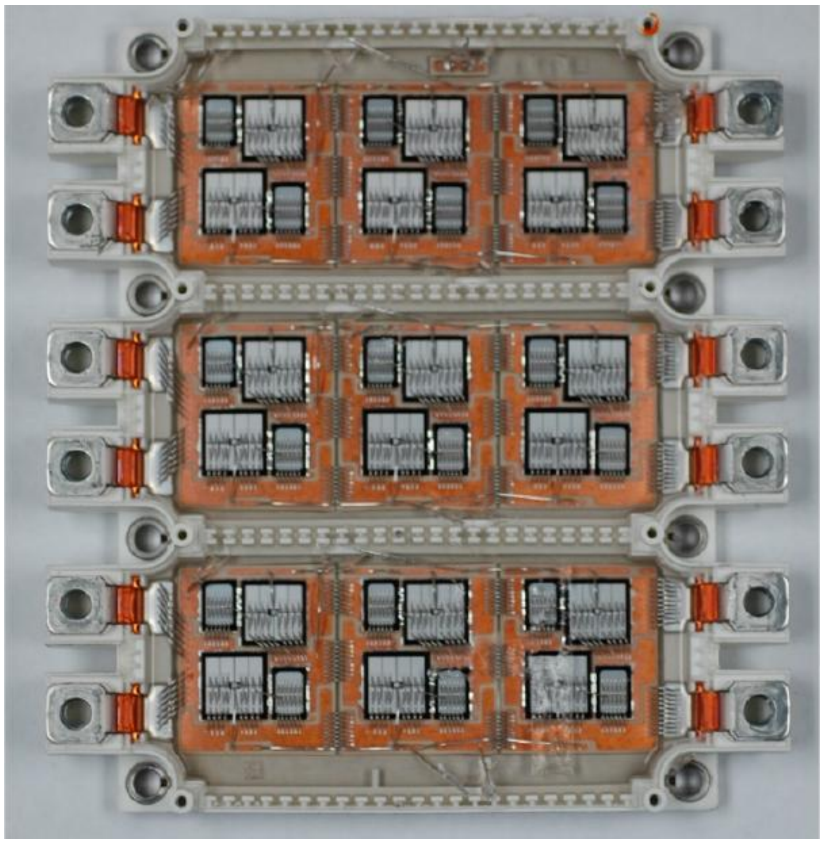
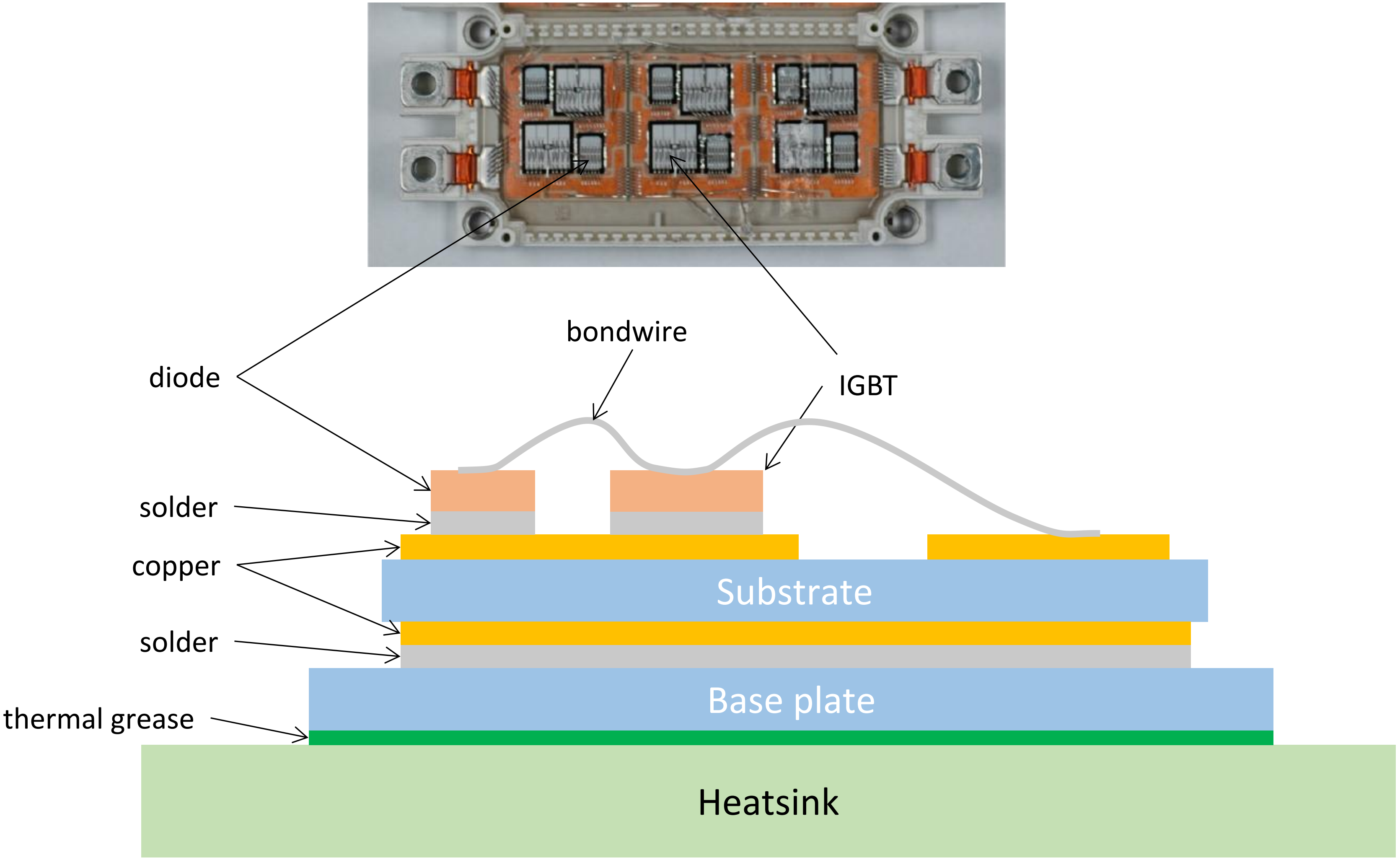
Need for Module Design Tool



- Reliability is cirtical
- Identify design weakness
- Eliminate common pitfalls
- Trade-off
  - Complexity vs Accuracy
  - Feature vs Distraction

Internal Structure of IGBT Module



Outline

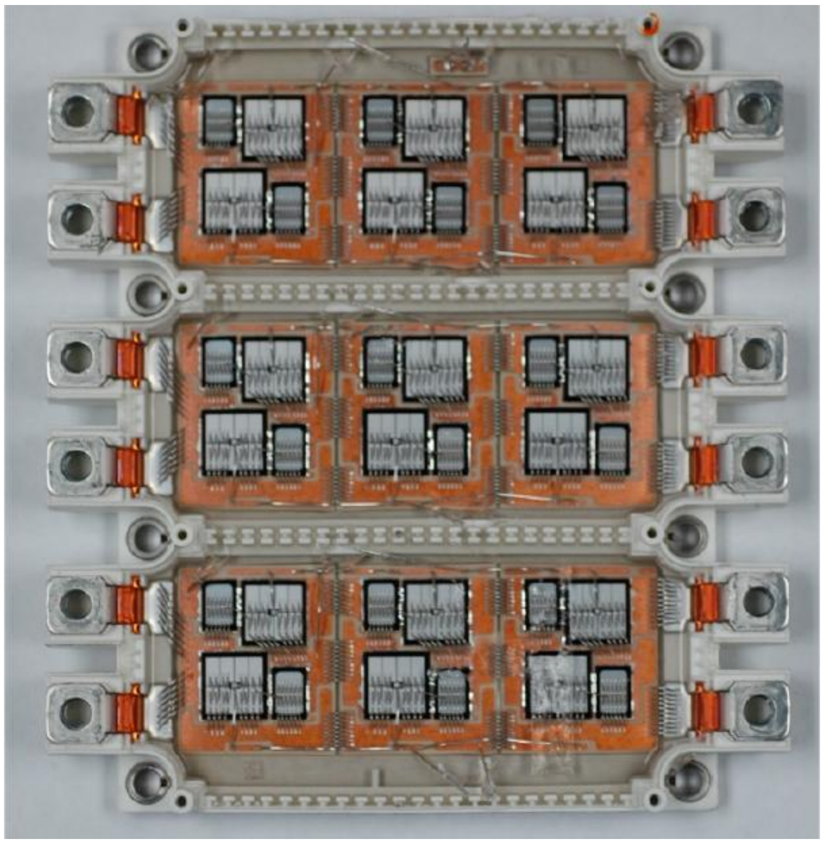
- Objectives
  - IGBT Module Failure Mechanisms
  - Features to include/skip
- Implementation
  - Inputs
  - Models
  - Numericals
- Simulation Results
- Next Plan

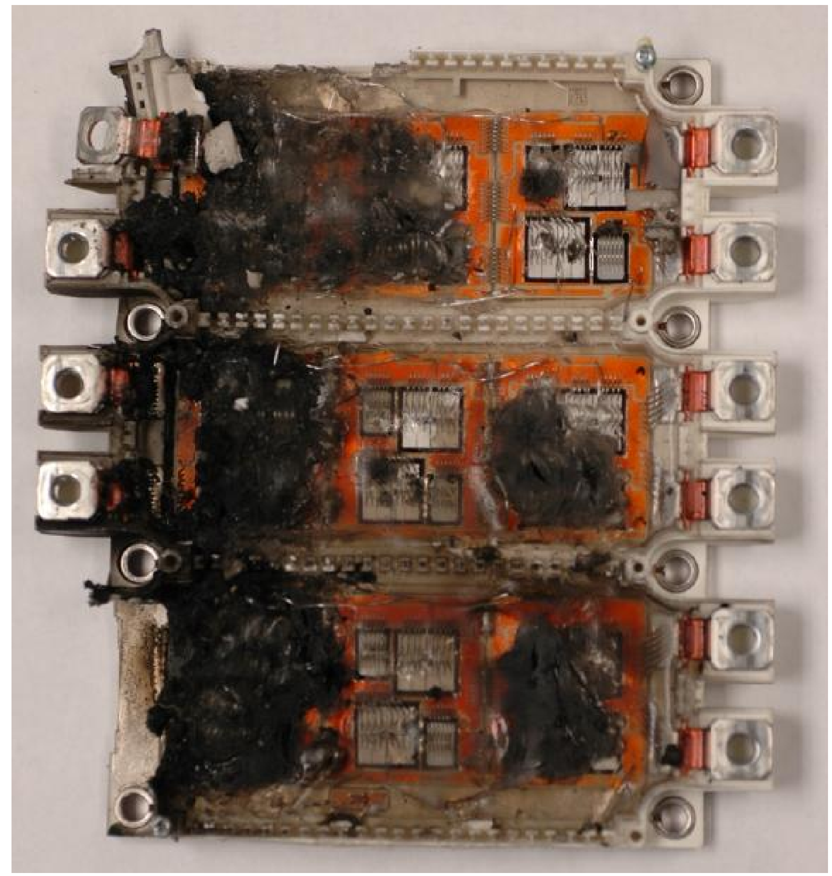
IGBT Module Failure Mechanisms (selected)

- Thermal Run-away
  - location: IGBT/FRD
  - cause: hotspot in module (max. T)
  - fix: improve electrical/thermal uniformity

- Fatigue
  - location: bond-wire, die attach, ...
  - cause: cyclic deformations (ΔT)
  - fix: improve electrical/thermal uniformity

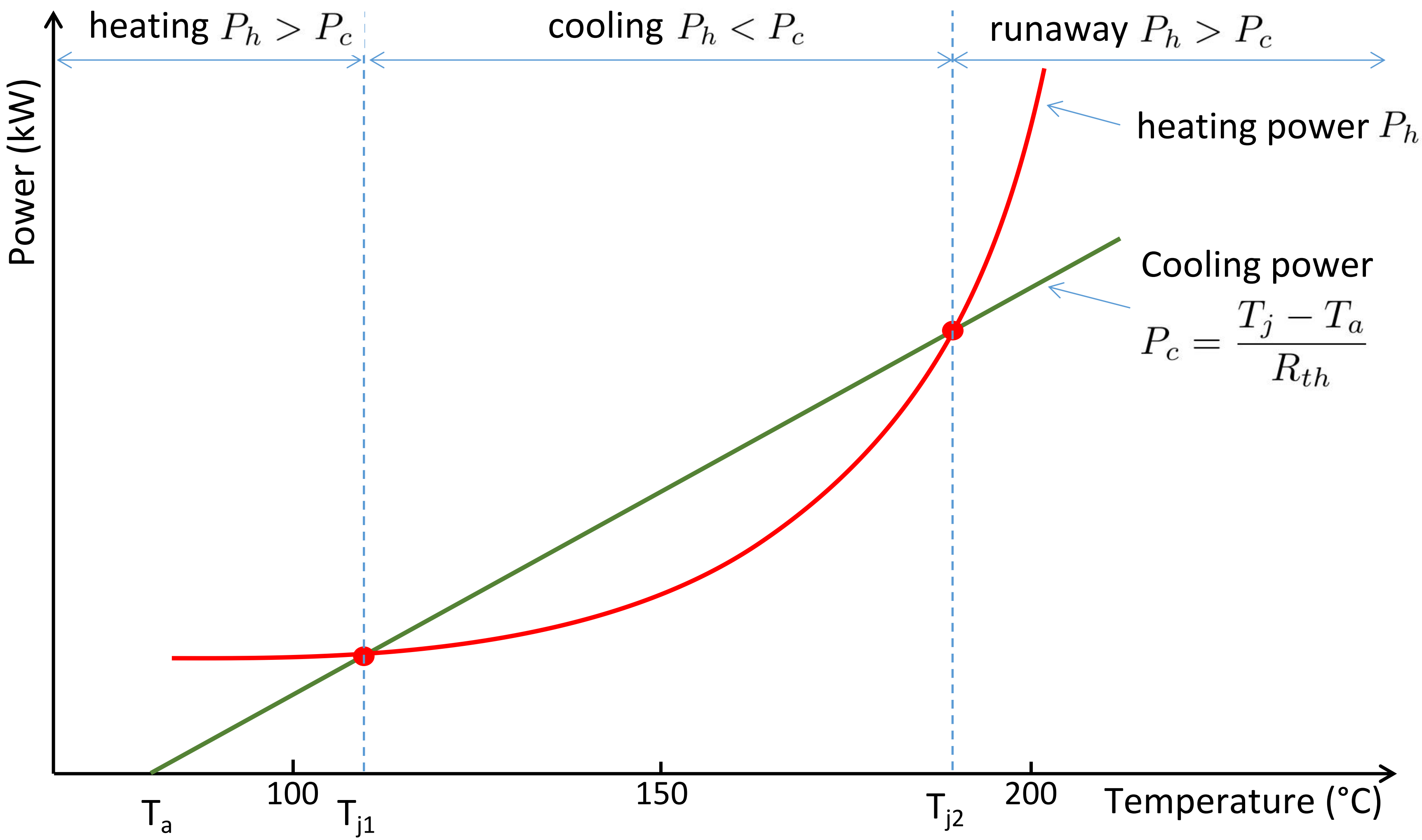
Thermal Runaway



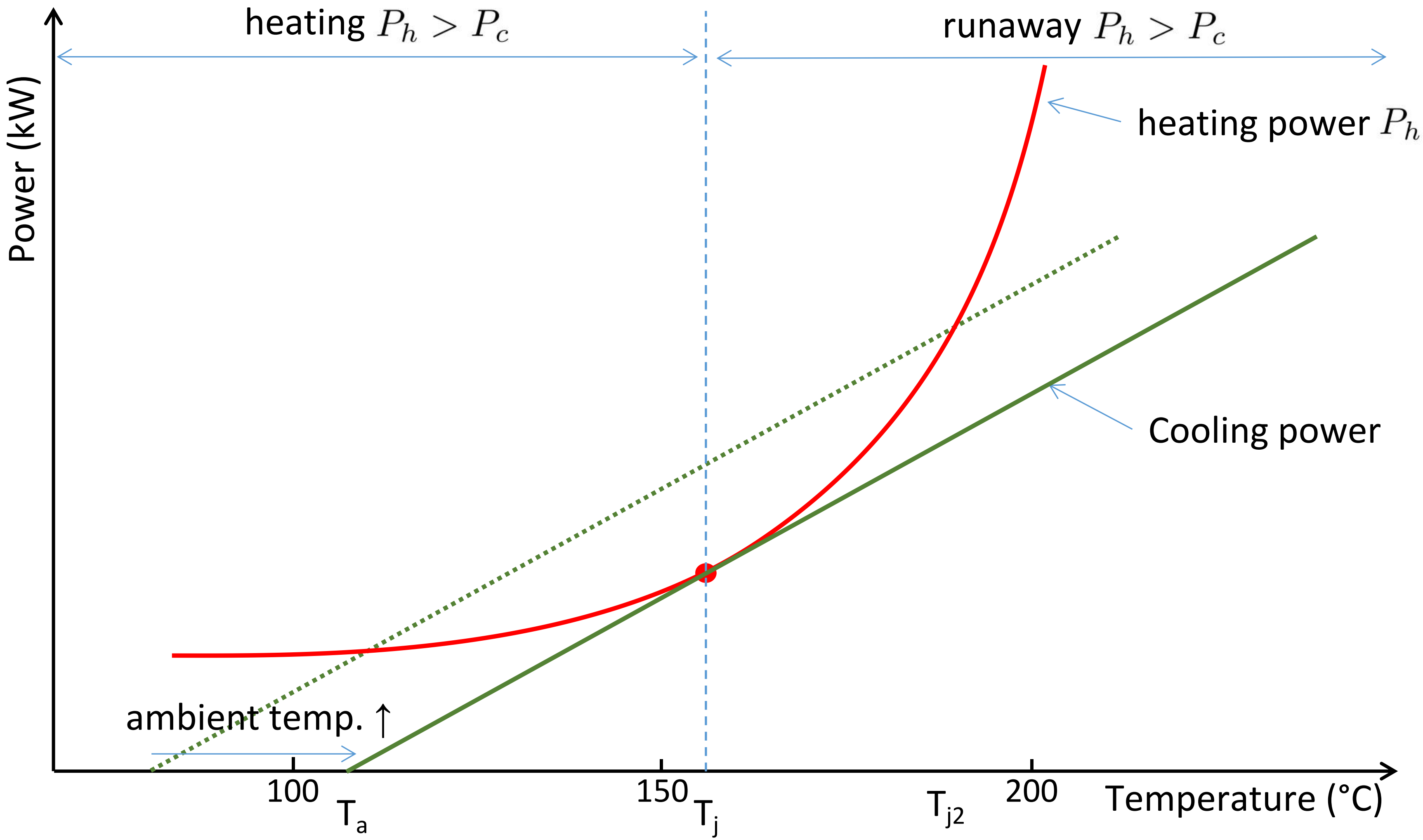


N Valentine 2015 NREL Photovoltaic Reliability Workshop

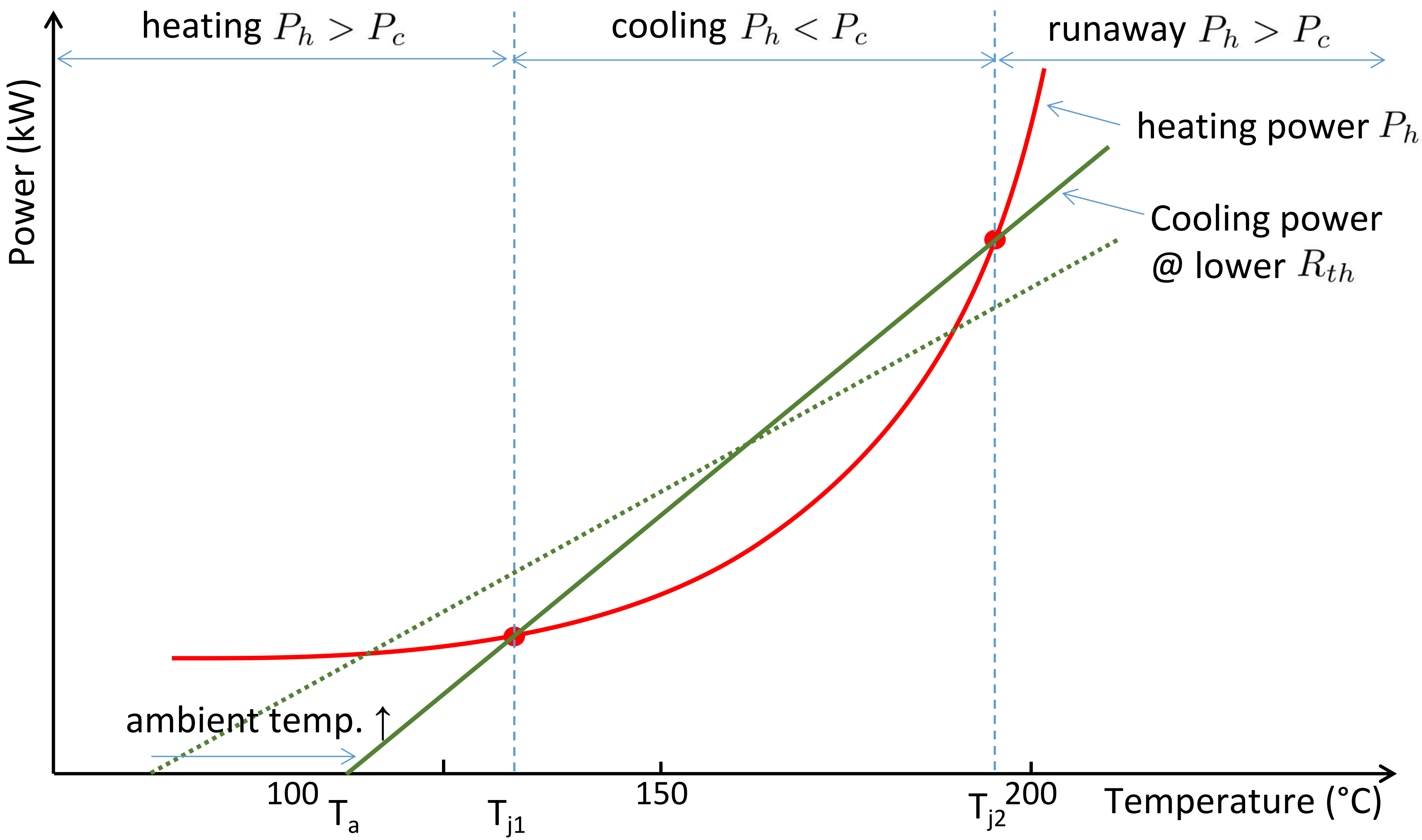
Thermal Stability in Power Module



Thermal Stability: High Ambient Temp.



Thermal Stability: Lower R_{th} is Better

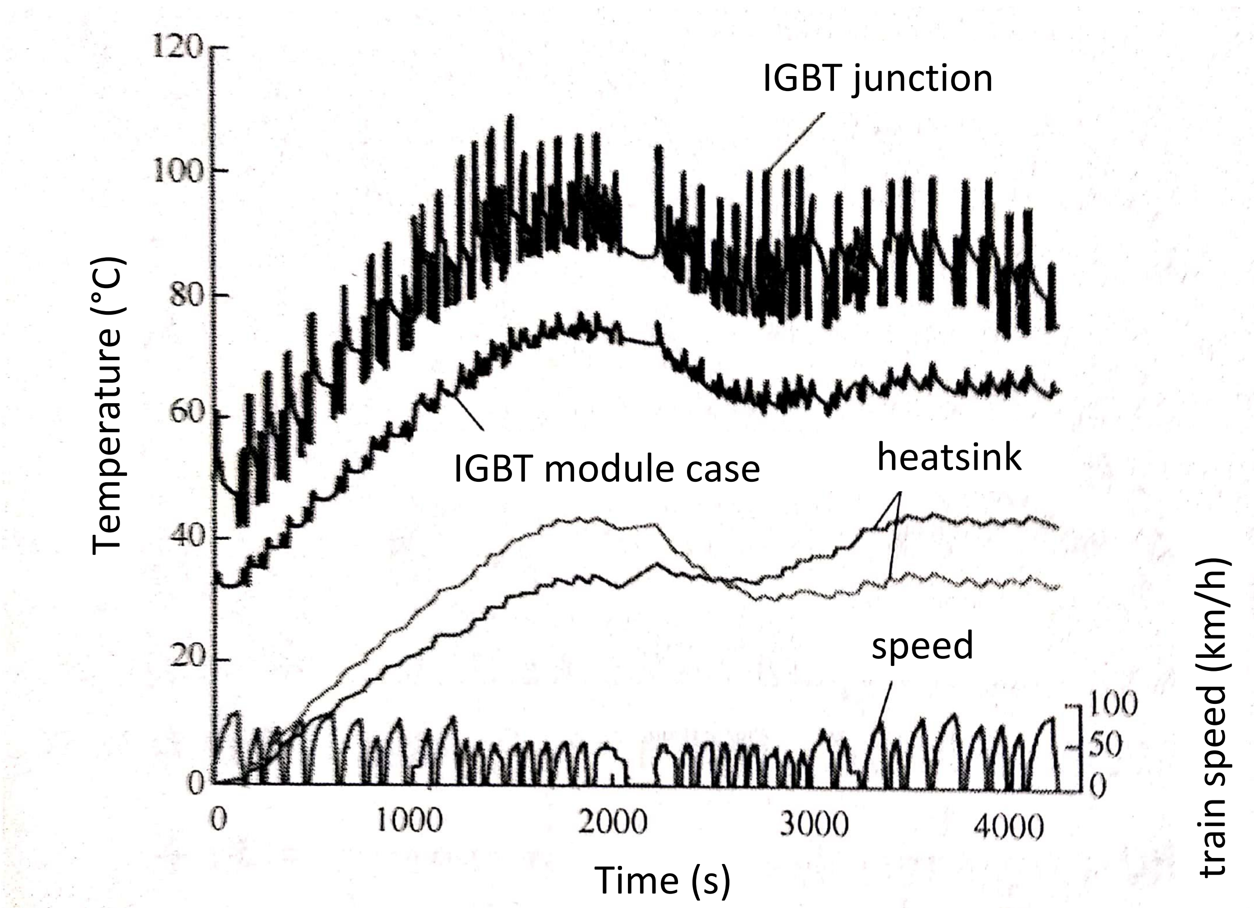


Thermal Stability: Complications

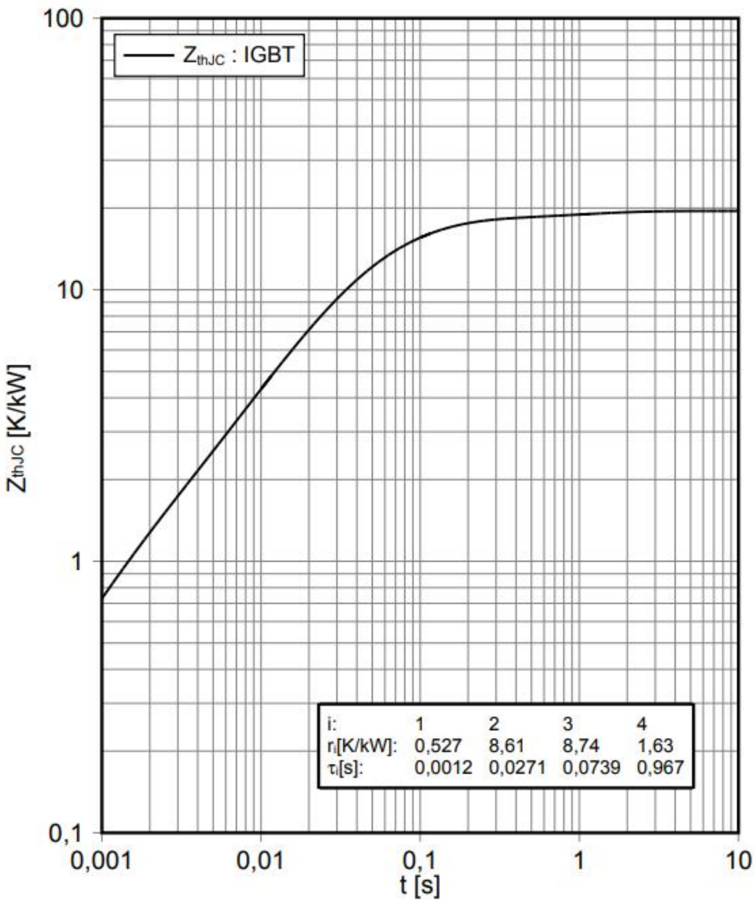
- Application circuits: switching operation
  - Heating power is not constant
    - cyclic, workload dependent heating power
  - Thermal resistance is not constant
    - Transient Thermal Impedance

- Multiple IGBT/FRD chips
  - chips affect each other
  - alternating direction of heat flow
  - one R_{th} value for each chip : inadequate

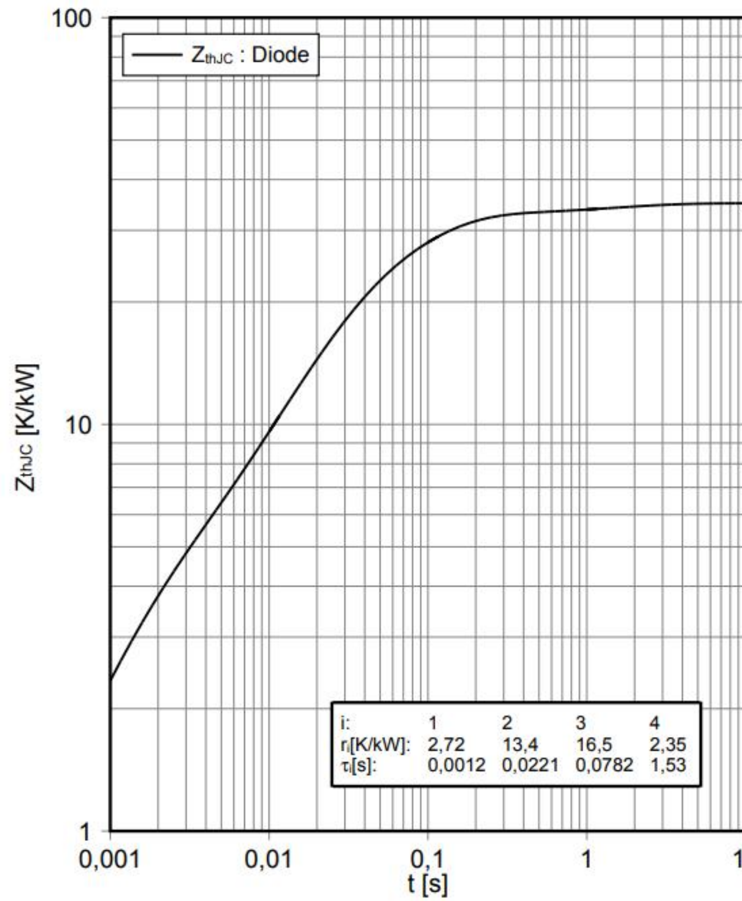
Realistic Mission Profile



Transient Thermal Impedance



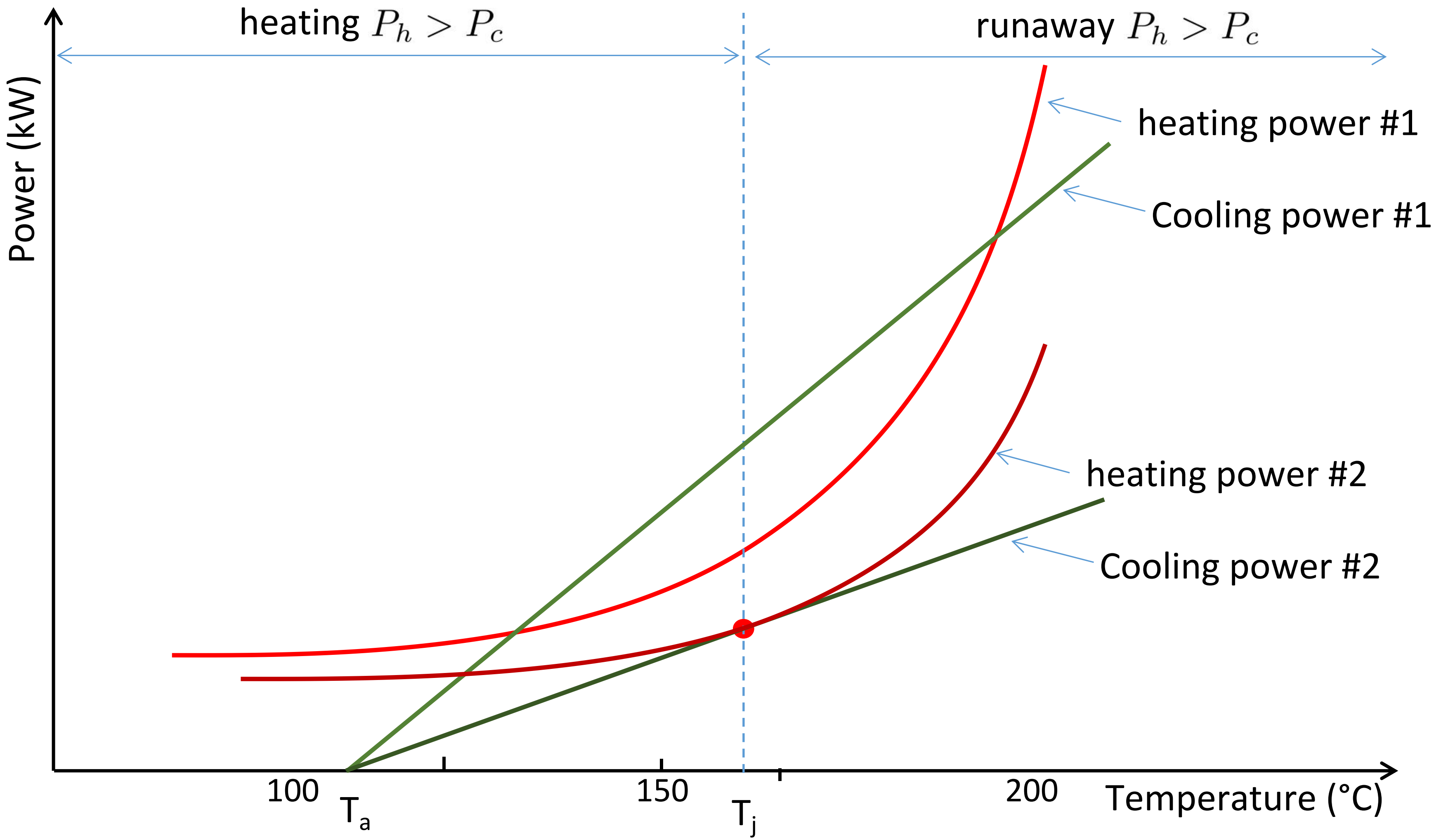
Transient thermal impedance of IGBT



Transient thermal impedance of FRD

Infineon FF1500R12IE5

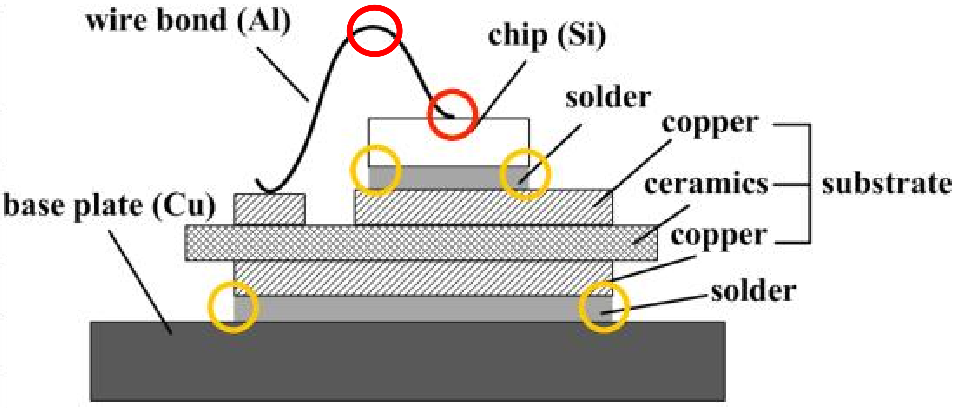
Thermal Stability: Multiple Chips



Fatigue: Repeted Stress Load

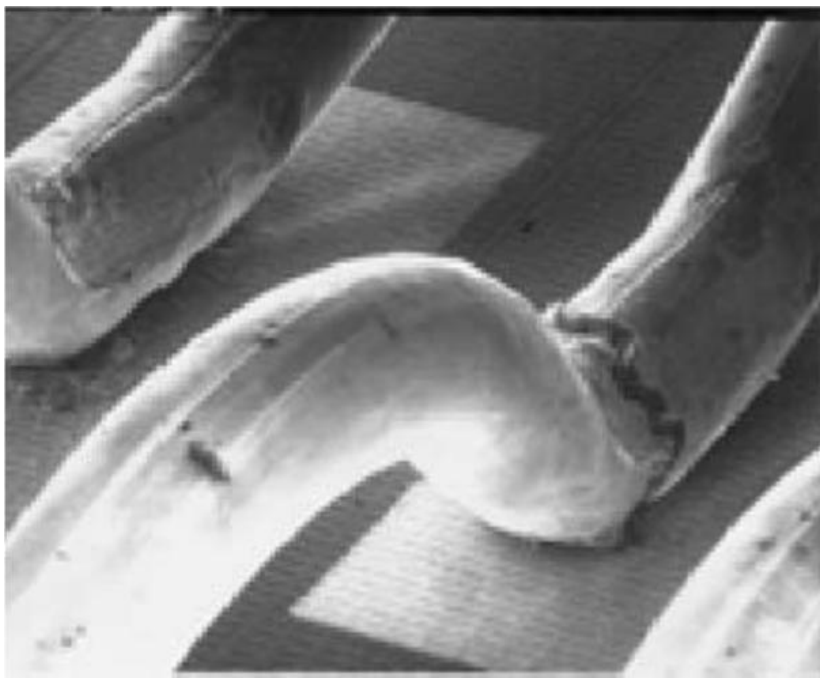
CTE mismatch + Temperature cycle → Stress Cycles

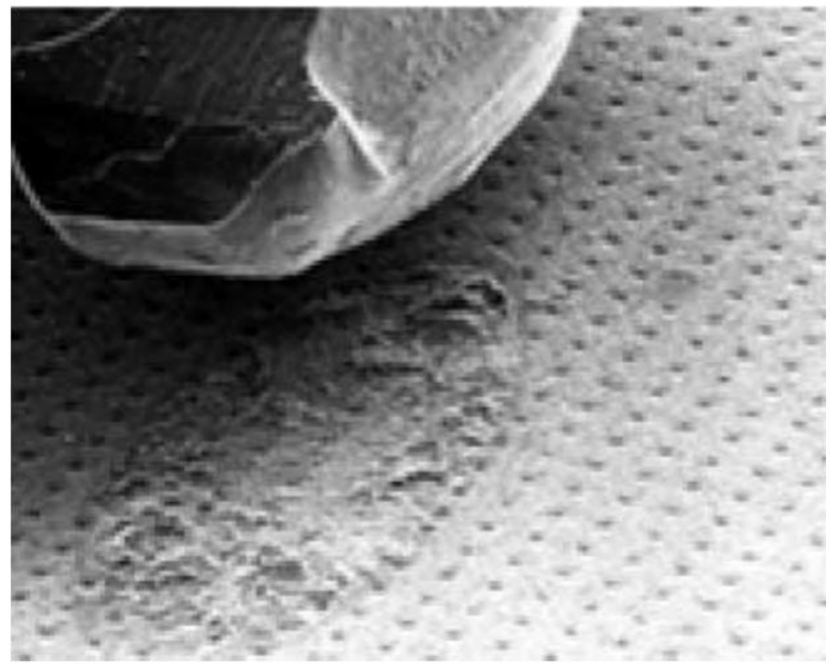
Material	CTE (10^{-6} K^{-1})	Conductivity (W m^{-1} K^{-1})
Al_2O_3	6.8	24
AlN	4.7	170
Si_3N_4	2.7	60
BeO	9	250
Al	23.5	237
Cu	17.5	394
Mo	5.1	138
Si	2.6	148
AlSiC	7.5	200



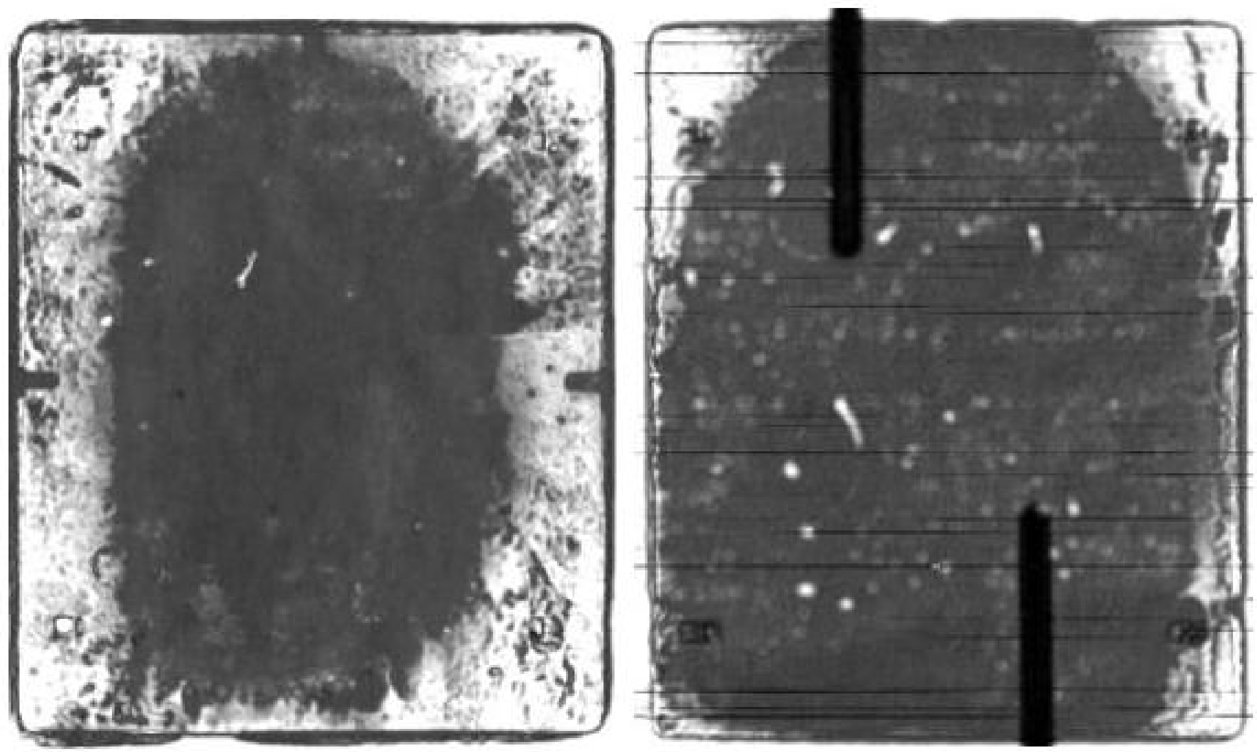
- Bond Wire Fatigue
- Solder Joint Fatigue

Fatigue: Bond Wire Fatigue





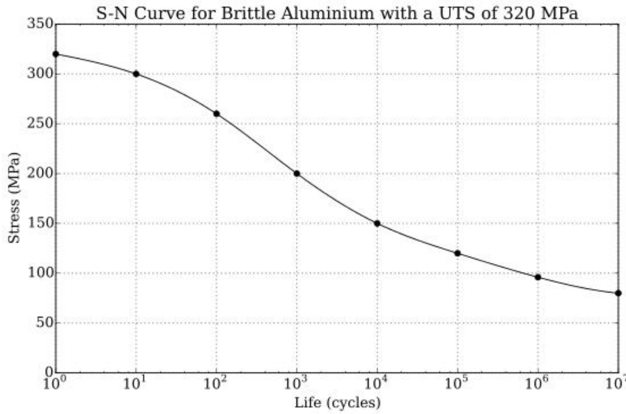
Fatigue: Crack in Die Attach



Marc Schäfer 2014

Fatigue: Failure Model

- S-N Curve predicts lifetime under low stress



- Palmgren-Miner Rule
  - Combined effects from large/small stress cycles

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

- Approximation:
  - ΔT-N instead of S-N

Objectives: “Necessary Features”

- Inputs
  - Complete circuit
  - Detailed 3D model
  - Material database
  - Look-up table model for IGBT/FRD
- Electrothermal simulation
  - Heating in IGBT, FRD, bondwire, etc.
  - Cooling by heatsink
  - Transient / steady-state analysis
- Outputs
  - I/V/P/T waveform
  - Temperature profile
  - hotspot/weakness report

Objectives: “A Bit Too Much”

- Sub-μs transients in circuit
  - Compact Model for IGBT/FRD
  - Stray inductance
- Stress/strain solver
- Air/liquid cooling

Features Compared

	PLECS	Simplorer	FloTherm	Ansys	This work
Complete circuit	Yes	Yes	No	No	Yes
PWM control signals	Yes	Yes	No	No	Yes
Parasitic RCL	No	with Q3D	No	No	R-only
IGBT/FRD model	Ideal	SubCkt	No	No	Ideal
Heating @ IGBT/FRD	LUT	SubCkt	No	No	LUT
Heating @ parasitics	No	No	No	No	Yes
Heat transport	Therm.RC	Therm. RC	Detailed	Detailed	Detailed
Air/water cooling	No	No	Yes	No	No
Temperature profile	No	No	Detailed	Detailed	Detailed
Stress profile	No	No	No	Detailed	No

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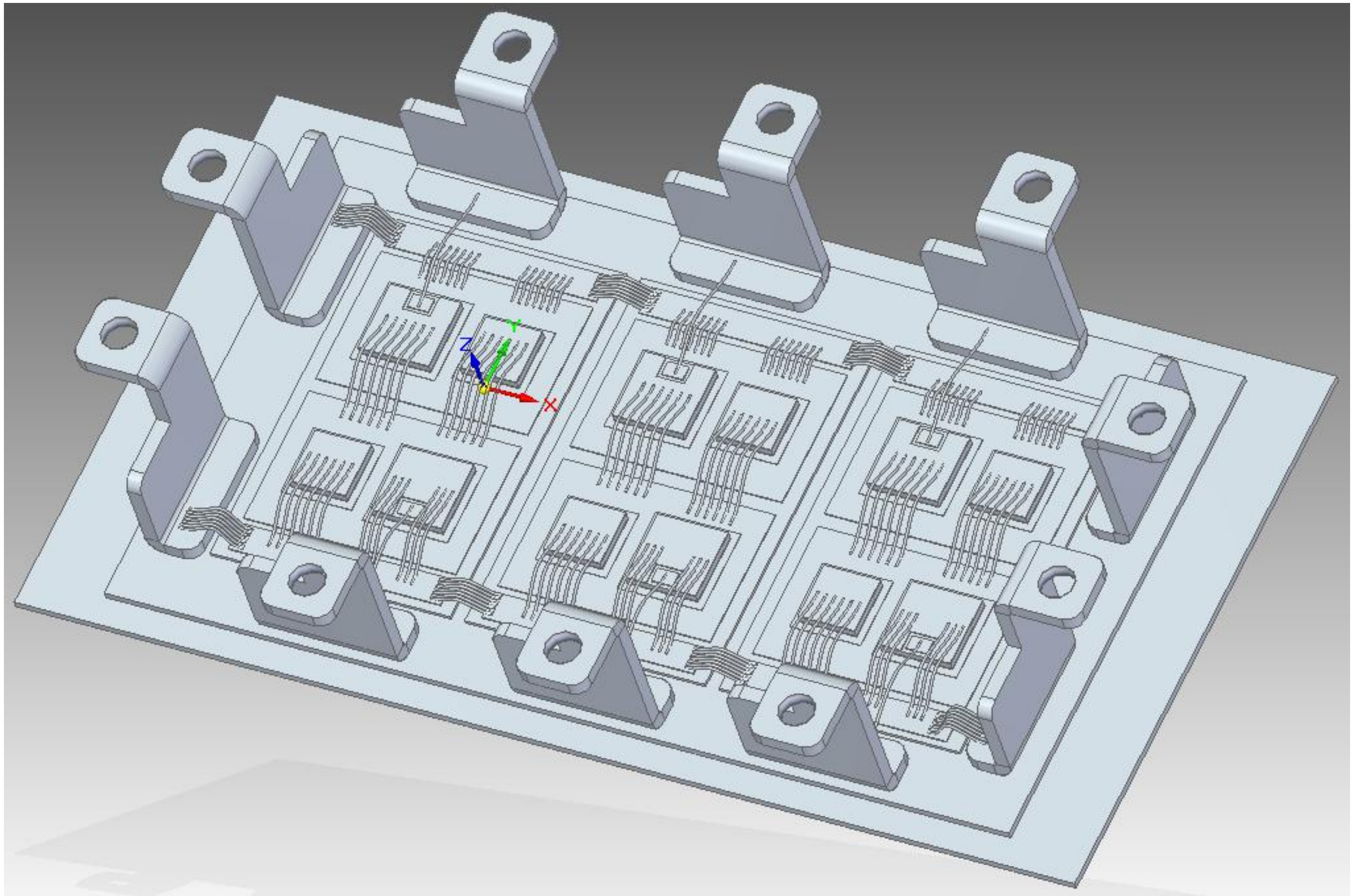
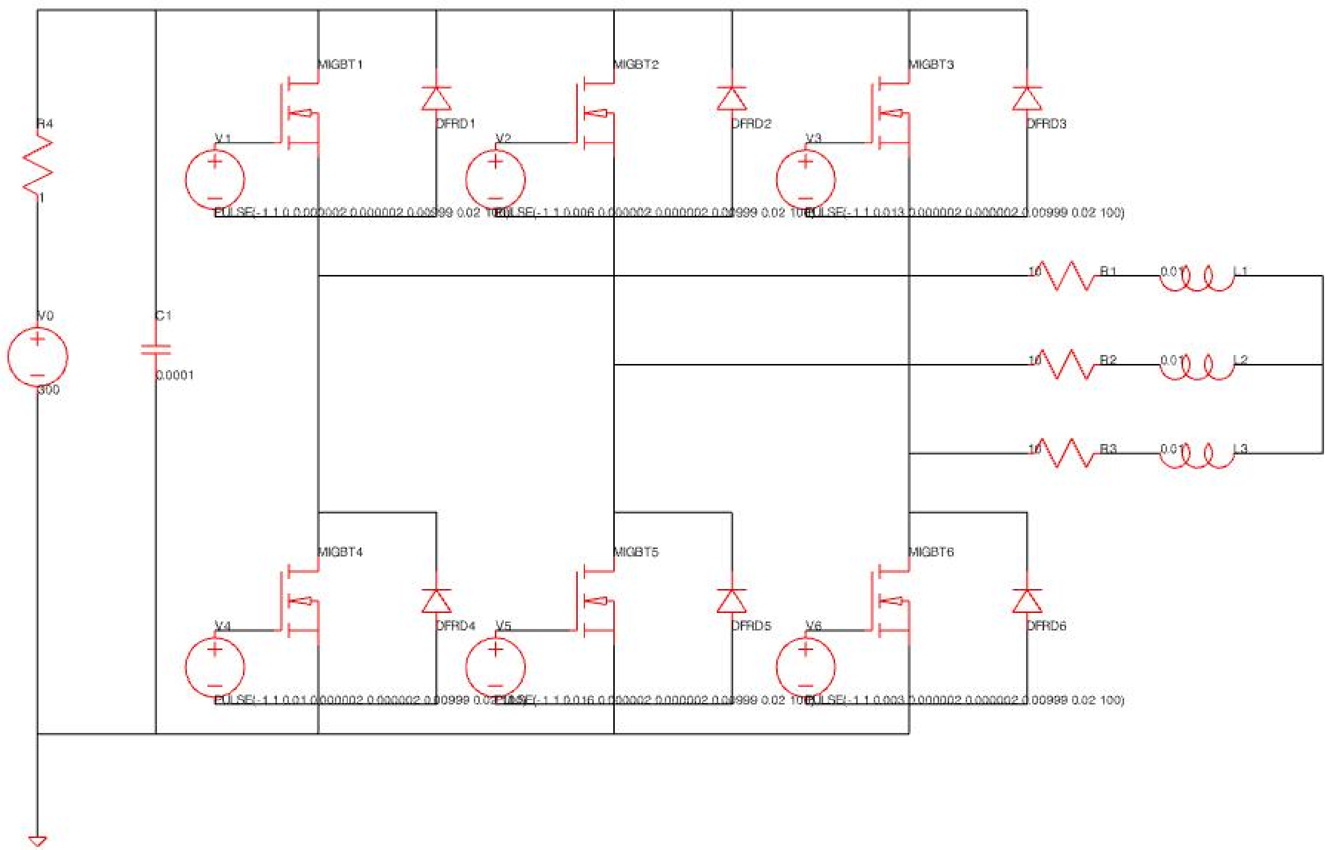
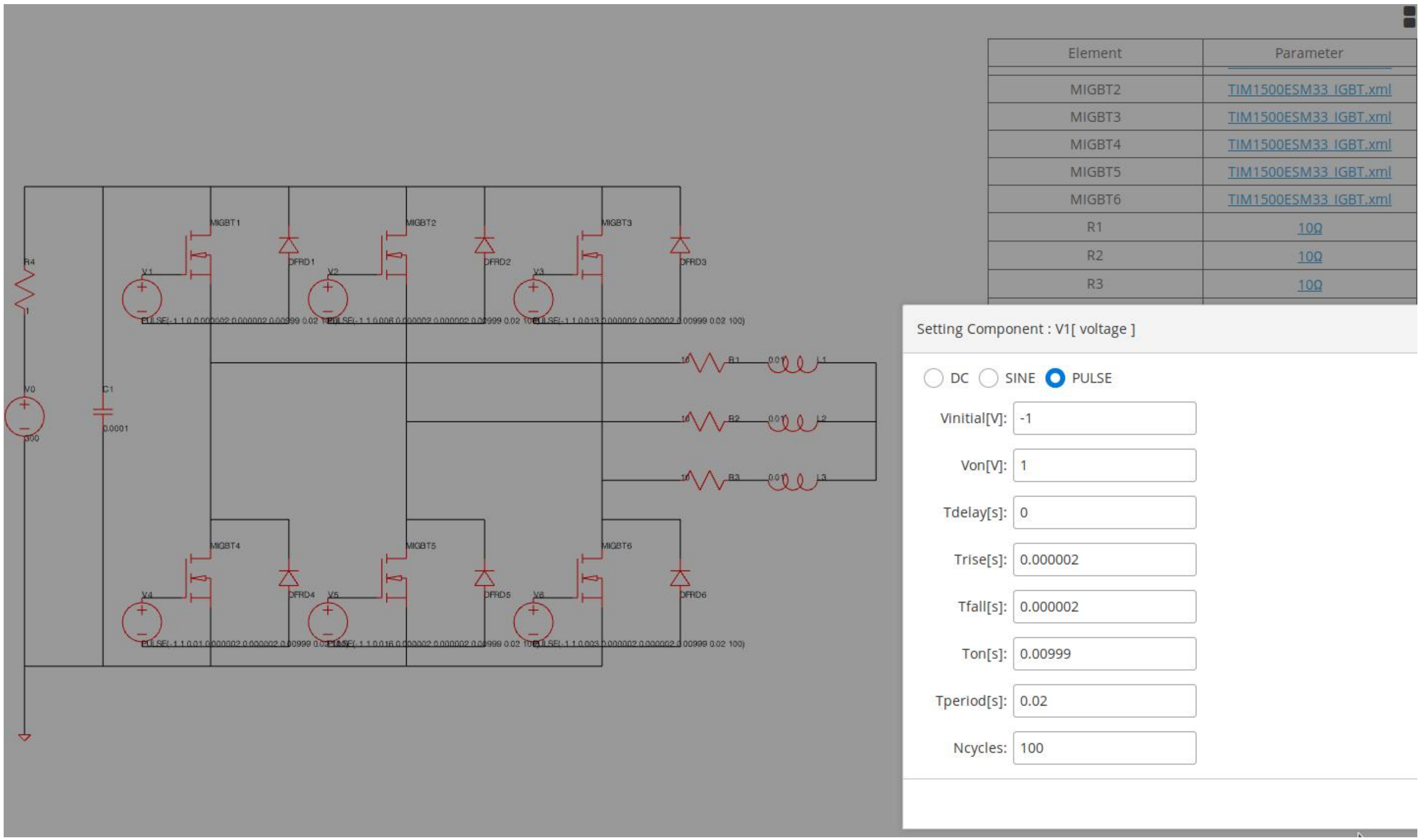
Input: Detailed 3D Model



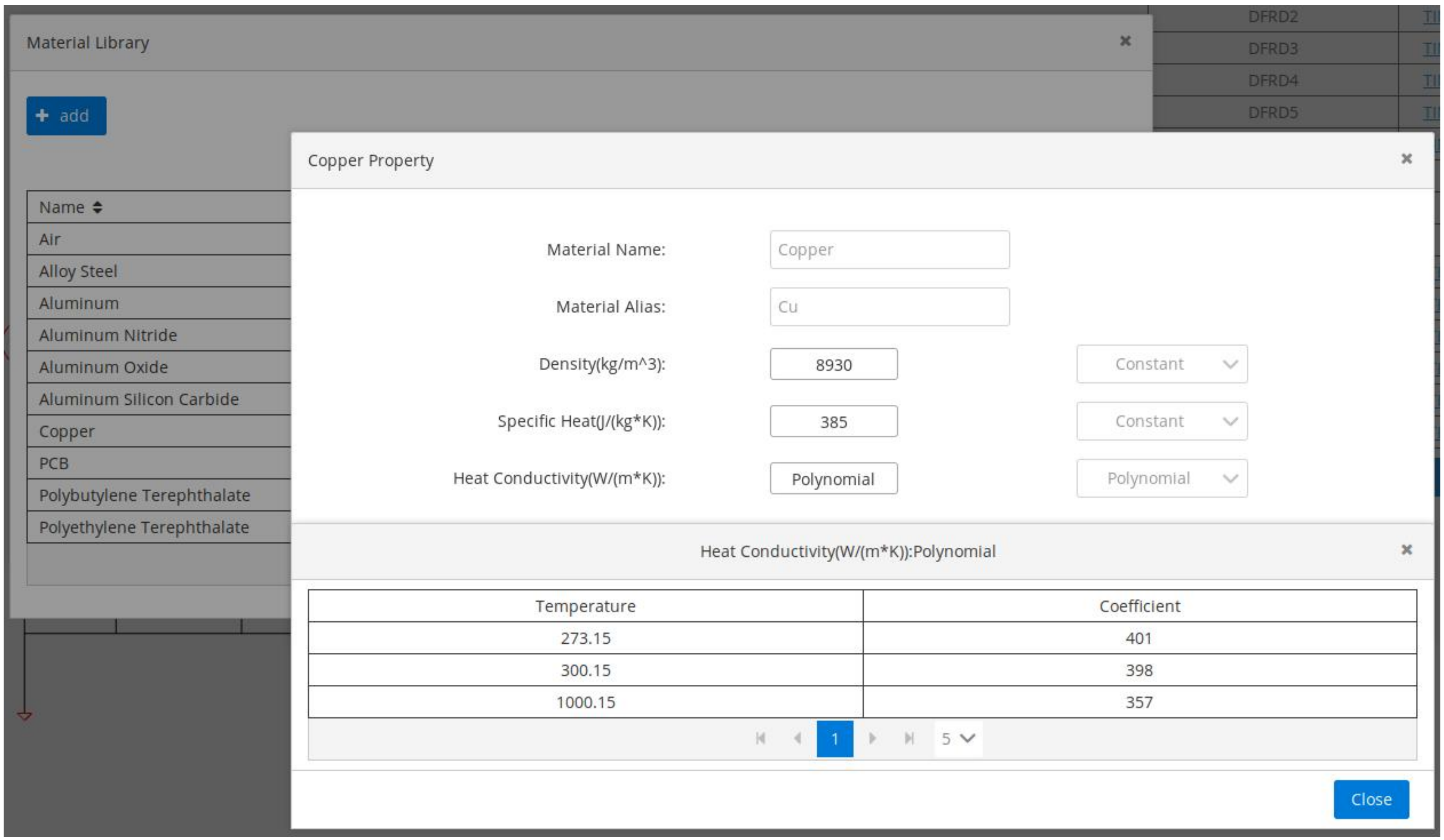
Input: Circuit Schematics



Input: Circuit Schematics



Input: Material Database

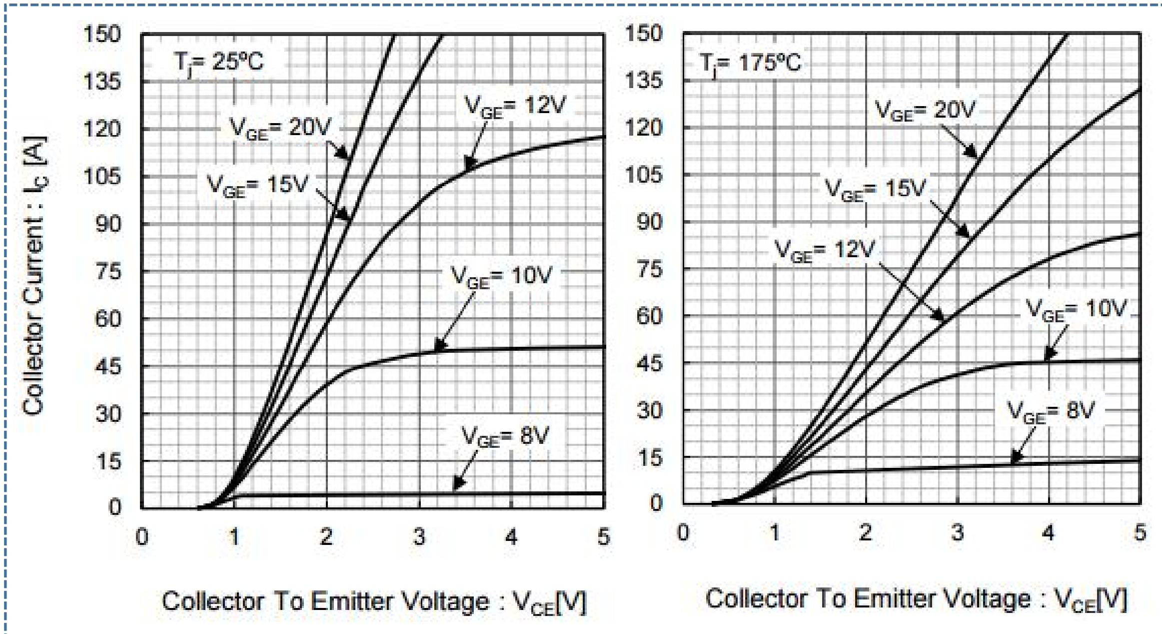


Input: Lookup Model for IGBT/FRD

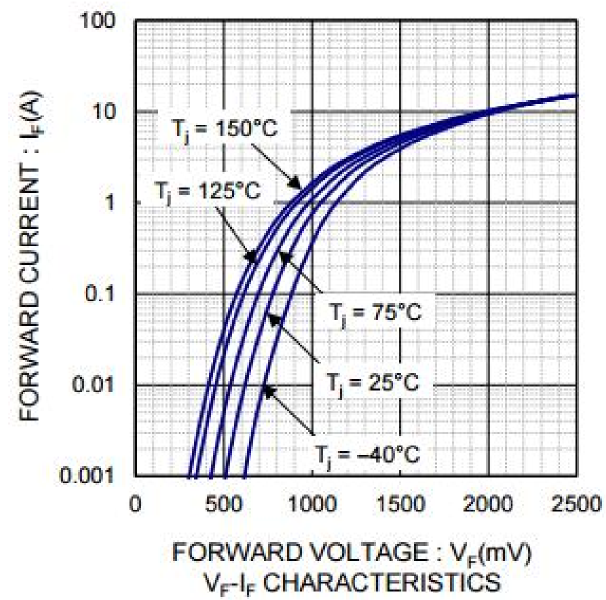
- Energy loss (heating) in IGBT/FRD
  - conduction loss
  - turn-on/off loss
- Routinely measured at chip level
- Ignore fast transients during turn-on/off
  - Allow fast circuit simulation

S. Munk-Nielsen, et al, 2000

Conduction Loss Charaterization of IGBT/FRD

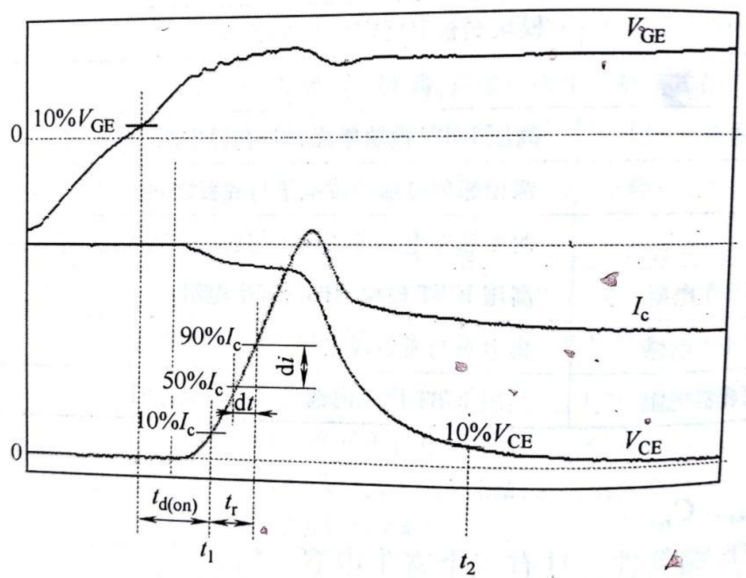


IGBT output characteristics at RT and 175°C

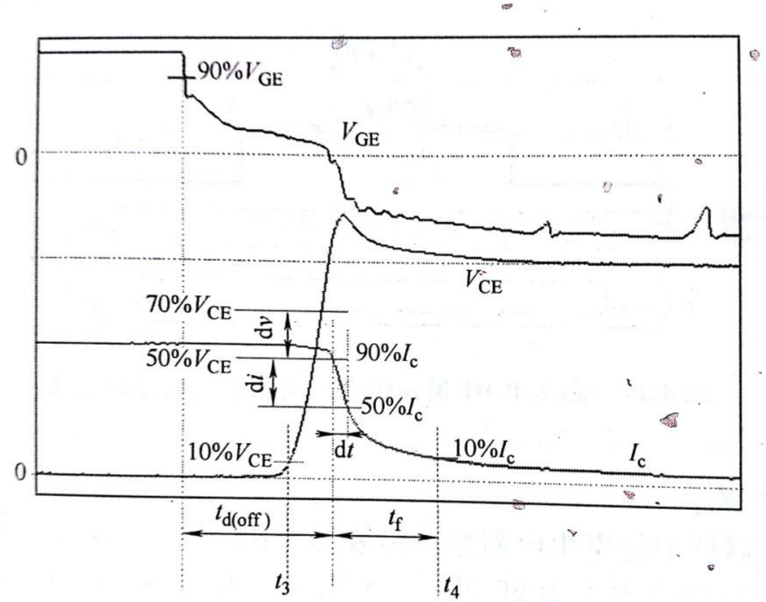


FRD forward I-V Curves

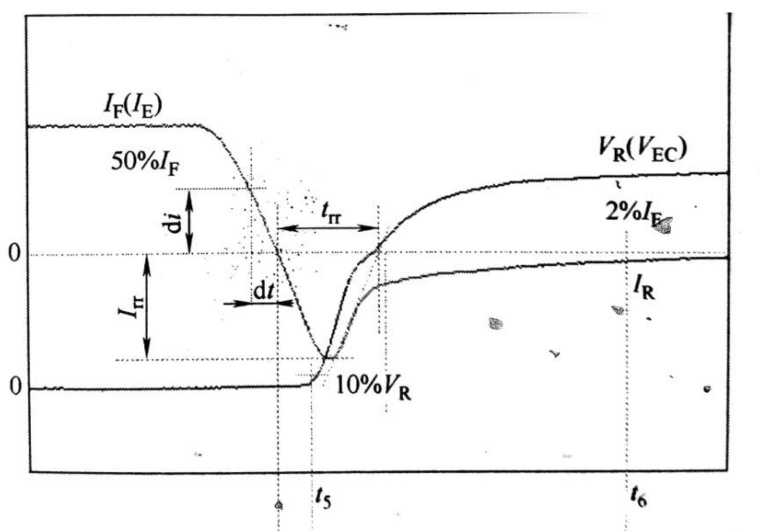
Dynamic Loss Charaterization of IGBT/FRD



IGBT turn-on waveform



IGBT turn-off waveform



FRD reverse recovery

$$E_{on} = \int_{t_1}^{t_2} I_c \cdot V_{ce} \, dt$$

$$E_{off} = \int_{t_3}^{t_4} I_c \cdot V_{ce} \, dt$$

$$E_{doff} = -\int_{t_5}^{t_6} I_R \cdot V_R \, dt$$

Constructing Lookup Table

$V_{ce}=f(I_c, T_j)$ and $V_F=f(I_F, T_j)$

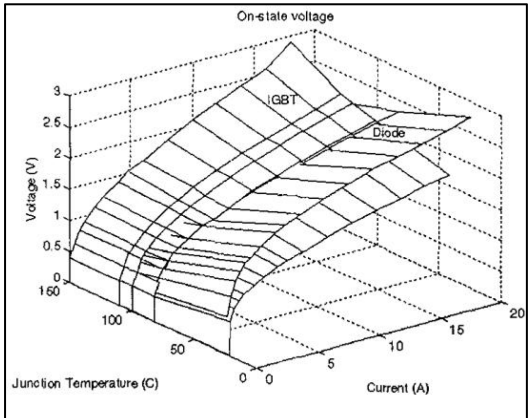


Fig. 8. Look-up table on state voltages of IGBT and diode

$E_{on}=f(V_{dc}, I_c, T_j)$

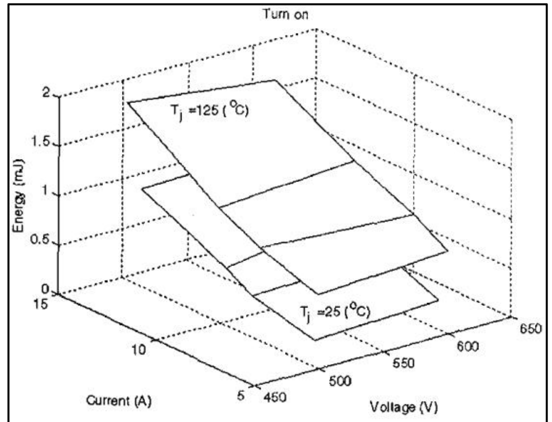


Fig. 9. Look-up table, IGBT turn-on energy

$E_{off}=f(V_{dc}, I_F, T_j)$

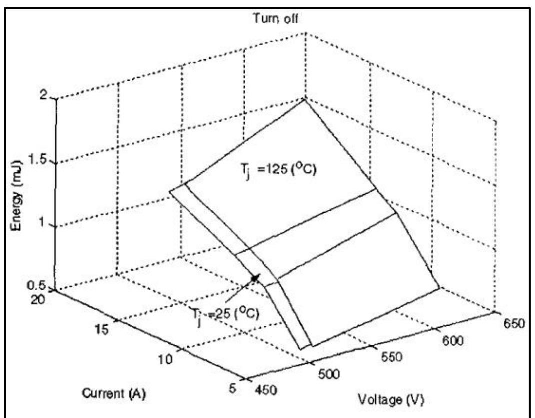


Fig. 10 Look-up table, IGBT turn-off energy

$E_{doff}=f(V_{dc}, I_c, T_j)$

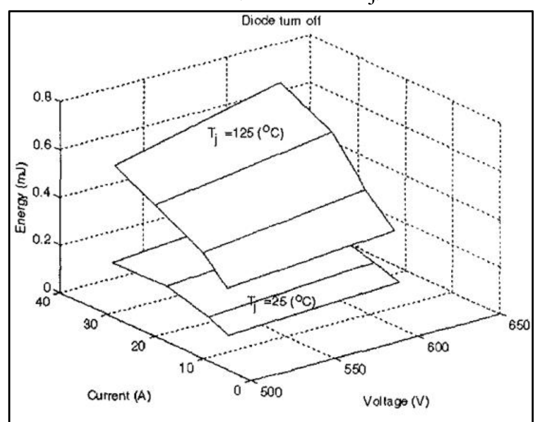


Fig. 11. Look-up table, Diode turn-off energy

V_{ce}: IGBT conduction voltage drop

I_c: IGBT current

V_F: FRD conduction voltage drop

I_F: FRD current

Tj: junction temperature

E_{on}: IGBT turn-on energy

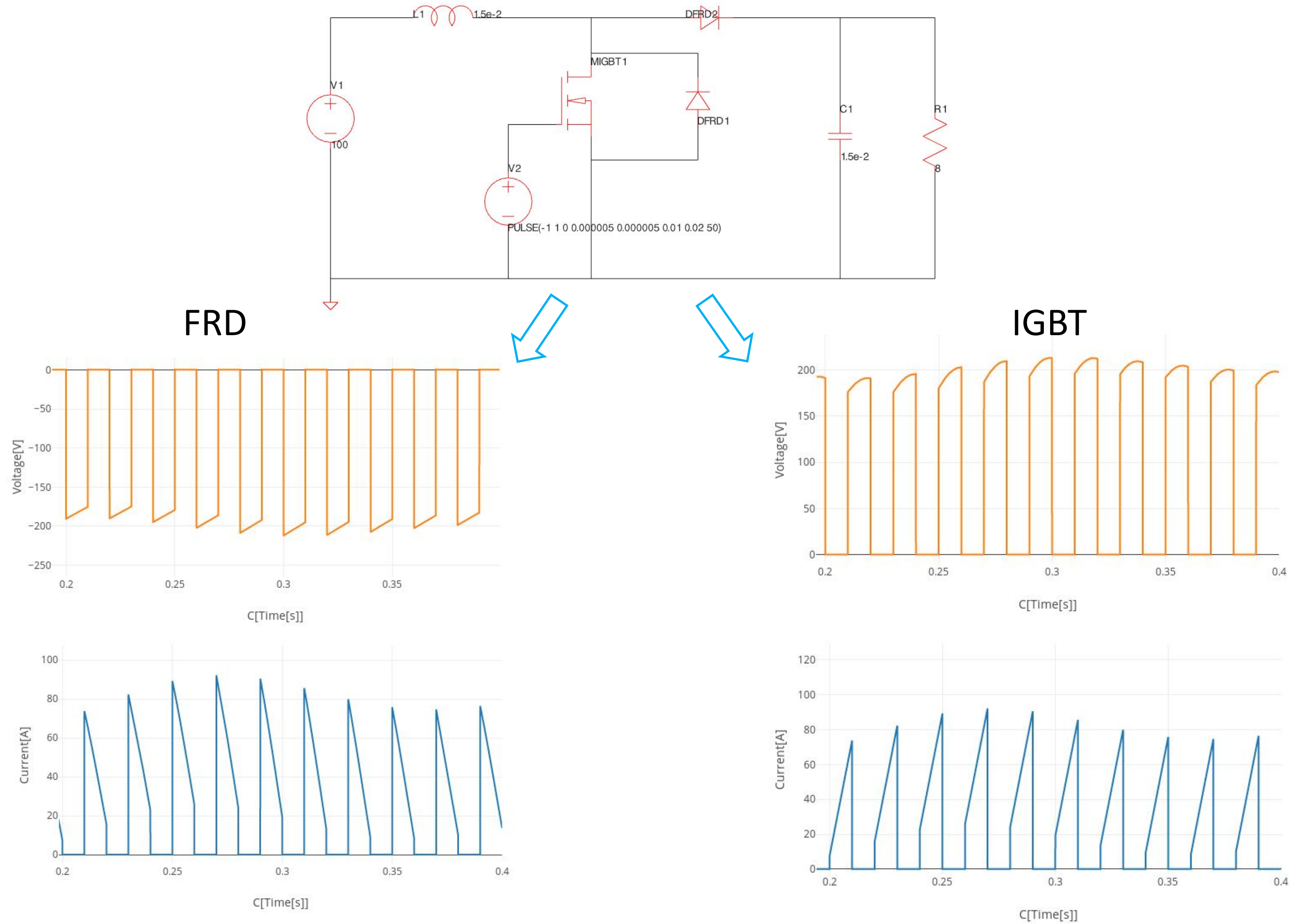
E_{off}: IGBT turn-off energy

E_{doff}: FRD turn-off energy

V_{dc}: reverse voltage

S. Munk-Nielsen, et al, 2000

Switching Events and Energy Loss



V-t and I-t waveforms from SPICE simulation

Switching Events and Energy Loss

$E_{on}=f(V_{dc}, I_c, T_j)$

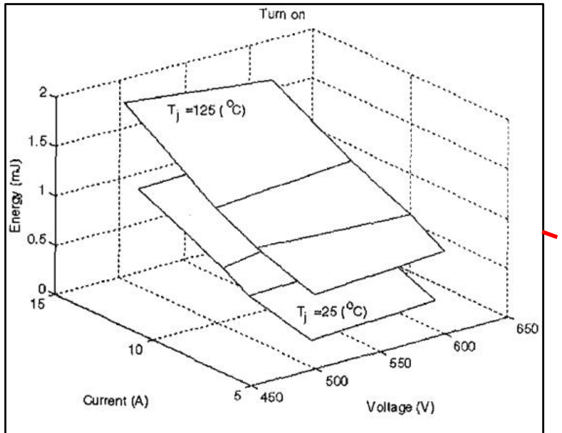
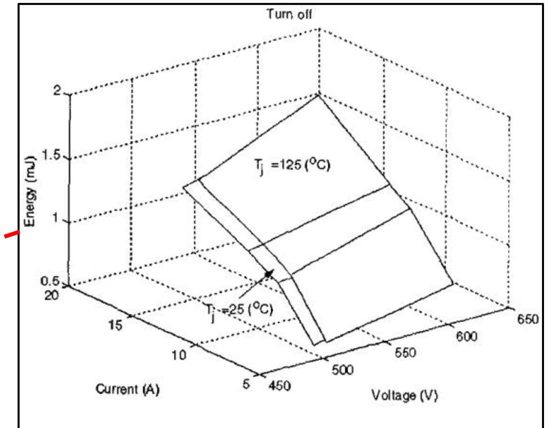


Fig. 9. Look-up table, IGBT turn-on energy

$E_{off}=f(V_{dc}, I_F, T_j)$



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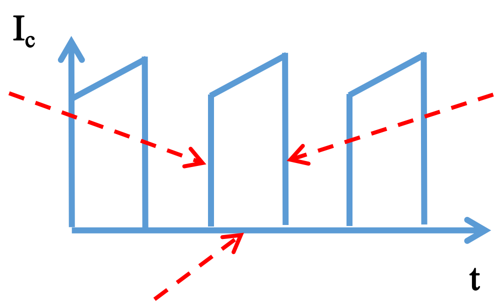

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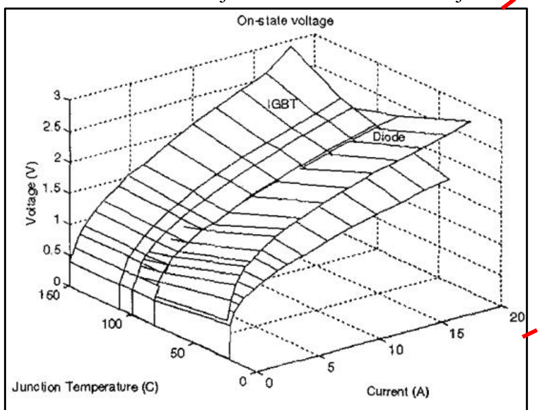

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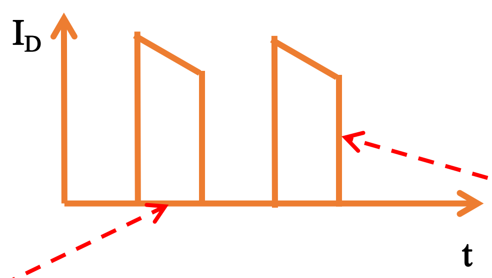


$E_{doff}=f(V_{dc}, I_c, T_j)$

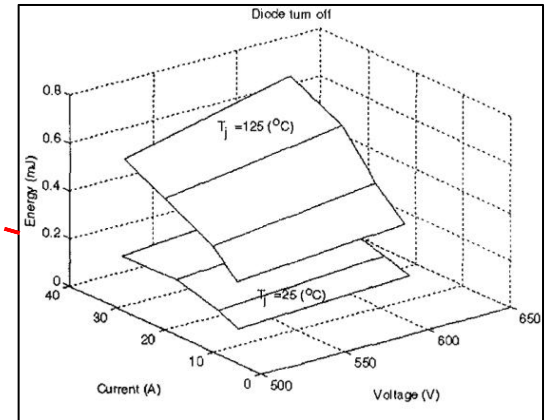
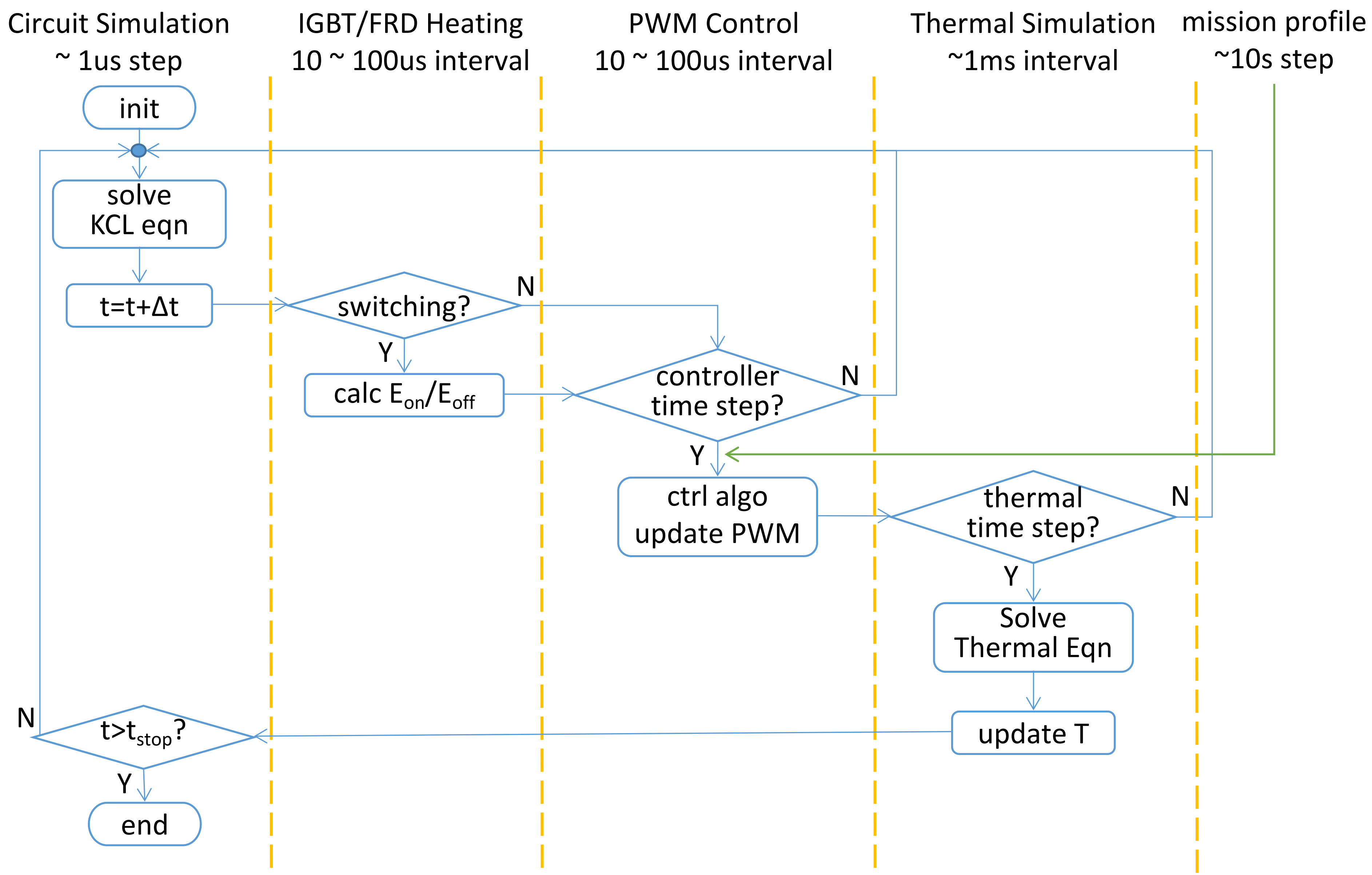


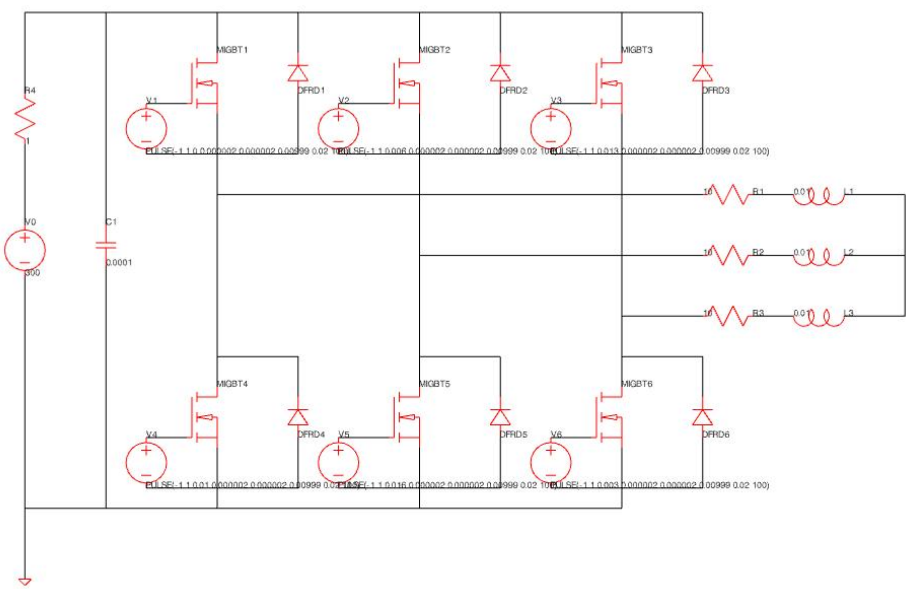
Fig. 11. Look-up table, Diode turn-off energy

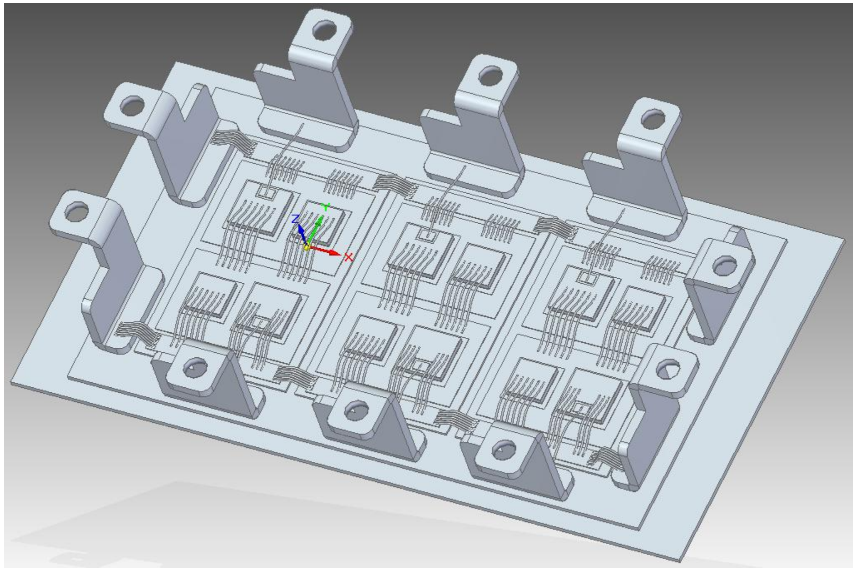
Multi-Physics/Scale Simulation



Implementation Details

- Matching CAD components to circuit schematics
  - primitive 3D LVS
  - extract bondwire and pad parasitic resistance
  - annotate parasitic resistance to netlist
  - annotate joule heating to 3D mesh





Implementation Details

- Thermal Equations (heat conduction)
  - Most expensive
  - Linear equation
    - LU decomposition + back-substitution
  - Temperature-dependent heat conductivity/capacity
    - reuse LU factors if ΔT is small
    - Need reconstruct equations for large ΔT
- Circuit Equations
  - Based on open-source ngspice
  - Smoothed ideal switch model for IGBT

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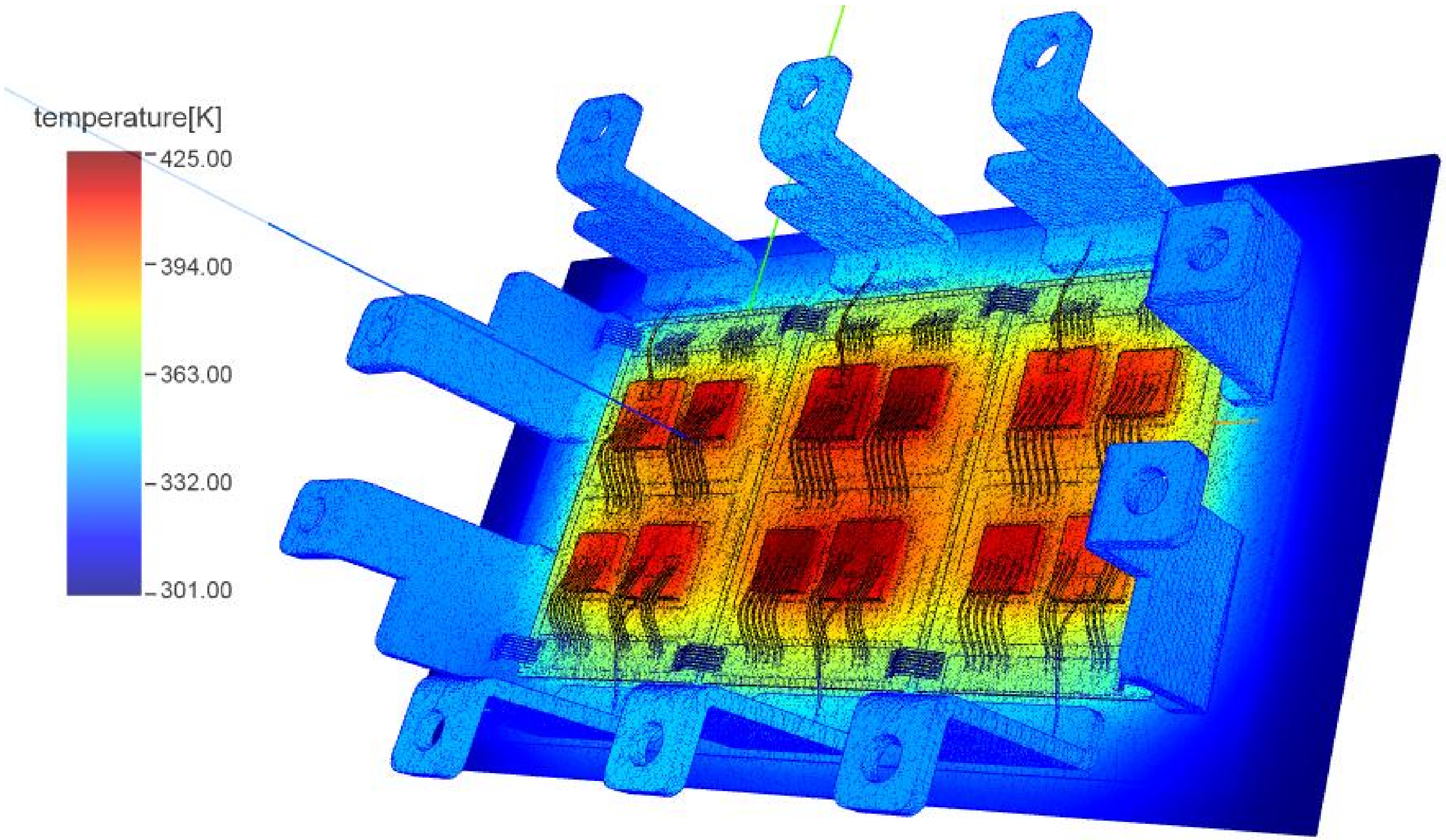
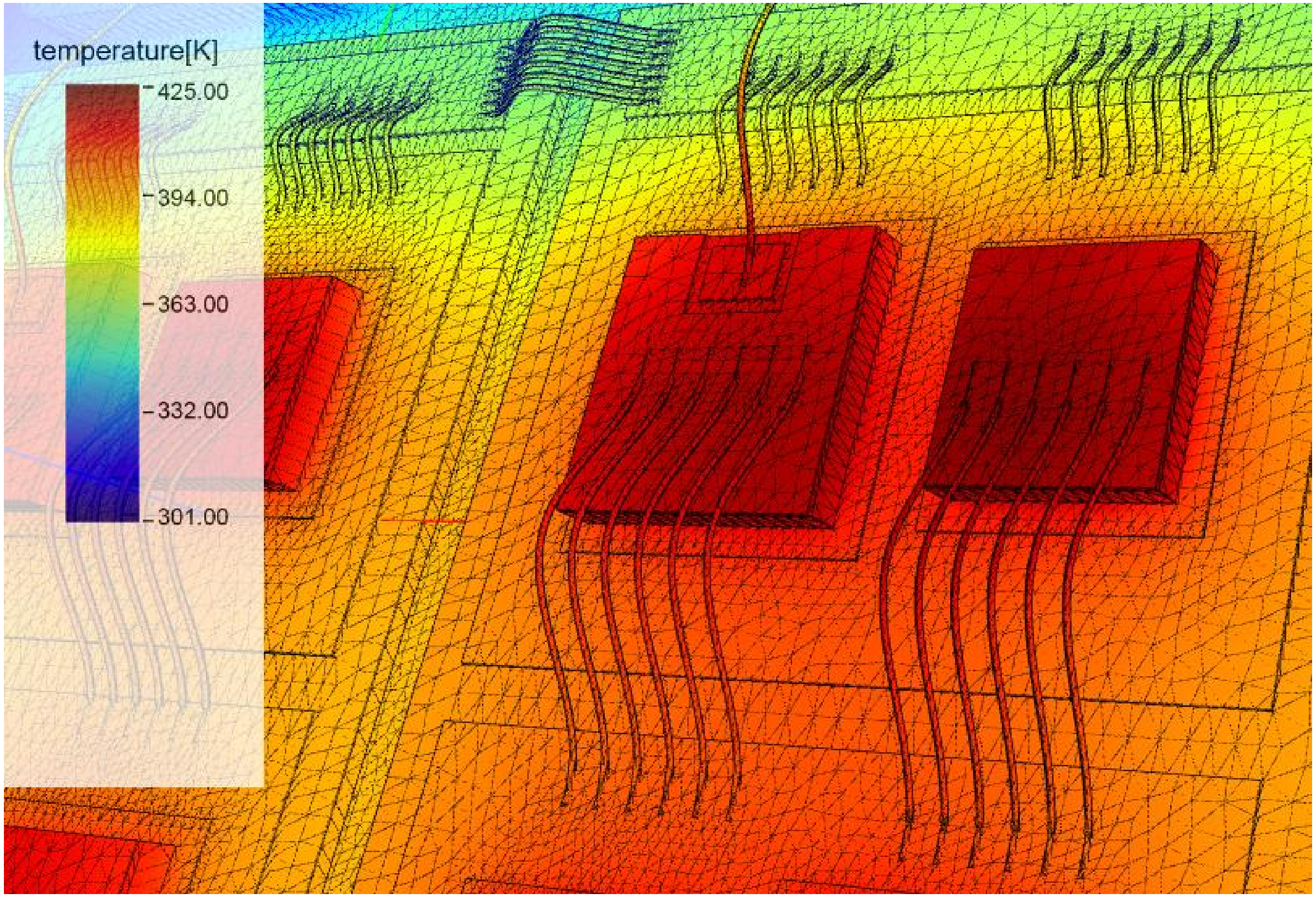
Results: 3-Phase Inverter



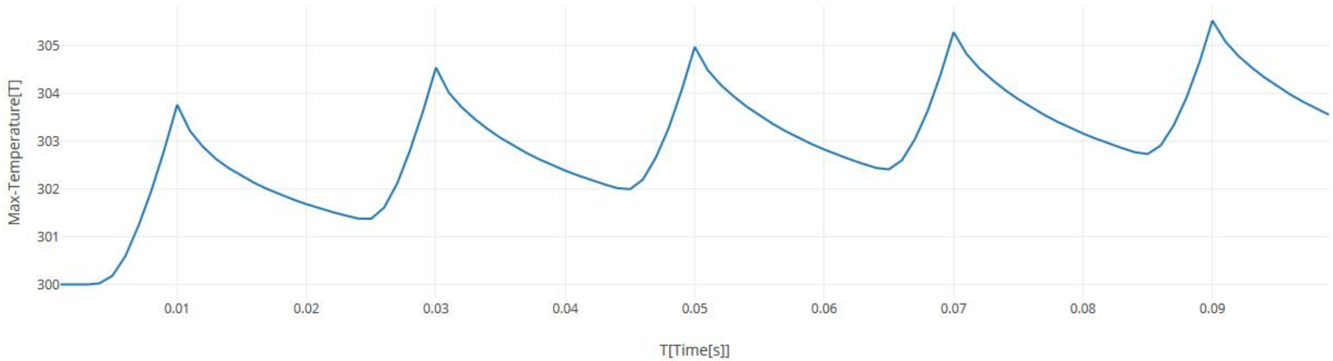
# of mesh nodes: 1,366,934
# of mesh elements: 832,673

Results: 3-Phase Inverter

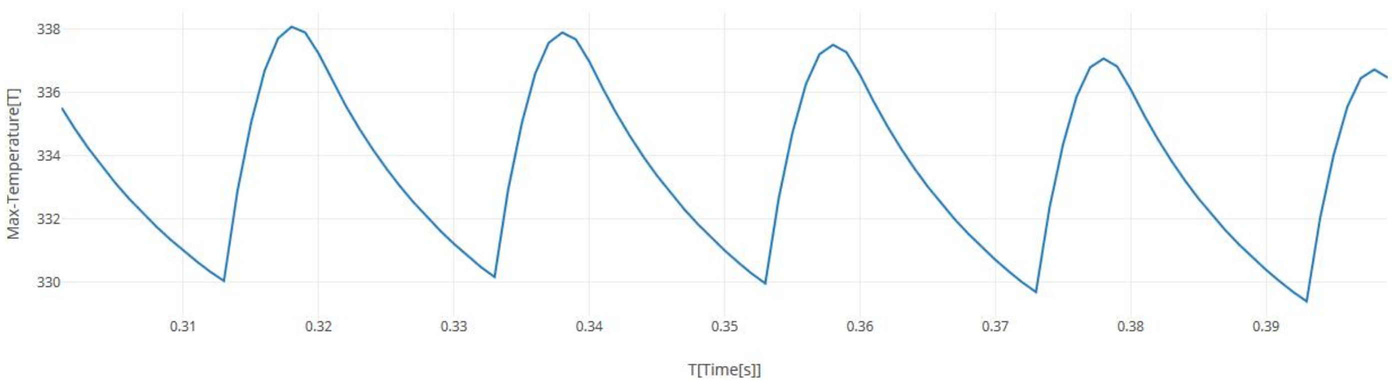


Results: 3-Phase Inverter

Initial temperature waveform @ IGBT1



Steady-state temperature waveform @ IGBT1



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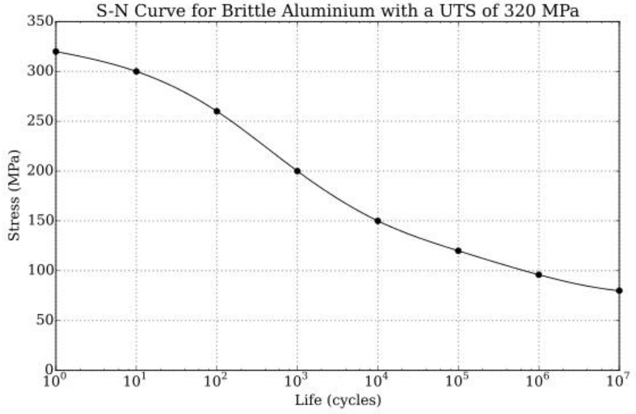
Fatigue: Failure Model

- S-N Curve predicts lifetime under low stress



- Palmgren-Miner Rule
  - Combined effects from large/small stress cycles

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

- Approximation:
  - ΔT-N instead of S-N

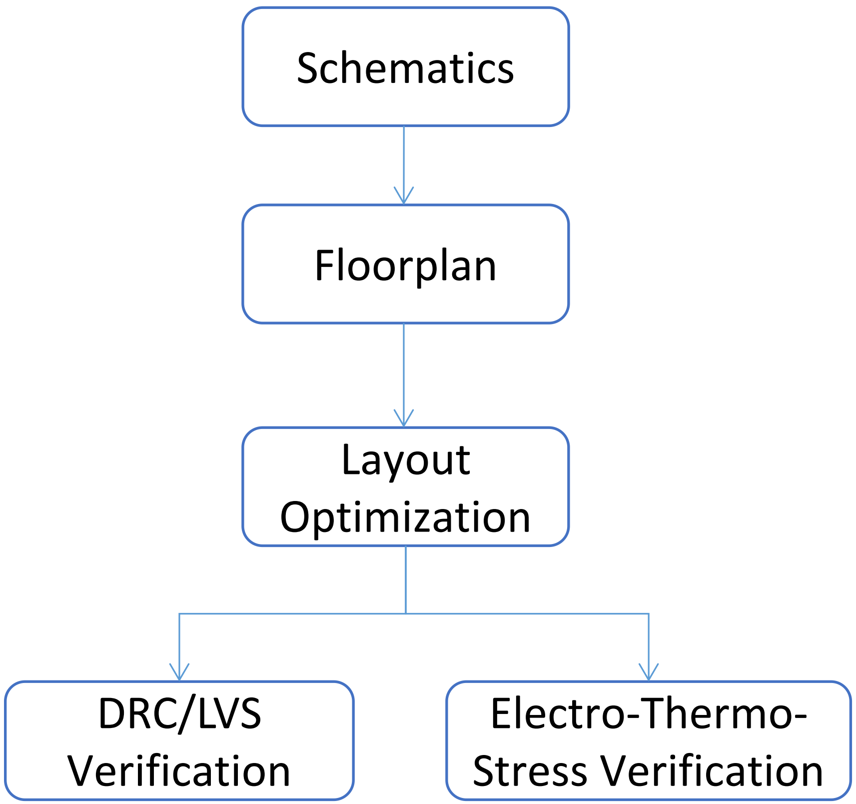
Shown to be incorrect

Next Step

- Electro-Thermo-Stress Simulator
  - Solve strain/stress equation
  - Identify fatigue hotspot w/ Palmgren-Miner rule

- More detailed circuit simulation
  - IGBT compact model
    - Hefner 1994, Kraus 1998, HiSIM IGBT, etc
  - Stray inductance

Conclusion: Outlook for the Future



- A CAD flow for IPM
  - similar concept as IC CAD
- Unique characteristics
  - 3-D
  - multi-physics
- Verification is our starting-point