

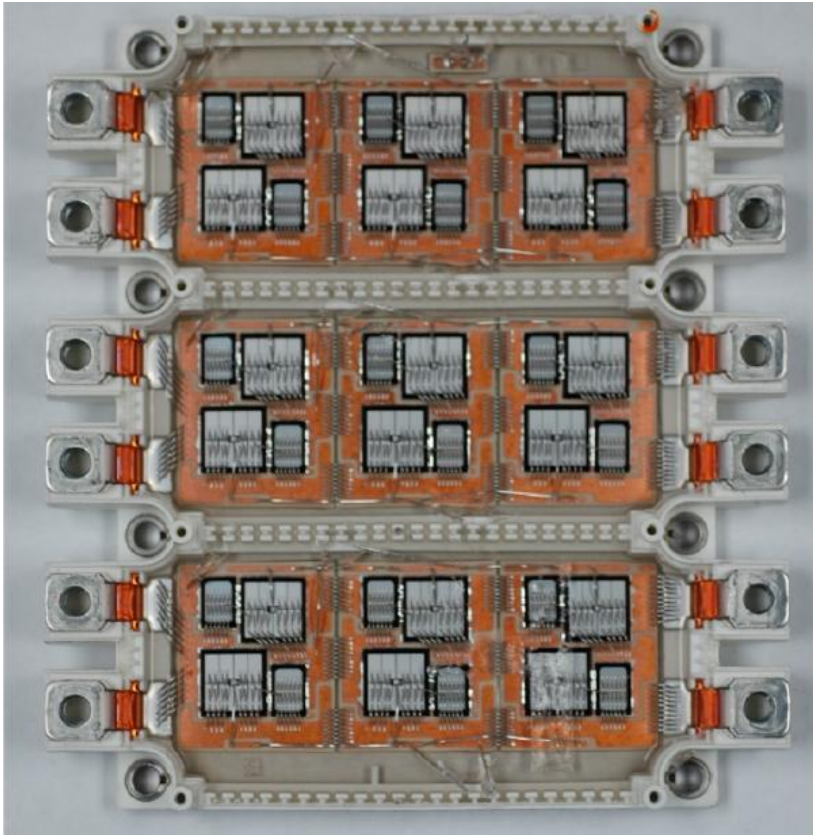
# A Simulation Platform for Electrothermal Design/Verification of IGBT Modules

2019.6

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苏州珂晶达电子

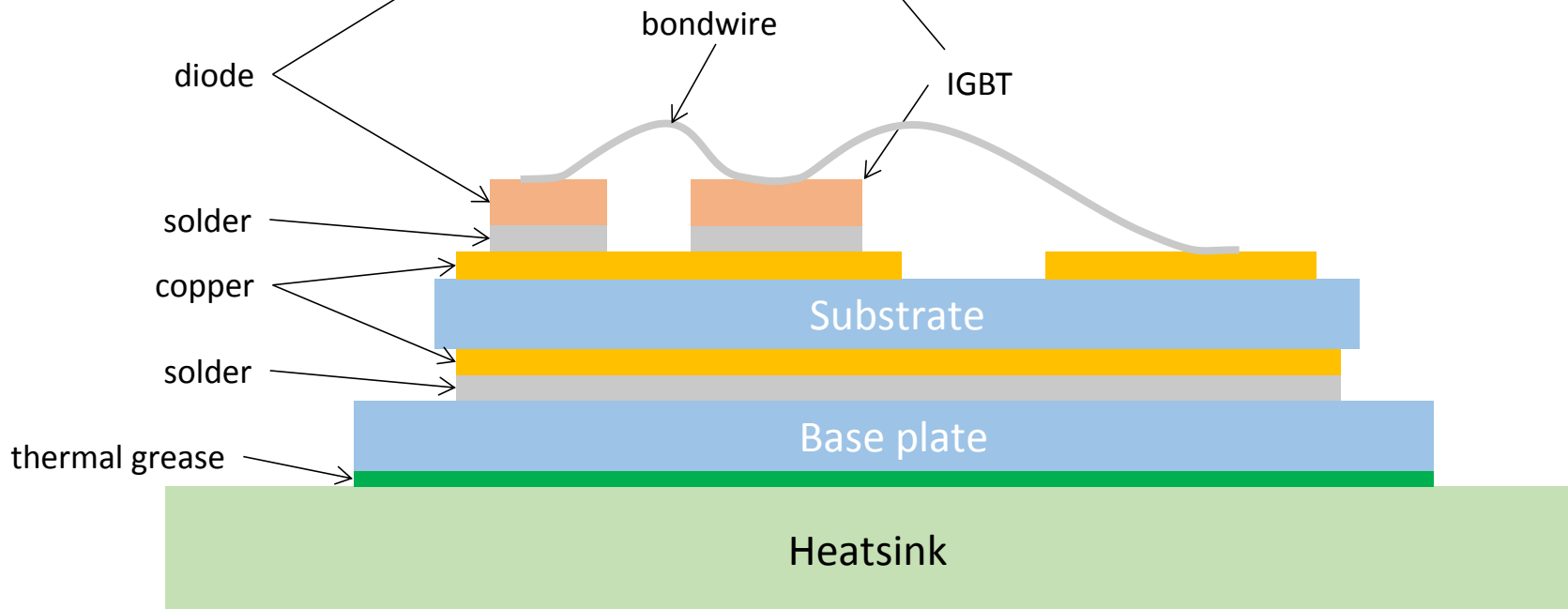
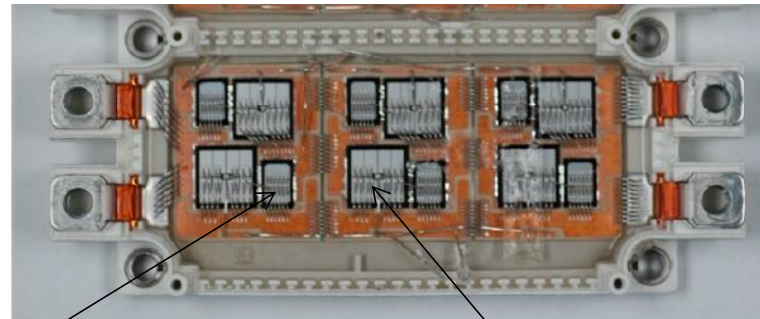


# Need for Module Design Tool



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

# Internal Structure of IGBT Module



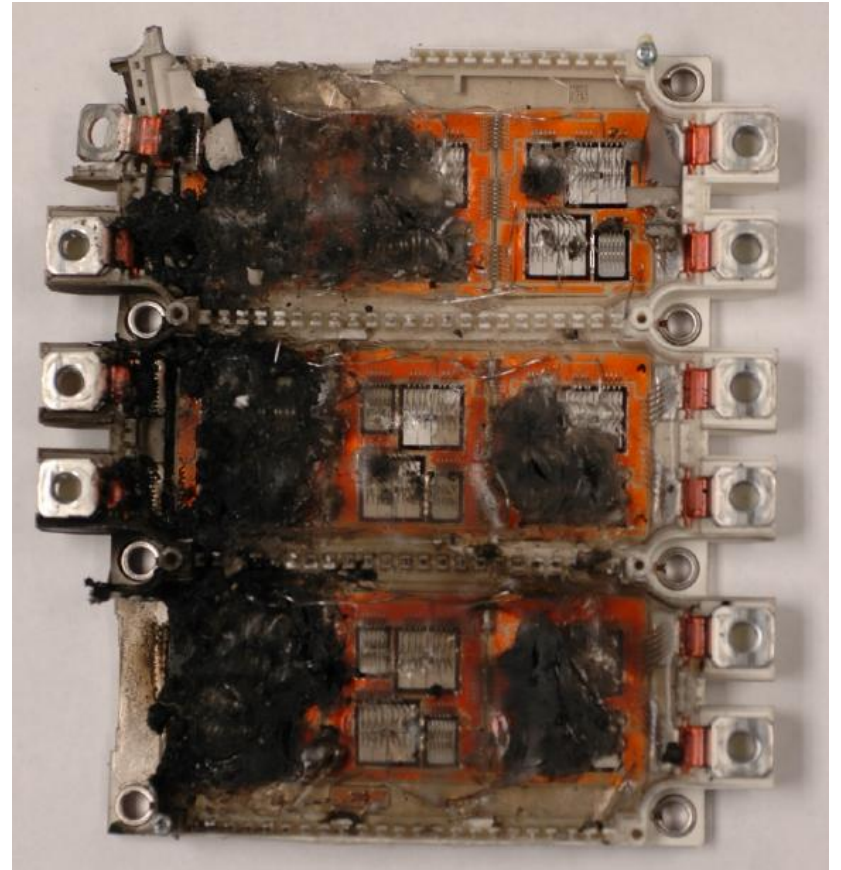
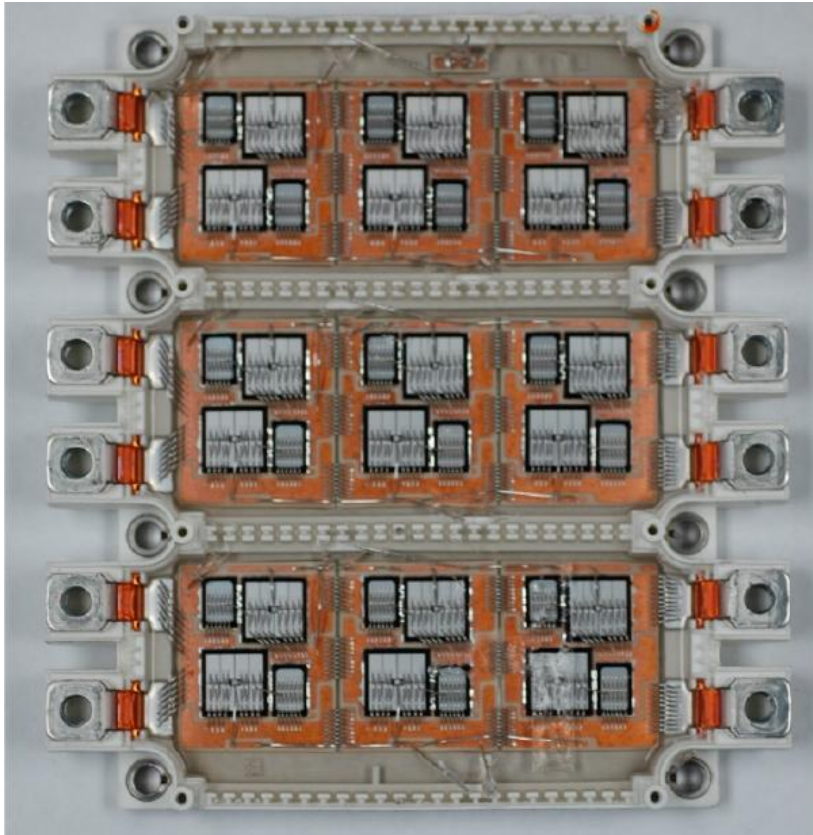
# Outline

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

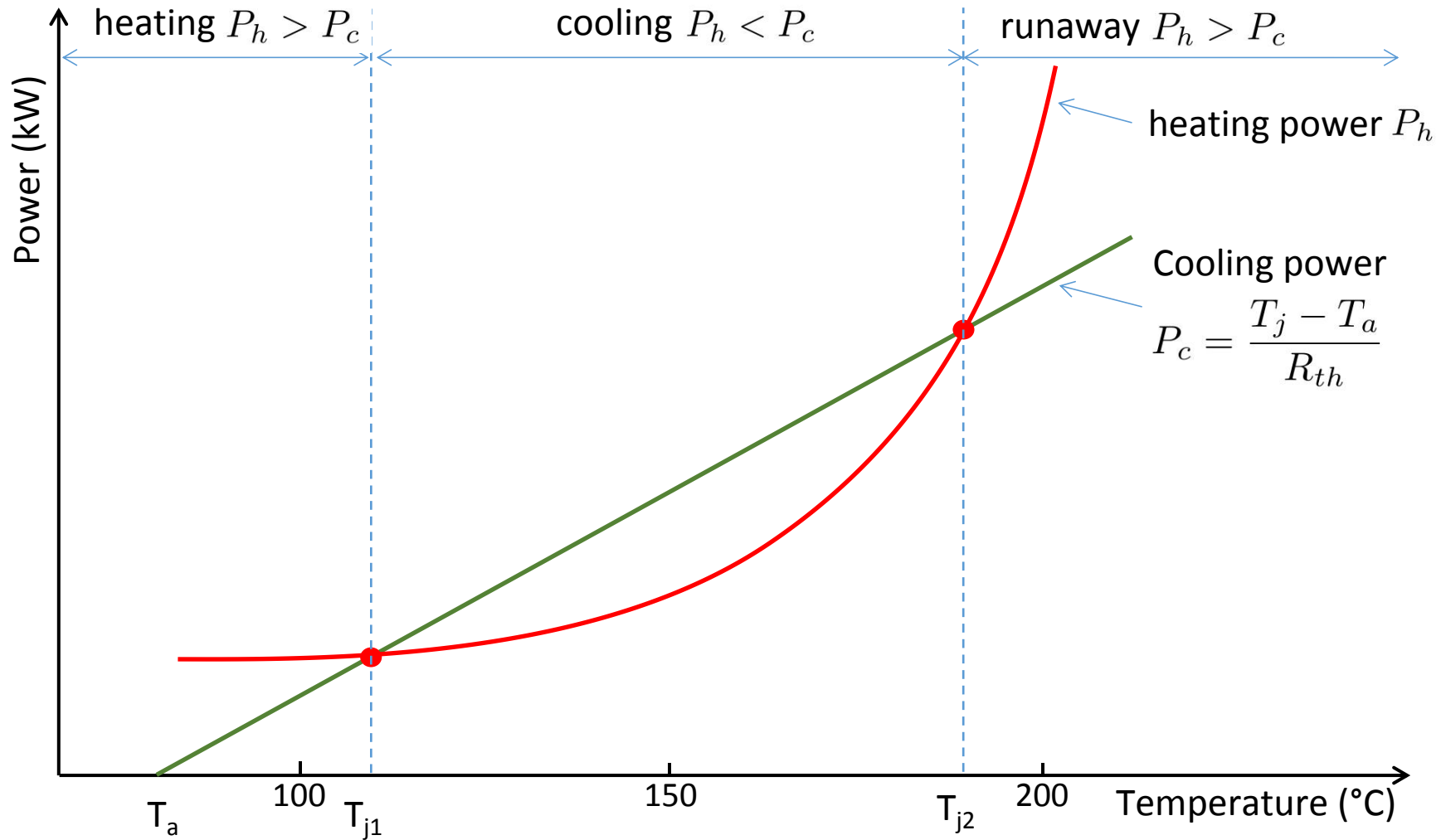
# IGBT Module Failure Mechanisms (selected)

- 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 ( $\Delta T$ )
  - fix: improve electrical/thermal uniformity

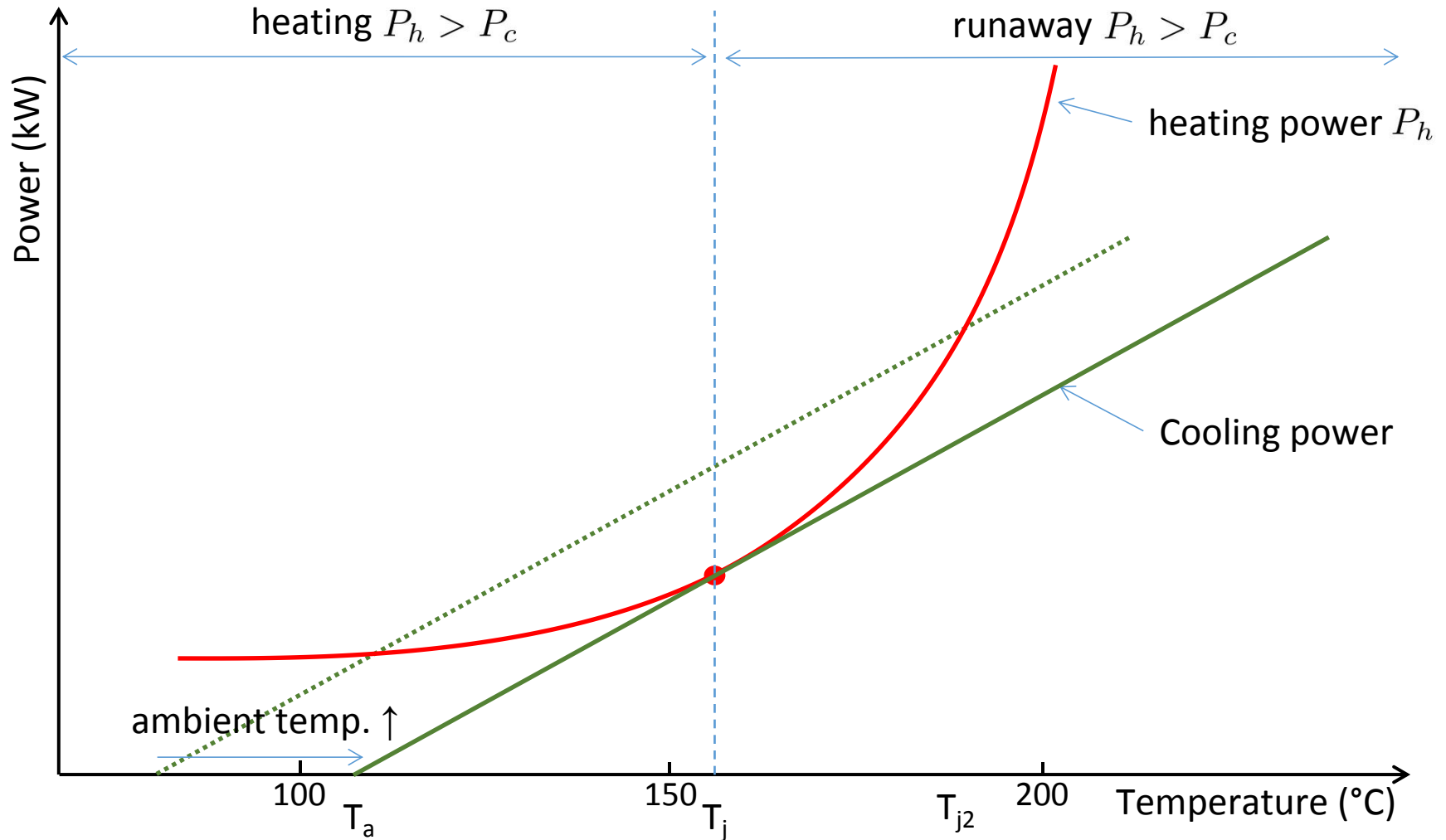
# Thermal Runaway



# Thermal Stability in Power Module

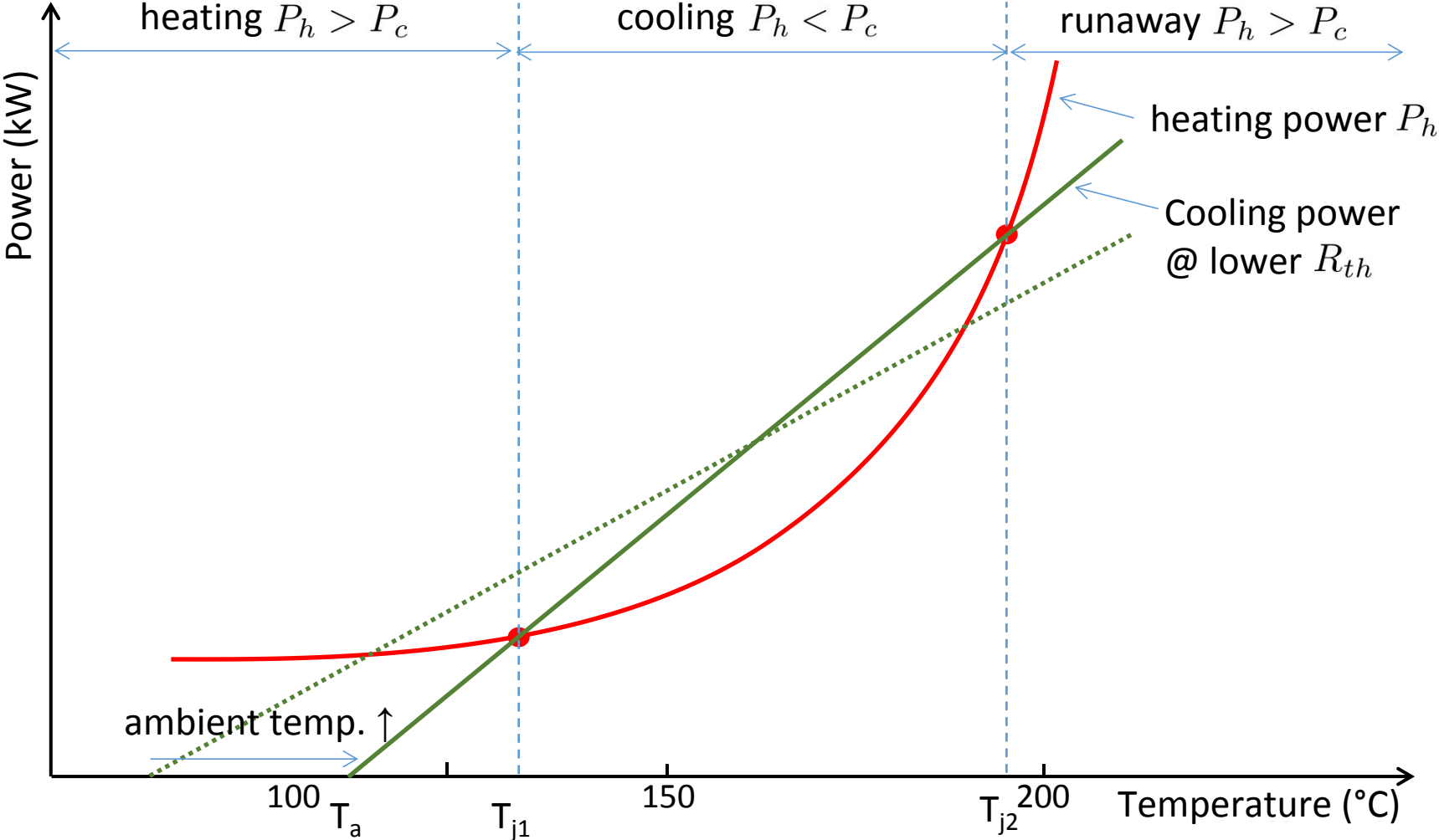


# Thermal Stability: High Ambient Temp.





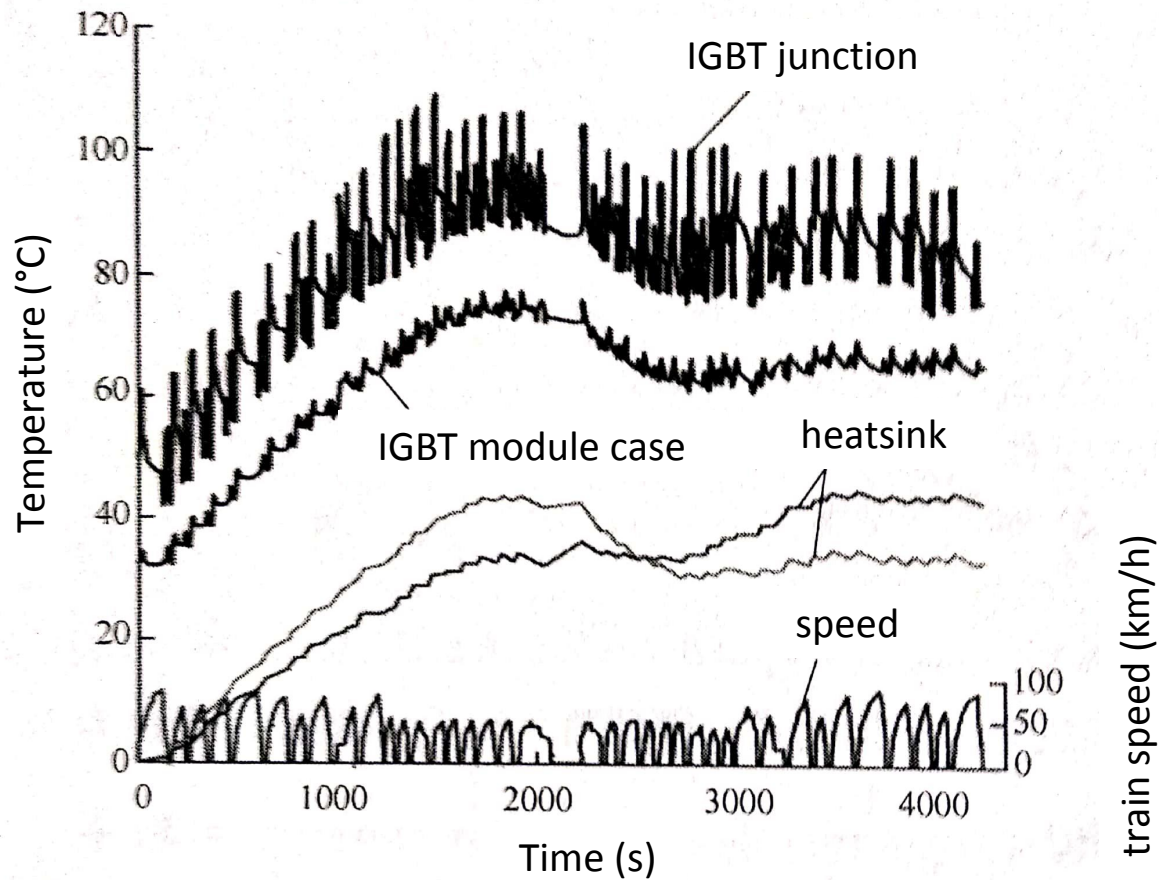
# Thermal Stability: Lower $R_{th}$ is Better



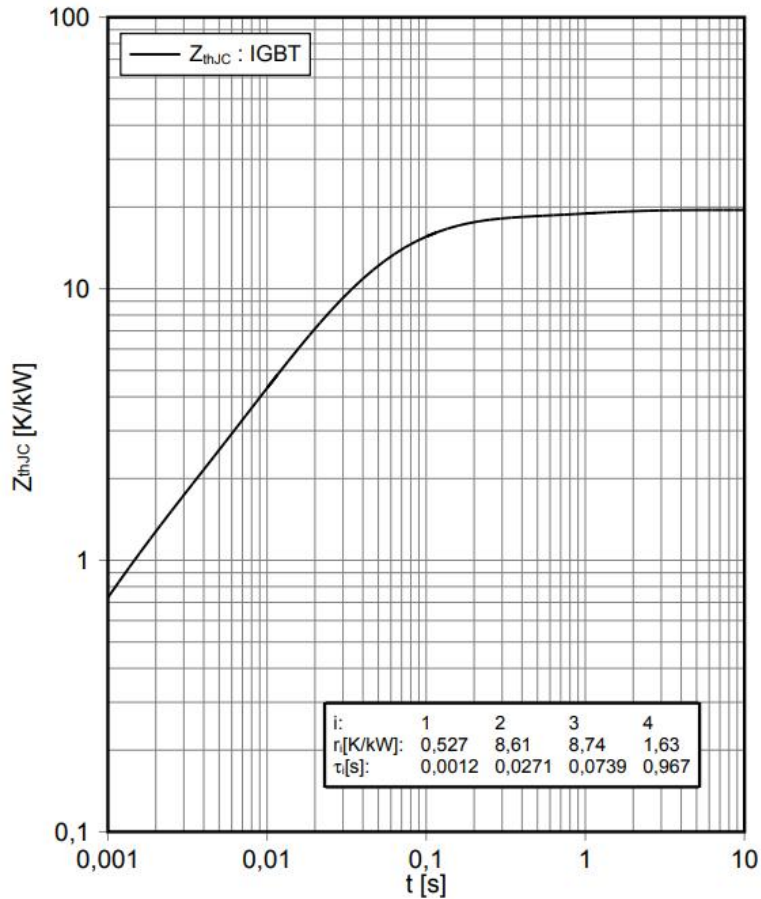
# Thermal Stability: Complications

- 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

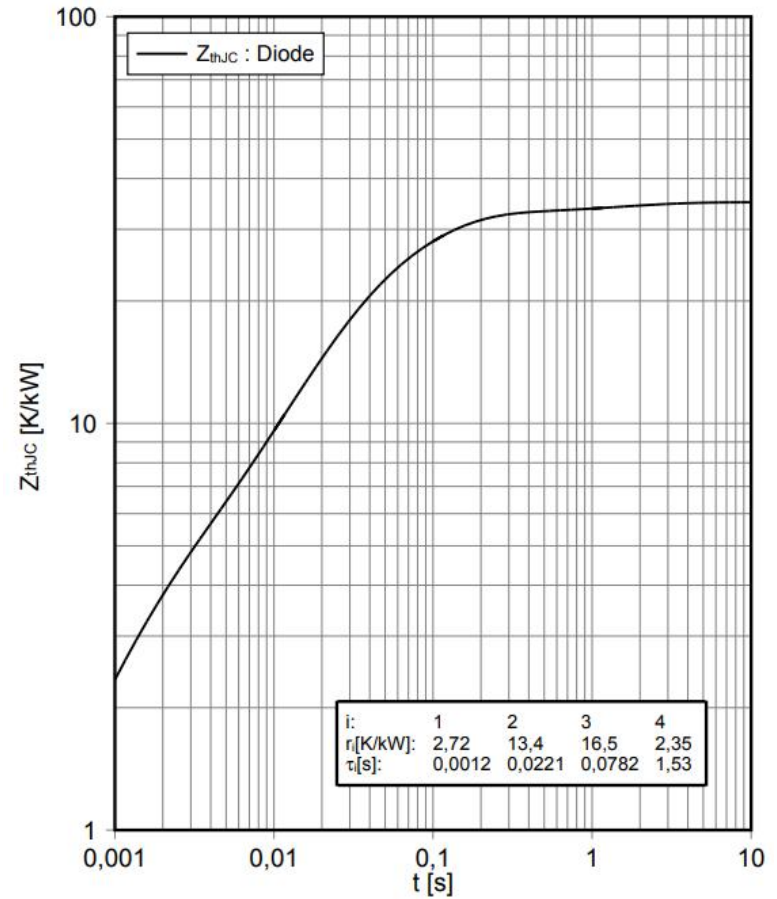
# Realistic Mission Profile



# Transient Thermal Impedance

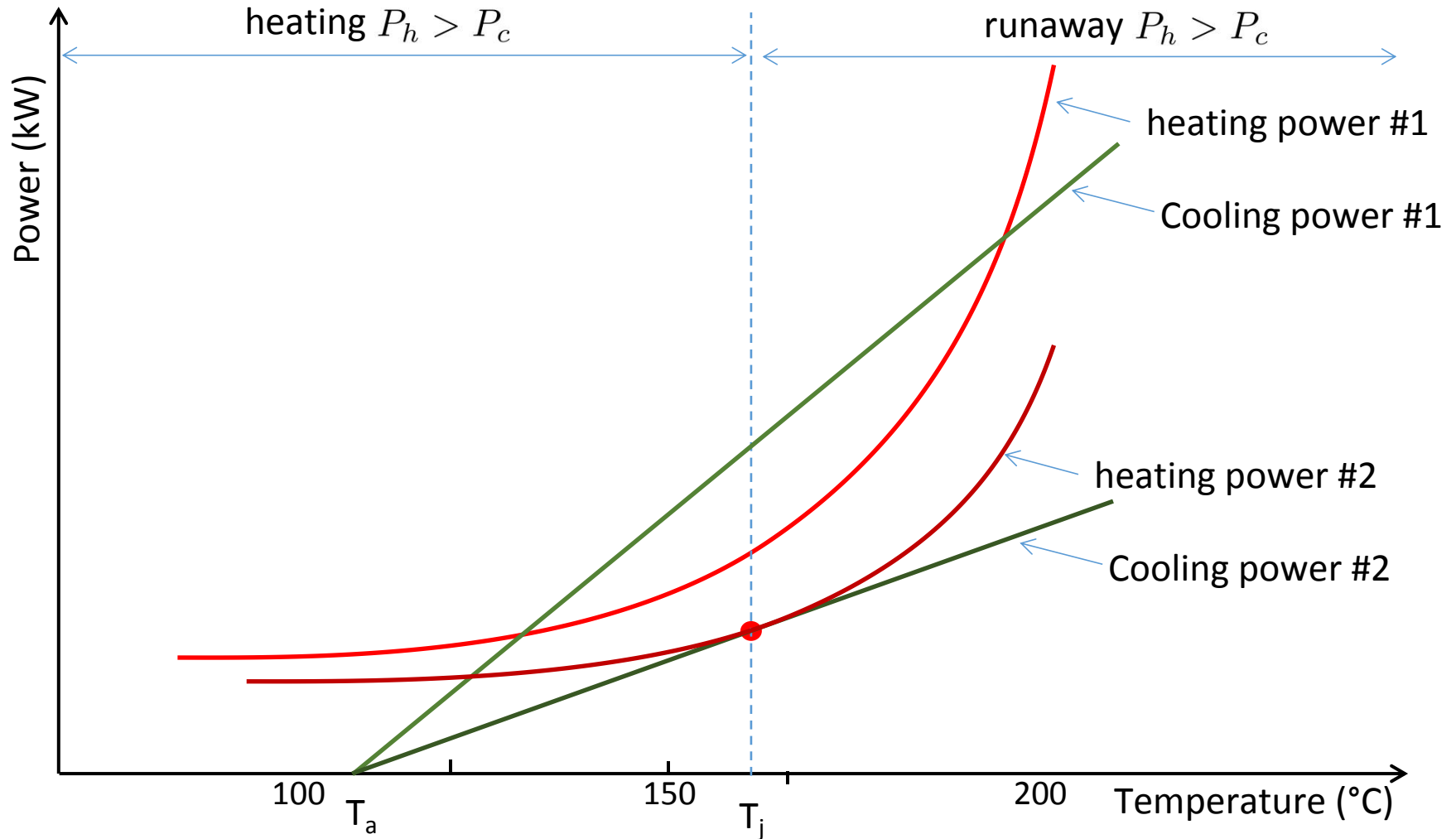


Transient thermal impedance of IGBT



Transient thermal impedance of FRD

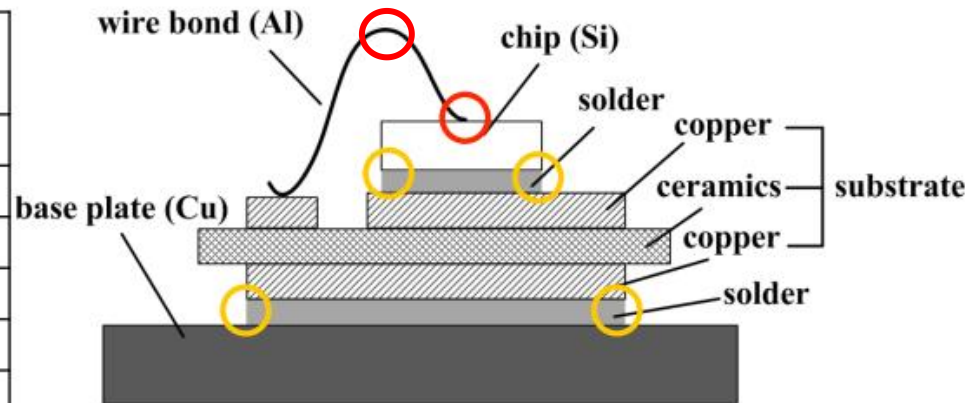
# Thermal Stability: Multiple Chips



# Fatigue: Repeted Stress Load

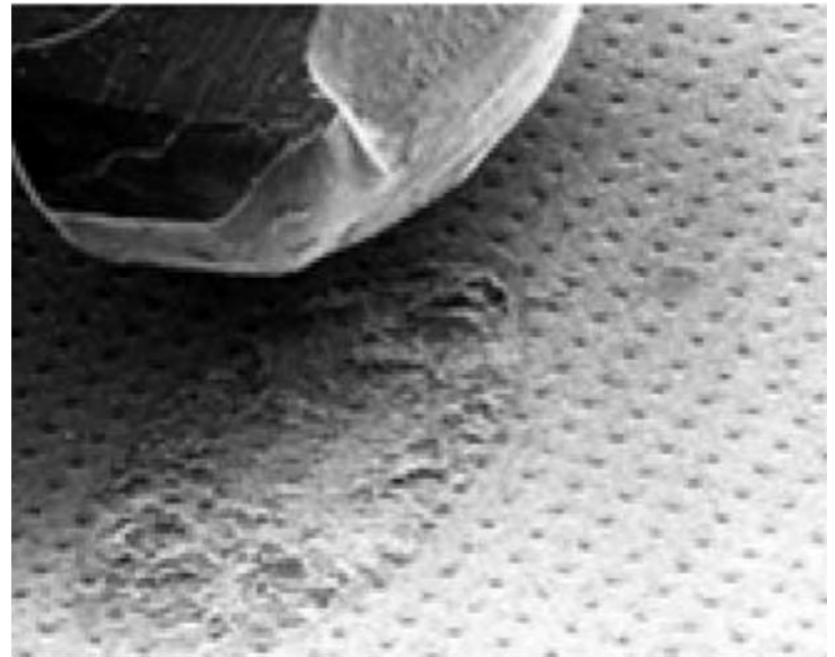
CTE mismatch + Temperature cycle → Stress Cycles

Material	CTE ( $10^{-6} \text{ K}^{-1}$ )	Conductivity ( $\text{W m}^{-1} \text{ K}^{-1}$ )
$\text{Al}_2\text{O}_3$	6.8	24
$\text{AlN}$	4.7	170
$\text{Si}_3\text{N}_4$	2.7	60
$\text{BeO}$	9	250
$\text{Al}$	23.5	237
$\text{Cu}$	17.5	394
$\text{Mo}$	5.1	138
$\text{Si}$	2.6	148
$\text{AlSiC}$	7.5	200

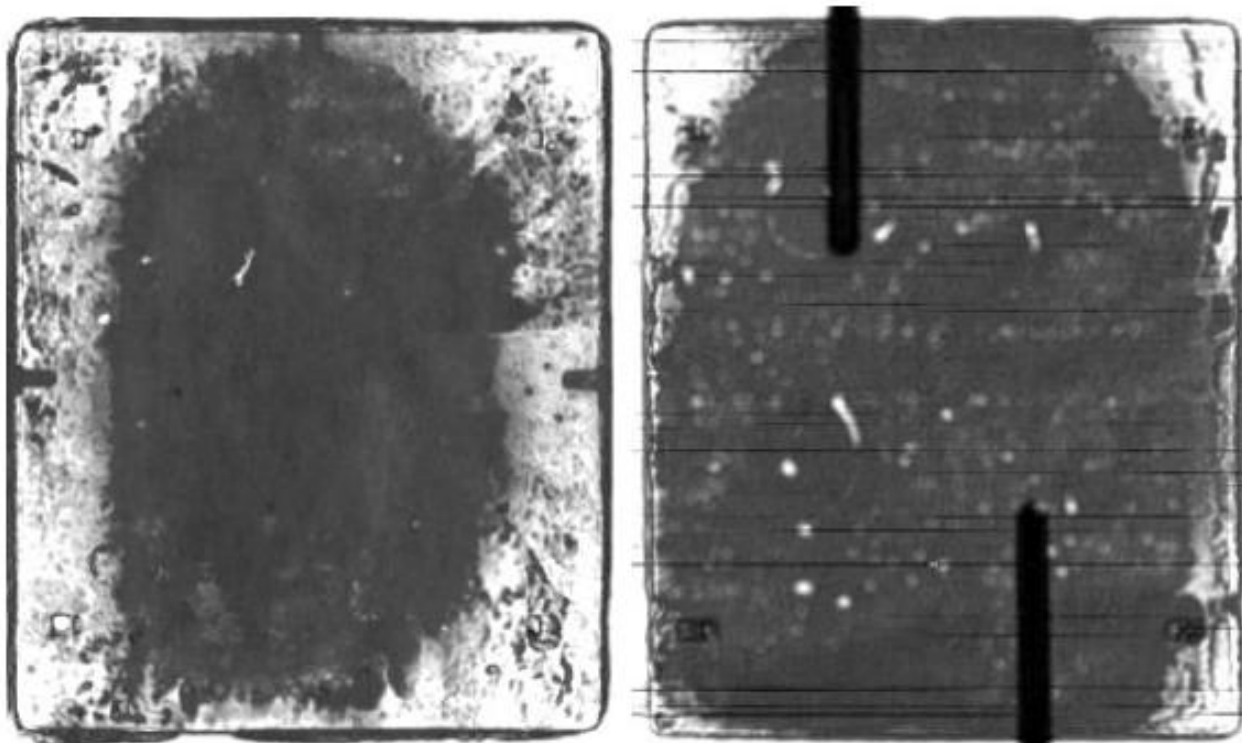


- Bond Wire Fatigue
- Solder Joint Fatigue

# Fatigue: Bond Wire Fatigue



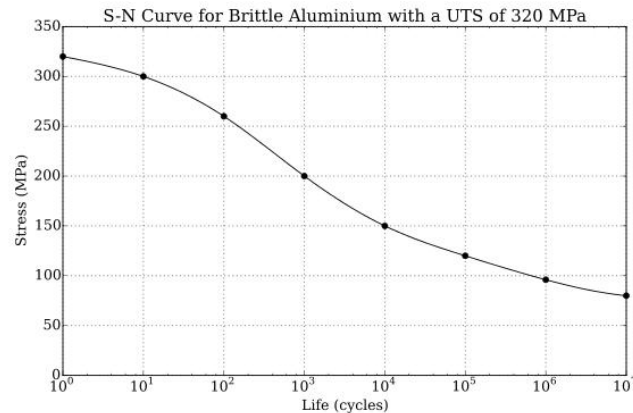
# Fatigue: Crack in Die Attach





# 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:
  - $\Delta T$ -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- $\mu$ s transients in circuit
  - Compact Model for IGBT/FRD
  - Stray inductance
- Stress/strain solver
- Air/liquid cooling

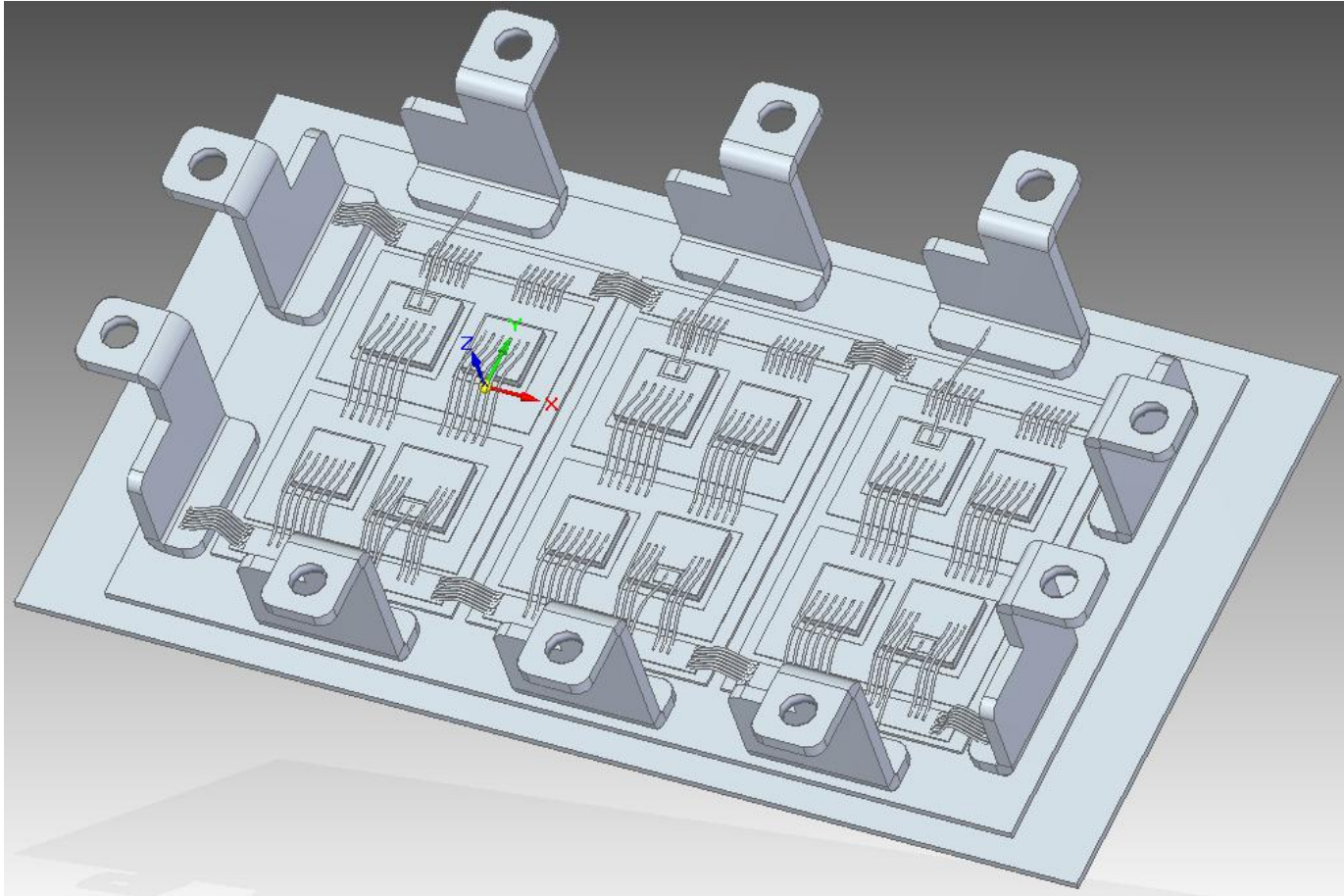
# Features Compared

	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

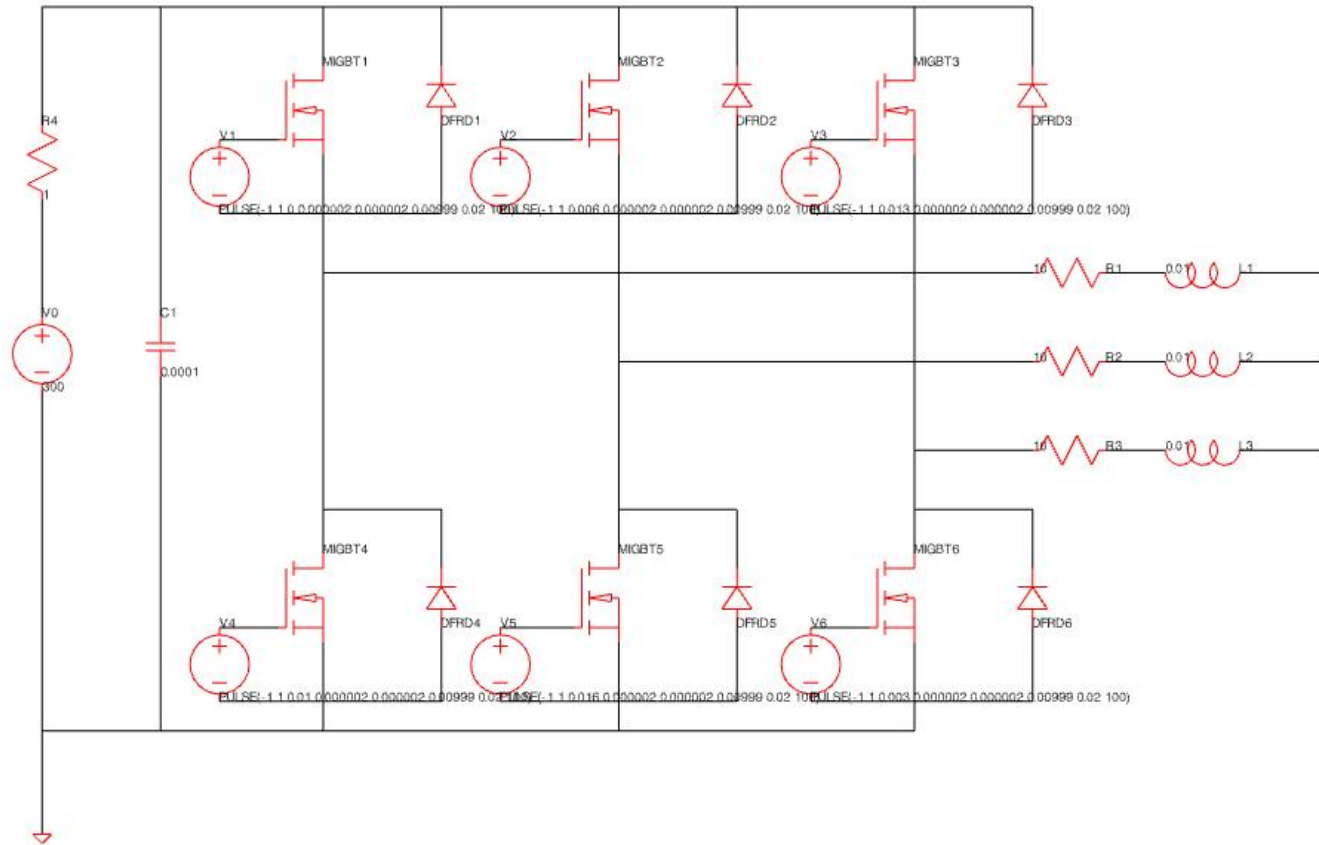
# Outline

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# Input: Detailed 3D Model



# Input: Circuit Schematics



# Input: Circuit Schematics

The image displays a circuit schematic of a six-transistor inverter. The circuit includes a DC voltage source V0 (300V) in series with a resistor R4 (1Ω). A capacitor C1 (0.0001F) is connected to the positive rail. The inverter consists of two half-bridges. The upper half-bridge has IGBTs MIGBT1, MIGBT2, and MIGBT3 with anti-parallel diodes DFRD1, DFRD2, and DFRD3. The lower half-bridge has IGBTs MIGBT4, MIGBT5, and MIGBT6 with anti-parallel diodes DFRD4, DFRD5, and DFRD6. Each IGBT is driven by a pulse generator (V1-V6). The load consists of three resistors (R1, R2, R3) in series with three inductors (L1, L2, L3).

Element	Parameter
MIGBT2	<a href="#">TIM1500ESM33_IGBT.xml</a>
MIGBT3	<a href="#">TIM1500ESM33_IGBT.xml</a>
MIGBT4	<a href="#">TIM1500ESM33_IGBT.xml</a>
MIGBT5	<a href="#">TIM1500ESM33_IGBT.xml</a>
MIGBT6	<a href="#">TIM1500ESM33_IGBT.xml</a>
R1	10Ω
R2	10Ω
R3	10Ω

Setting Component : V1[ voltage ]

DC  SINE  PULSE

Vinitial[V]: -1

Von[V]: 1

Tdelay[s]: 0

Trise[s]: 0.000002

Tfall[s]: 0.000002

Ton[s]: 0.00999

Tperiod[s]: 0.02

Ncycles: 100



# Input: Material Database

The screenshot displays a software interface for a material database. A 'Material Library' window is open, showing a list of materials on the left. The 'Copper Property' dialog box is active, allowing for the input of material properties. The properties shown are:

- Material Name: Copper
- Material Alias: Cu
- Density(kg/m<sup>3</sup>): 8930 (Constant)
- Specific Heat(J/(kg\*K)): 385 (Constant)
- Heat Conductivity(W/(m\*K)): Polynomial (Polynomial)

The Heat Conductivity polynomial is defined by the following table:

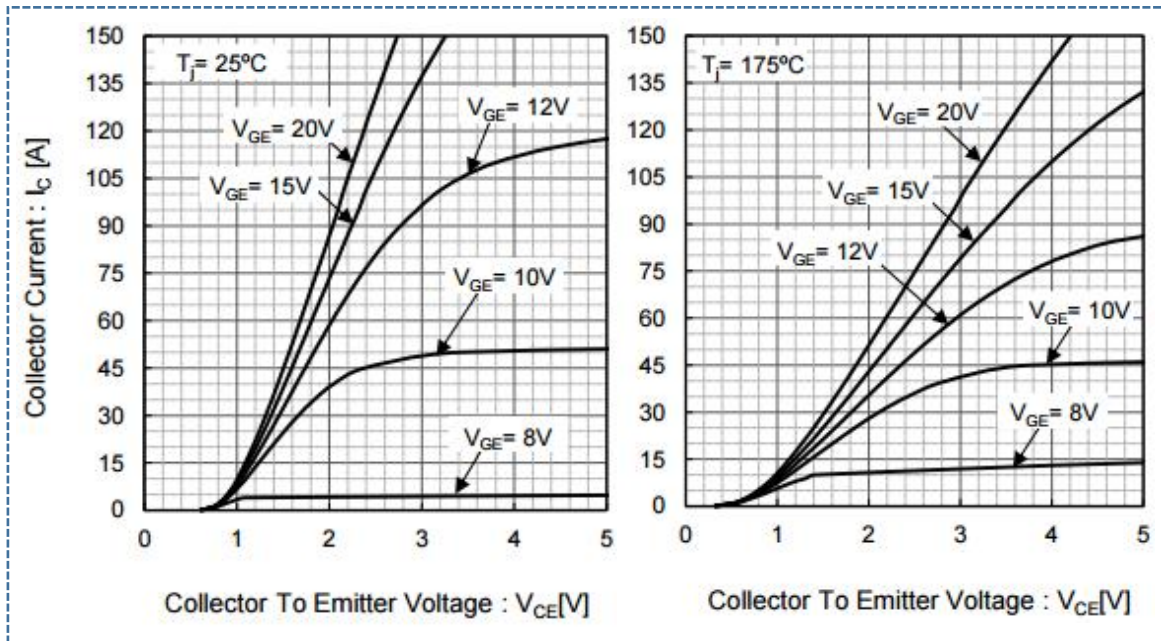
Temperature	Coefficient
273.15	401
300.15	398
1000.15	357

The interface also includes a 'Close' button at the bottom right of the dialog box.

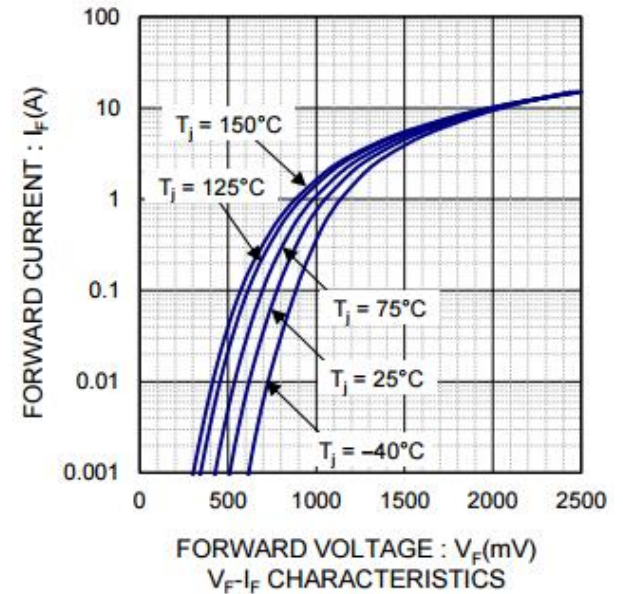
# Input: Lookup Model for IGBT/FRD

- 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

# Conduction Loss Charaterization of IGBT/FRD

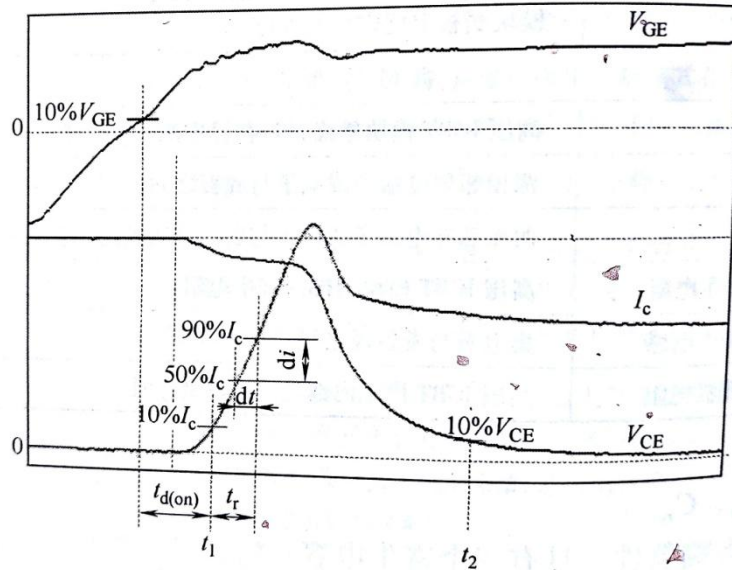


IGBT output characteristics at RT and 175°C

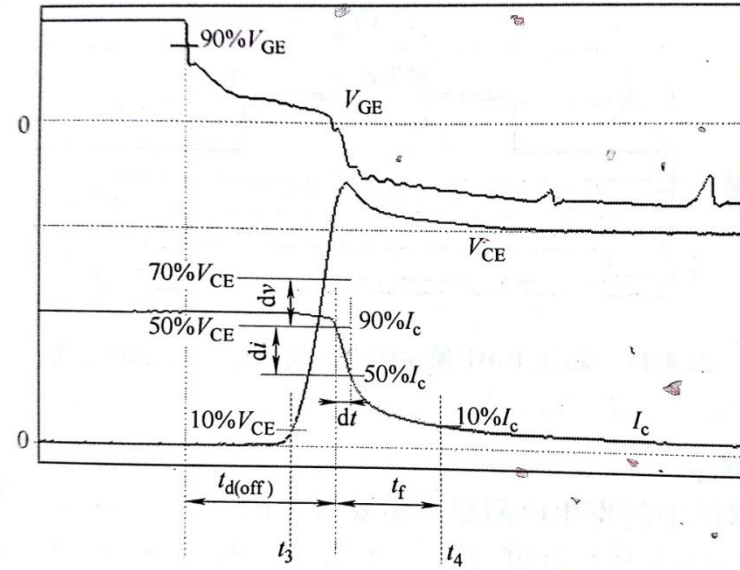


FRD forward I-V Curves

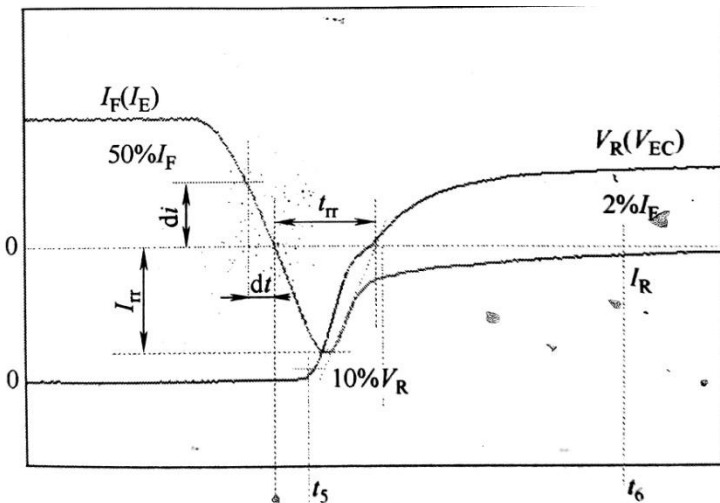
# Dynamic Loss Characterization of IGBT/FRD



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

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

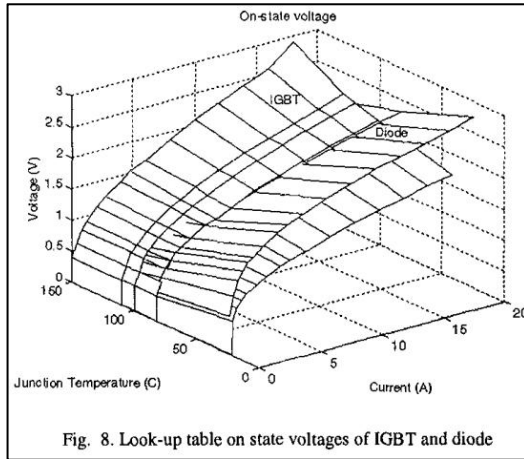


Fig. 8. Look-up table on state voltages of IGBT and diode

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

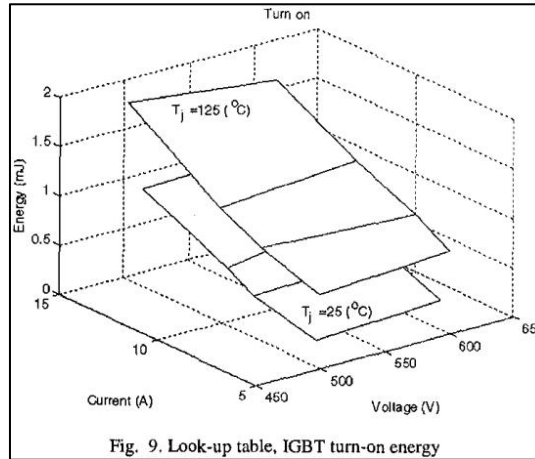


Fig. 9. Look-up table, IGBT turn-on energy

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

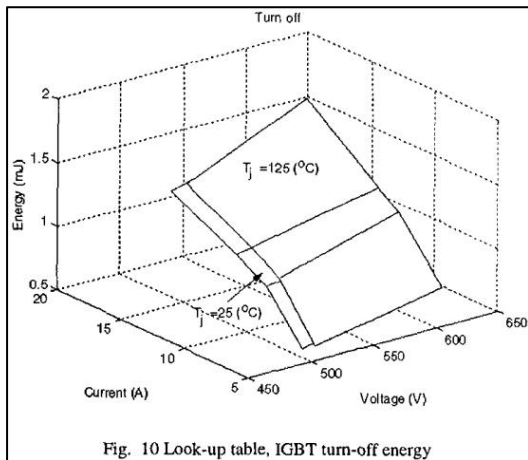


Fig. 10 Look-up table, IGBT turn-off energy

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

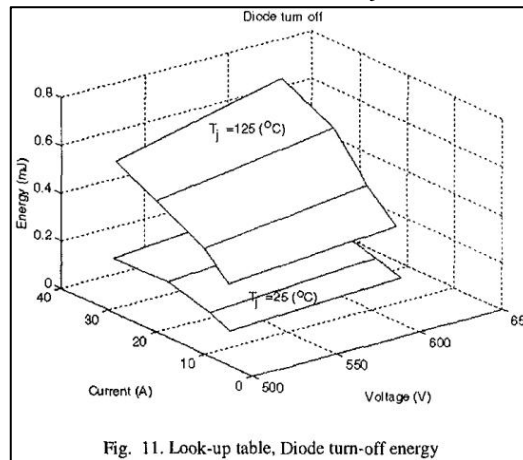


Fig. 11. Look-up table, Diode turn-off energy

$V_{ce}$ : IGBT conduction voltage drop

$I_c$ : IGBT current

$V_F$ : FRD conduction voltage drop

$I_F$ : FRD current

$T_j$ : junction temperature

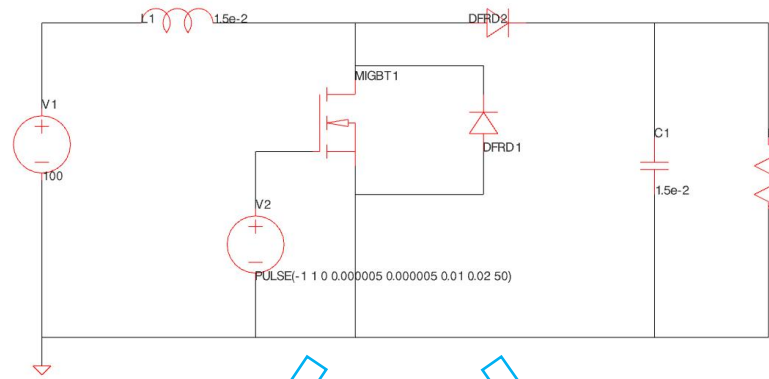
$E_{on}$ : IGBT turn-on energy

$E_{off}$ : IGBT turn-off energy

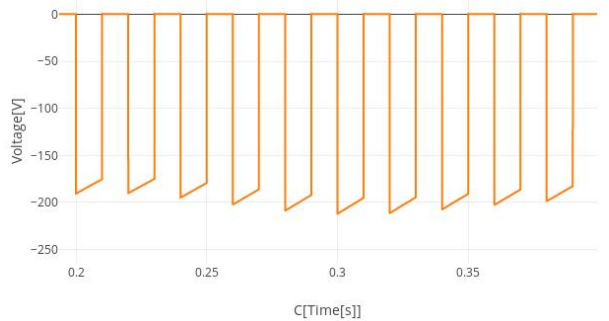
$E_{doff}$ : FRD turn-off energy

$V_{dc}$ : reverse voltage

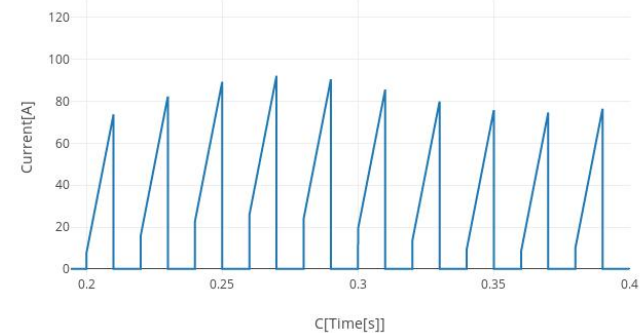
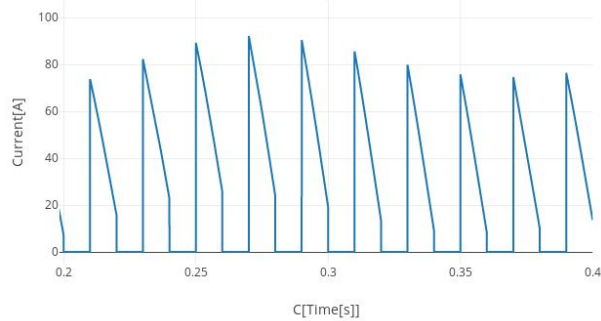
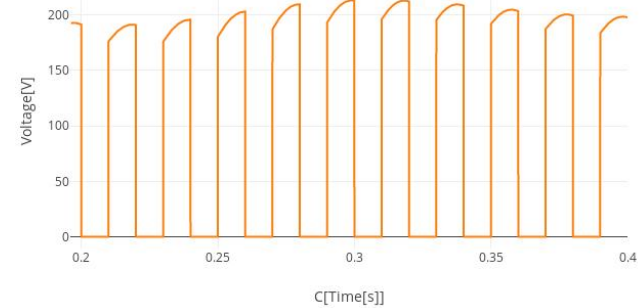
# Switching Events and Energy Loss



FRD



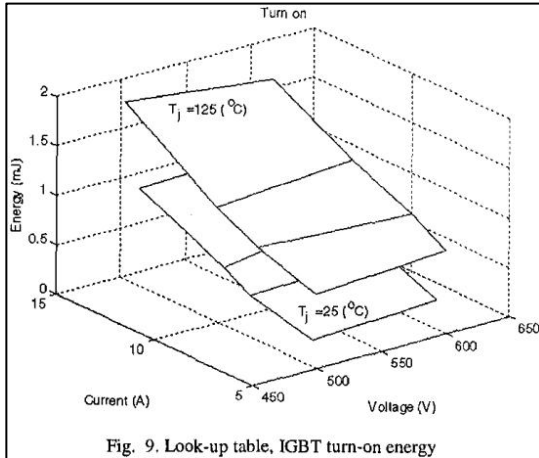
IGBT



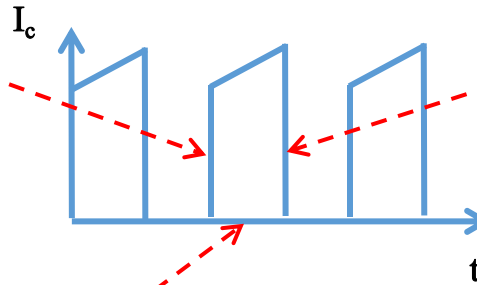
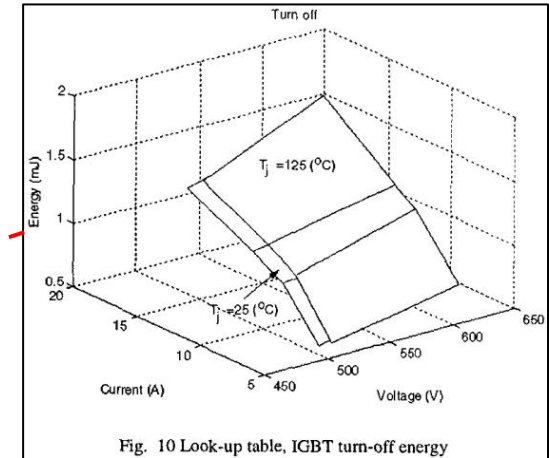
V-t and I-t waveforms from SPICE simulation

# Switching Events and Energy Loss

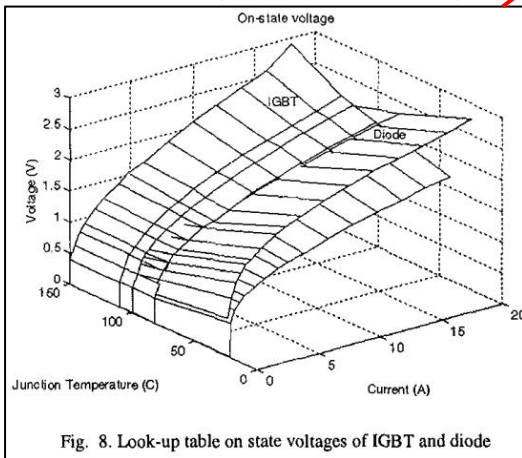
$$E_{on} = f(V_{dc}, I_c, T_j)$$



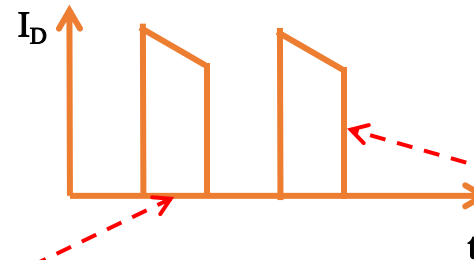
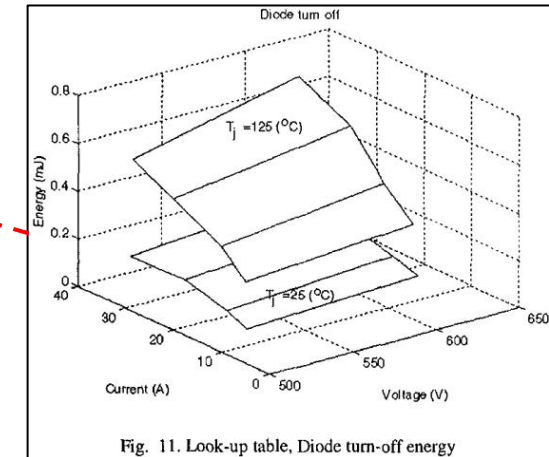
$$E_{off} = f(V_{dc}, I_F, T_j)$$



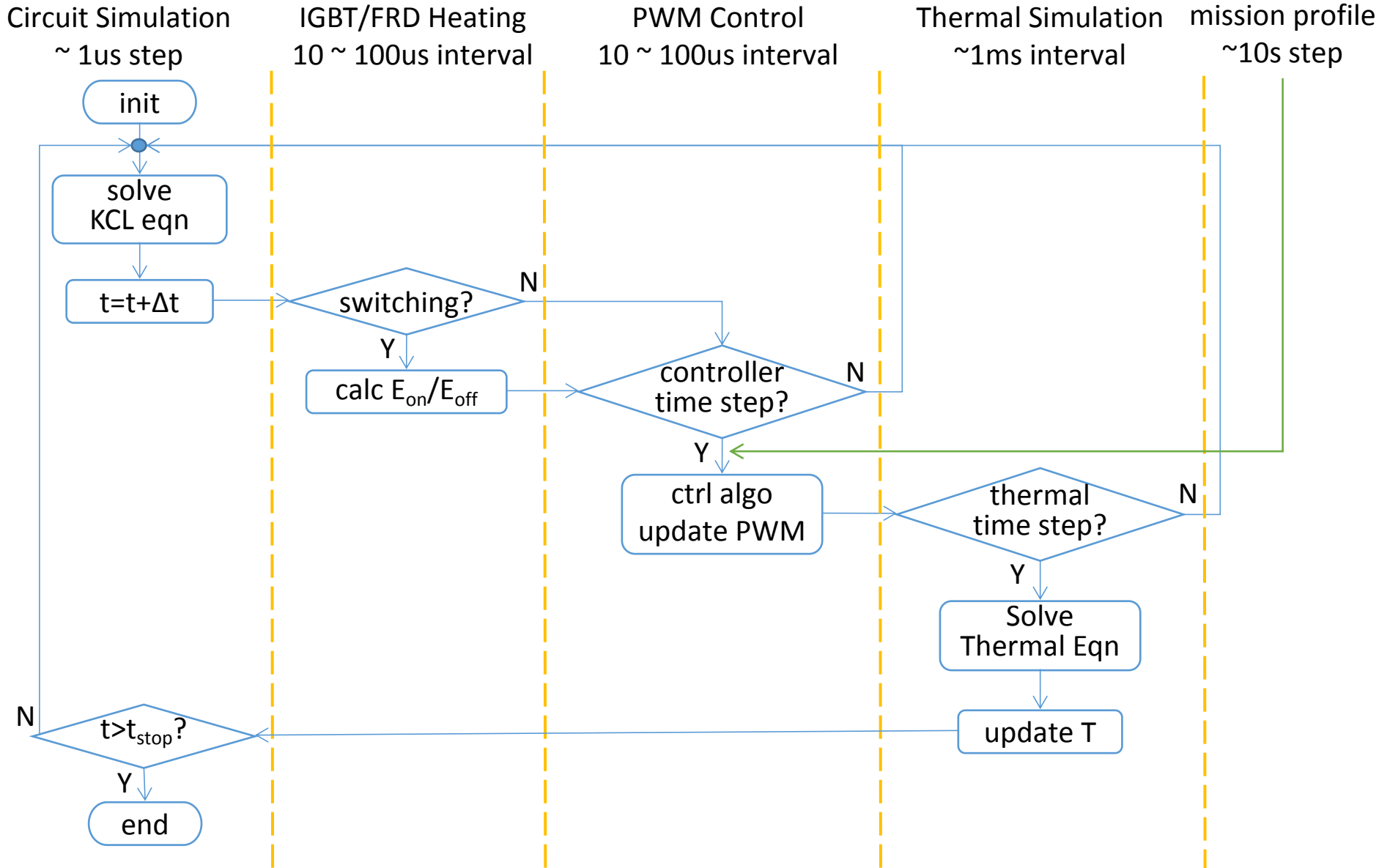
$$V_{ce} = f(I_c, T_j) \text{ and } V_F = f(I_F, T_j)$$



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



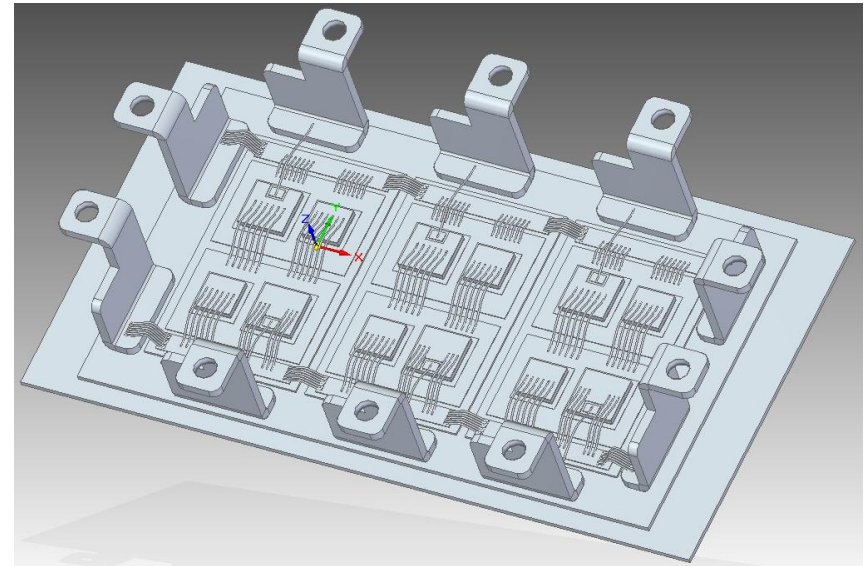
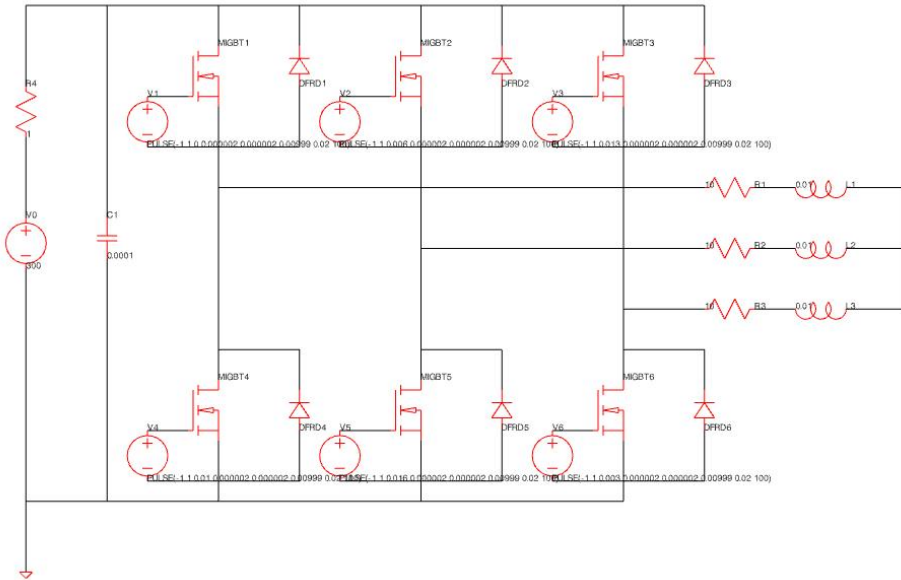
# Multi-Physics/Scale Simulation





# 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



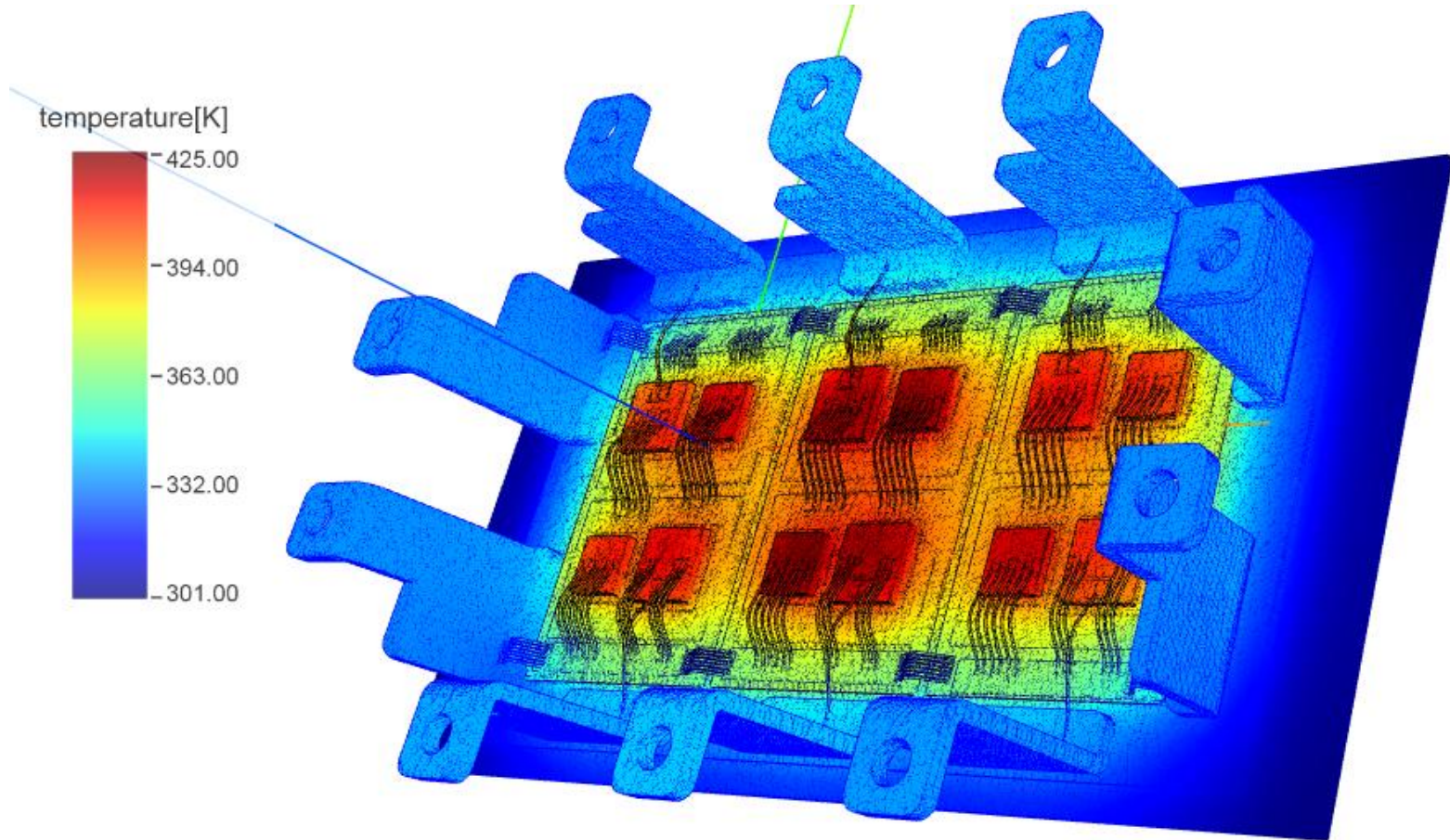
# Implementation Details

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

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# Results: 3-Phase Inverter

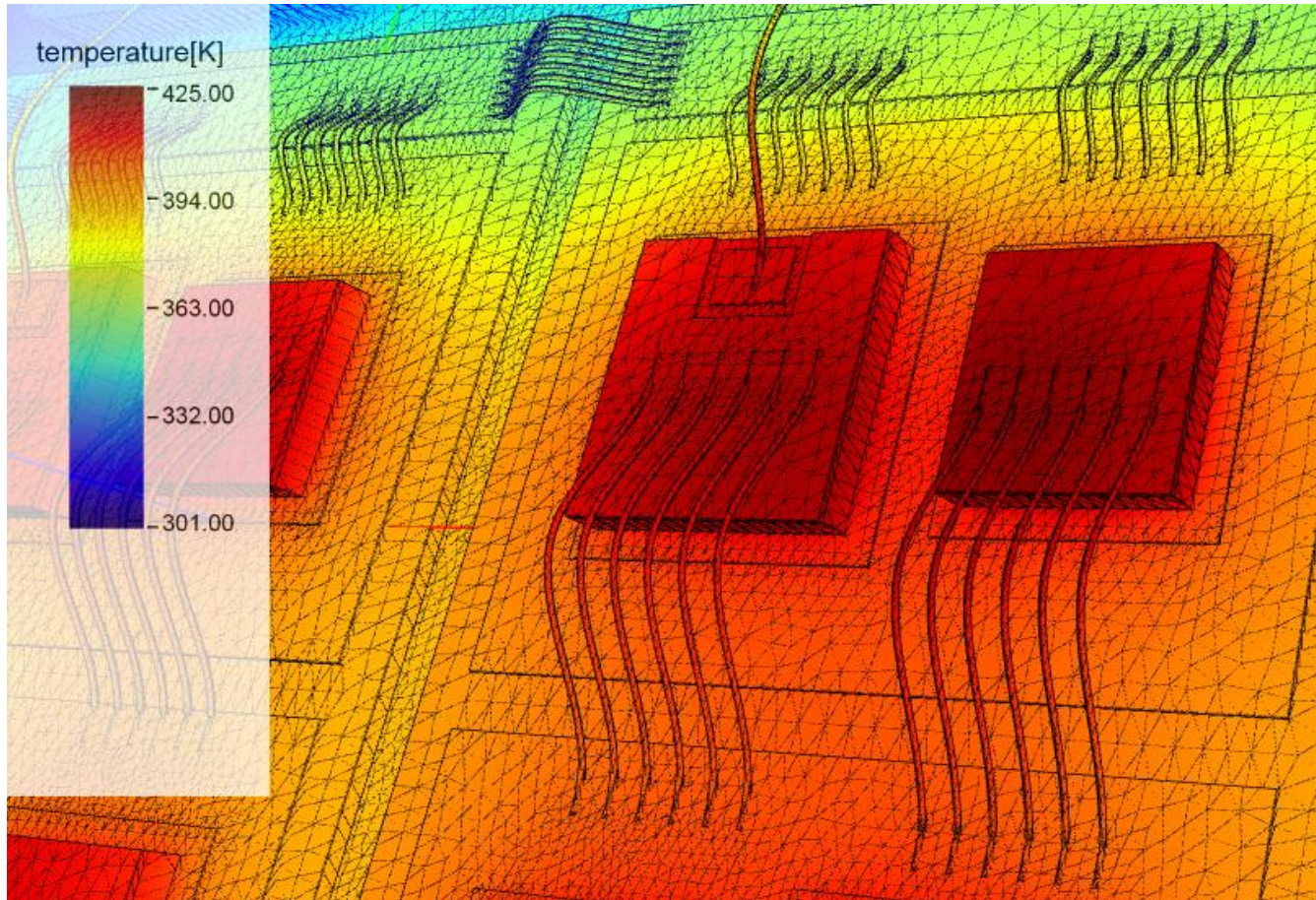


# of mesh nodes: 1,366,934

# of mesh elements: 832,673

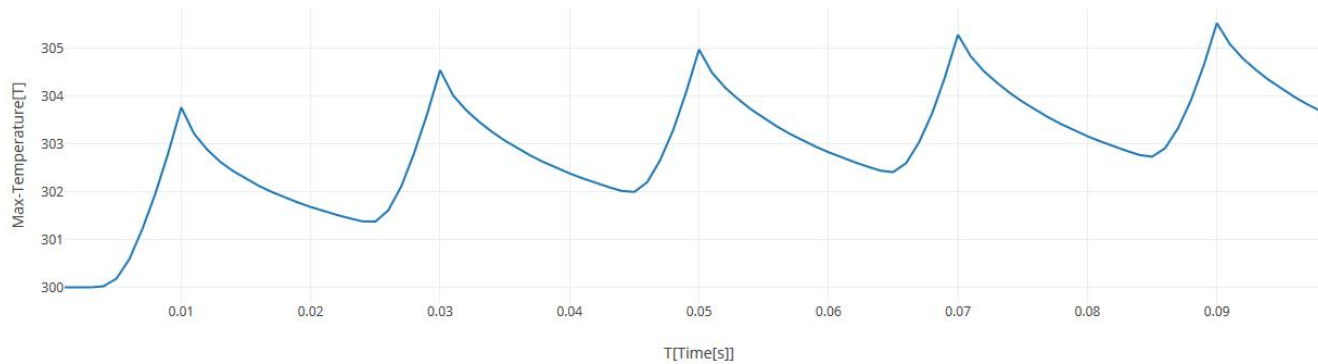


# Results: 3-Phase Inverter

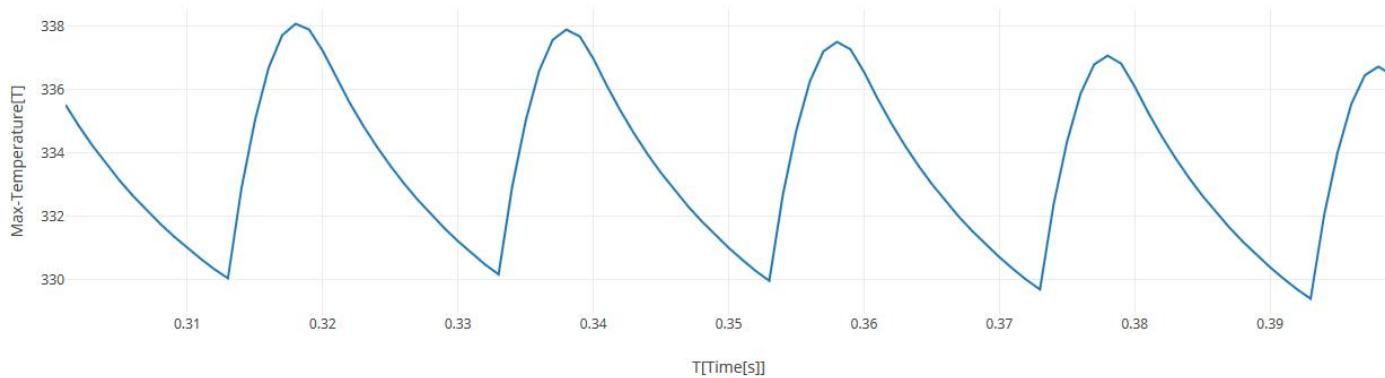


# Results: 3-Phase Inverter

Initial temperature waveform @ IGBT1



Steady-state temperature waveform @ IGBT1

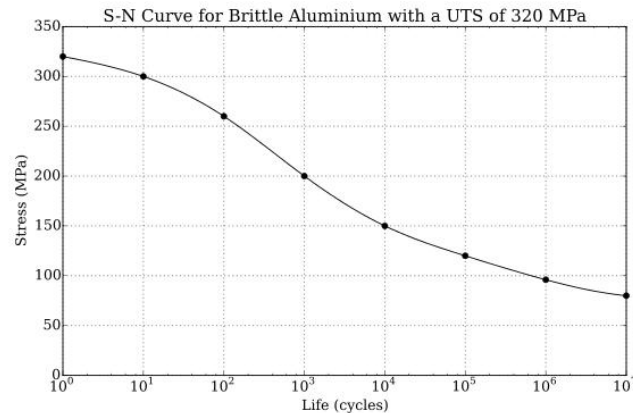


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# Fatigue: Failure Model

- 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:
  - $\Delta T$ -N instead of S-N

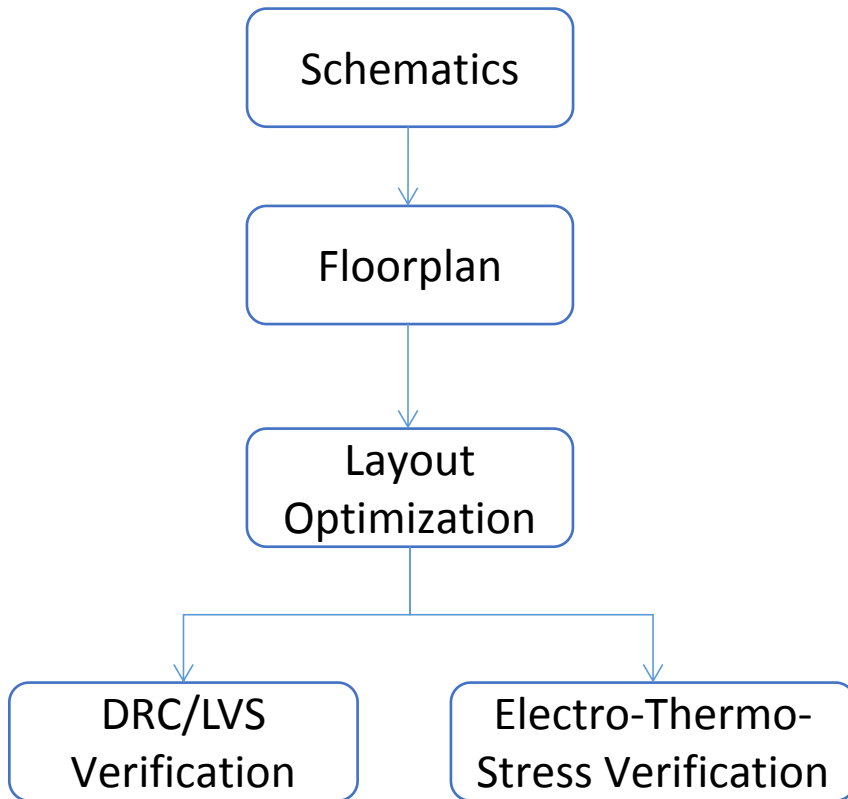
Shown to be incorrect



# 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