VIRGINIA TECH

Lecture 10

Thermal Design

Thermal Conduction & Thermal Resistance

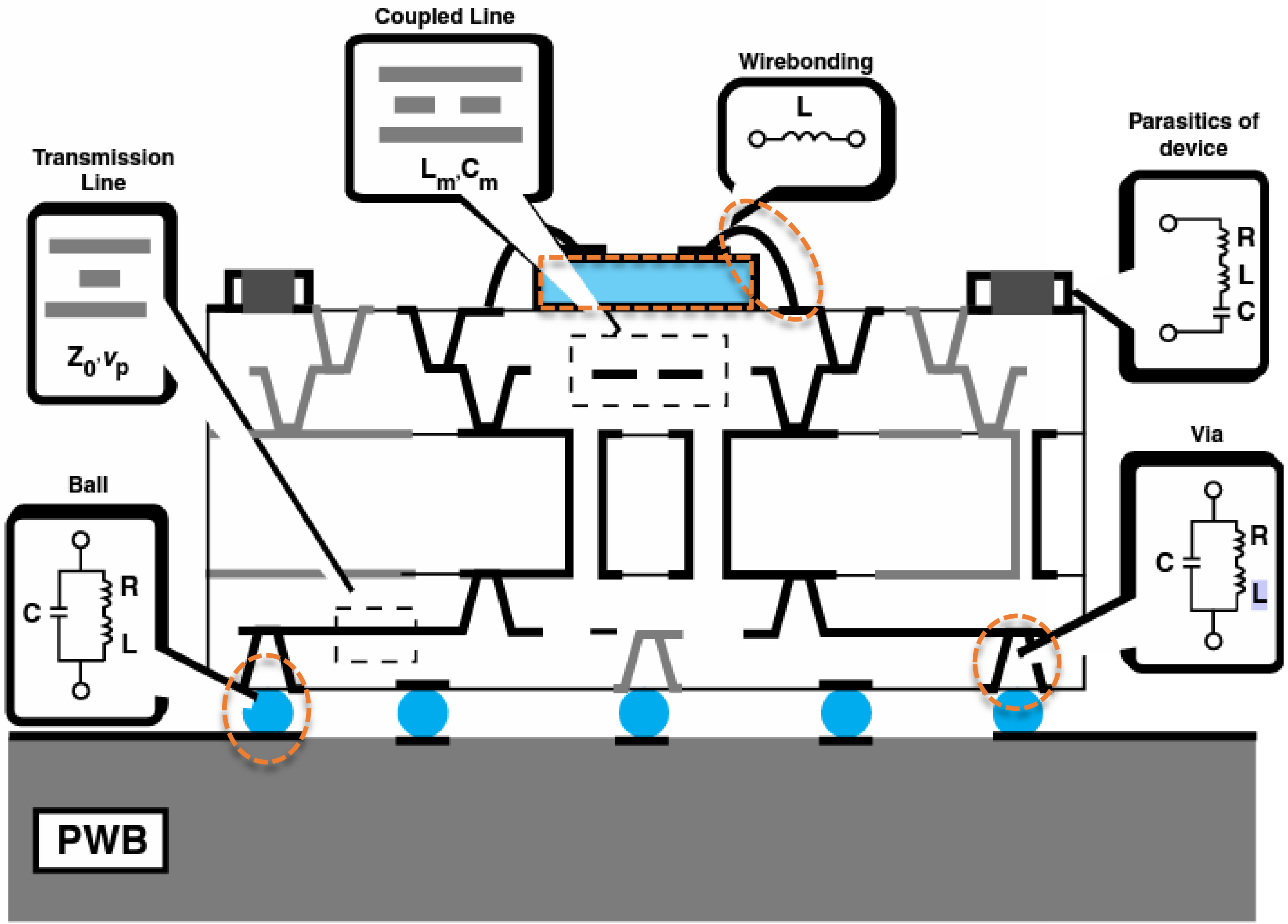
February 25, 2025

Reminders and Announcements

- Homework #2 due Wednesday, Feb. 26th, by 11:59pm
- Homework #3 will be assigned on Thursday, Feb. 27th
- Office Hours: Wednesday, 3:00pm-4:30pm

What Generates Heat Within a Package?

- Semiconductor/die/chip
  - On-resistance
  - Switching losses
- Interconnects
  - Resistance
- Terminals
  - Resistance

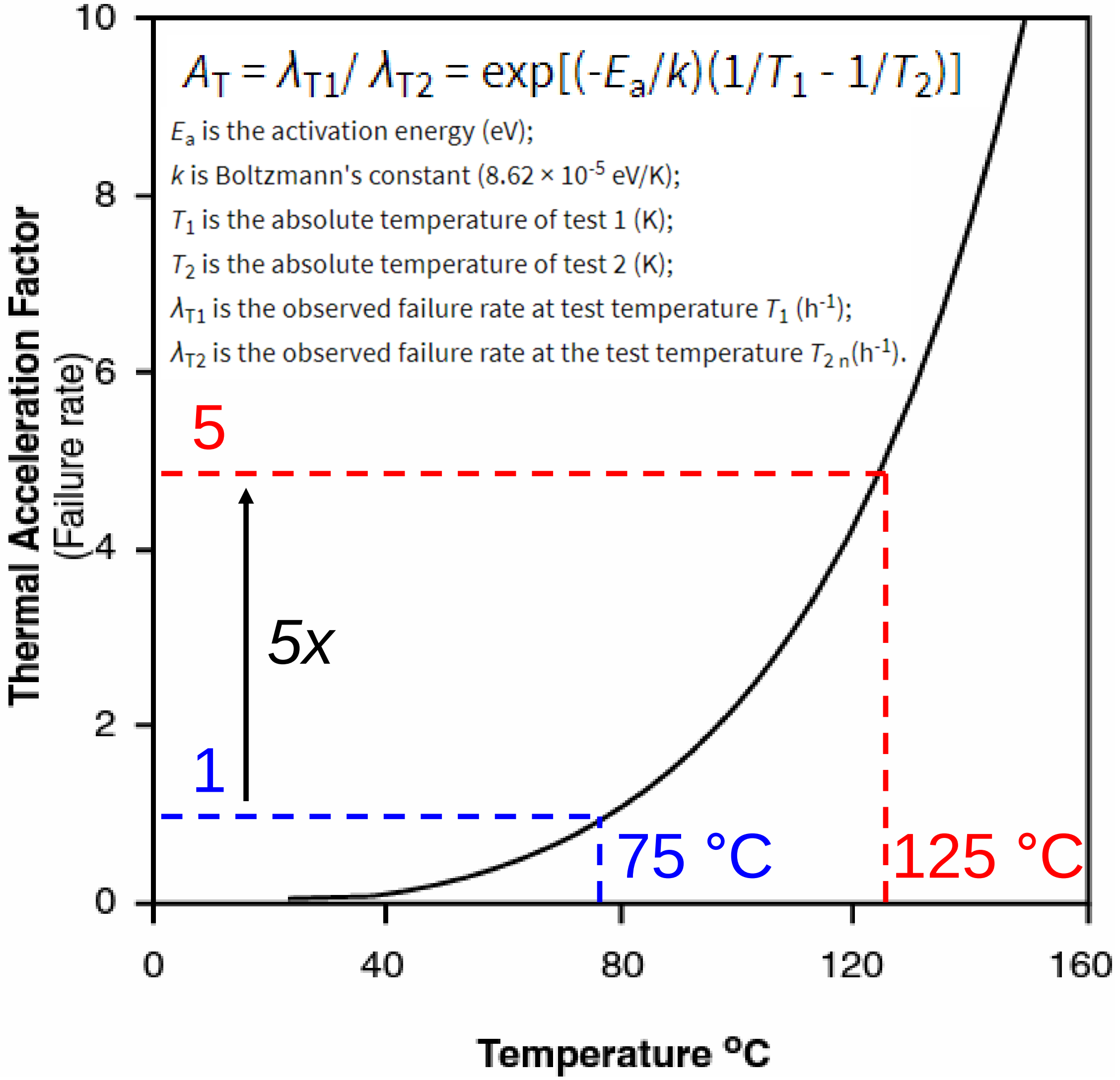


Impacts of High Temperatures

- Lower efficiency
- Reduced reliability
- Potentially catastrophic failure

Reliability

- The probability that the system will meet the required specifications for a given period of time
- A rise in temperature results in an increase in failure rate
- For many package types, temperature is the strongest contributor to the loss of reliability
- Thermal management is critical to the success of the system



Heat Removal

- Without cooling, the **temperature** of the heat-generating components **would rise at a constant rate** until it reaches a value at which the electronic operation of the device ceases, or the component loses its physical integrity
- By placing the device in contact with a lower-temperature solid or fluid, heat flow away from the component is facilitated
- With this **cooling**, the temperature rise is moderated as it **asymptotically** approaches a **steady-state** value
- At steady-state, the heat generated by the component(s) is **transferred to the surrounding** structure and/or fluid

Thermal Management

- Heat transfer mechanisms: **conduction**, **convection**, and **radiation**, as well as phase change
- Successful thermal management relies on a careful combination of **materials and heat transfer** mechanisms
- The enhanced reliability of the components due to the lower temperature T should be sufficient to compensate for the additional life-cycle **cost** and inherent **failure** rate of fans, pumps, and special interface materials
- Increase in reliability due to lower T should be > decrease in reliability due to adding a fan or other cooling components

Modes of Thermal Transport

- **Conduction**

  $$q = \frac{kA_c\Delta T}{L}$$

  - Flow of heat from a region of higher temperature to a region of lower *temperature* ***within a solid, stationary liquid,*** *or* ***static gaseous medium***
  - Direct energy exchange among molecules
- **Convection**

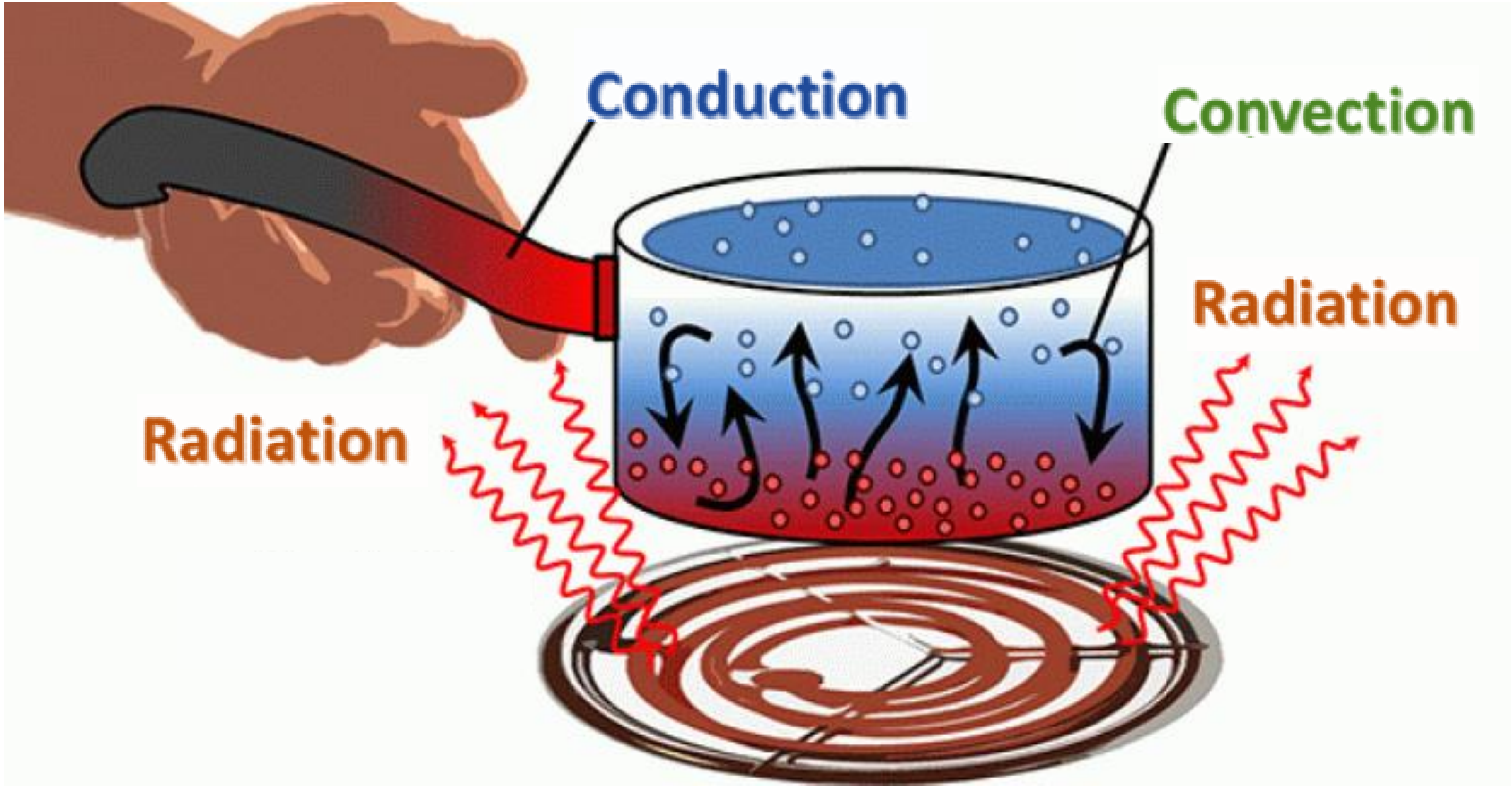
  $$q = hA_s\Delta T$$

  - Transfer of heat from a solid to a ***fluid in motion***
  - Mechanisms:
    - Exchange among nearly-stationary molecules adjacent to the solid surface (as in conduction)
    - Transport of heat away from the solid surfaces by the bulk motion of the fluid
- **Radiation**

  $$Q = \varepsilon\sigma F_{12}A_s(T_1^4 - T_2^4)$$

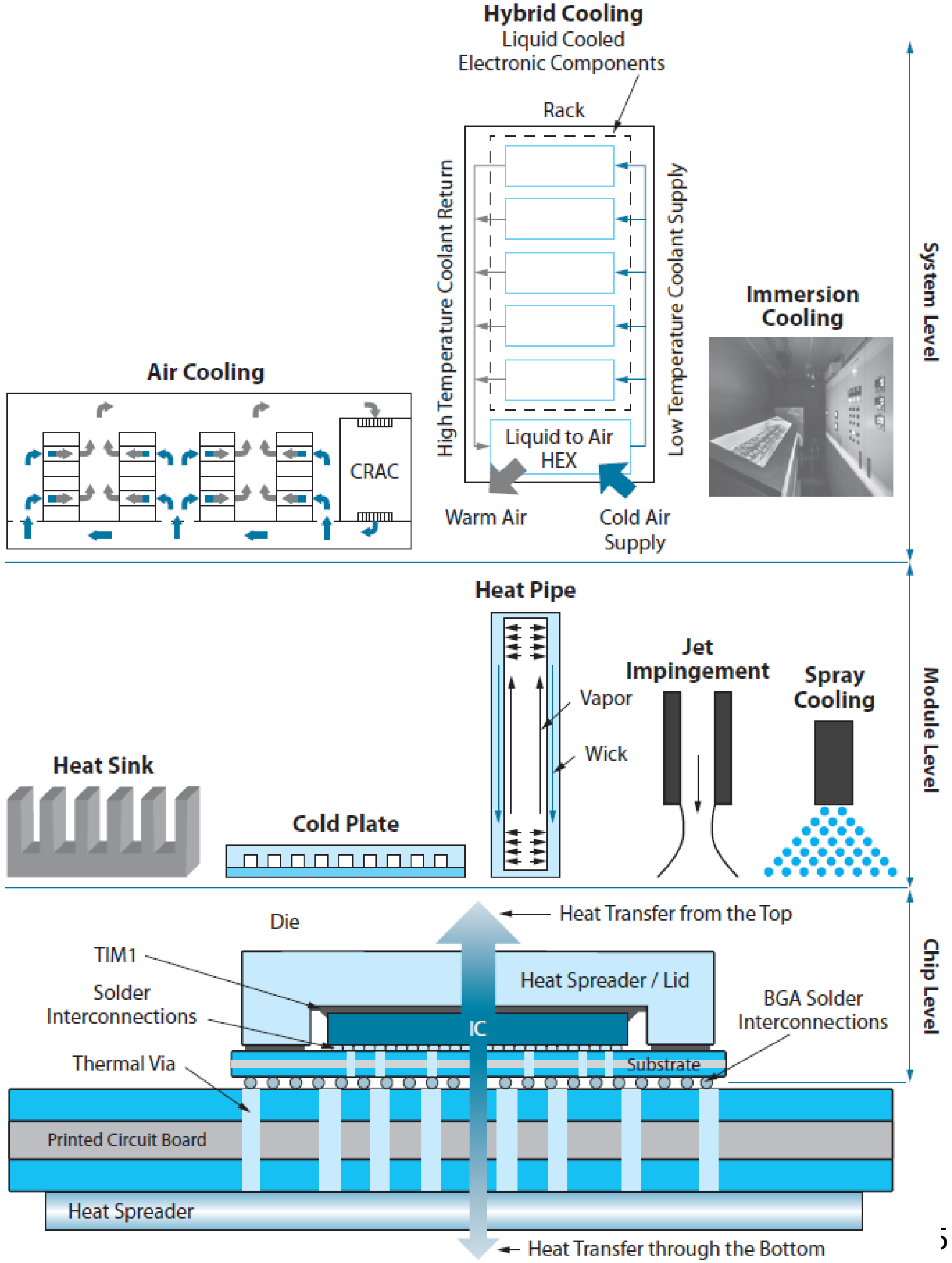
  - Heat transfer is a result of the ***emission and absorption*** of the energy contained in the electromagnetic waves or photons
  - Can occur across a vacuum or any medium that is transparent to infrared wavelengths
  - Not linearly dependent on the temperature difference

Modes of Thermal Transport



Thermal Management Levels & Technologies

Level	Mode	Thermal Technologies
System	Thermal control system	Air cooling (natural or forced) Hybrid cooling (liquid & air) Immersion cooling
PWB / Module	Conduction and convection to ambient	Thermal via Heat spreader Heat sink Cold plate Heat pipe Jet impingement Spray cooling
Package	Conduct heat from chip to the package surface	Die attach Thermal interface material Thermal via Heat spreader Heat pipe

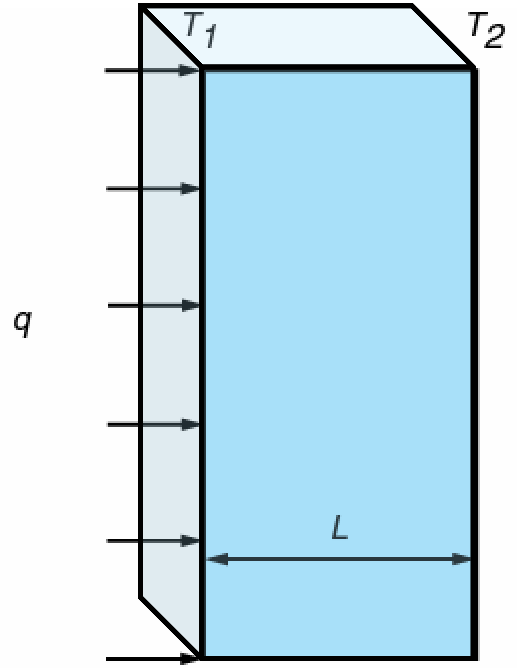


Heat Conduction

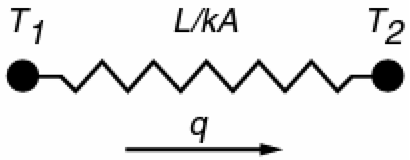
$$q = \frac{kA_c\Delta T}{L}$$

q = heat (W)
k = thermal conductivity (W/(m·K))
A_c = area that q flows through (m^2)
L = length q flows through (m)

Material	Density (kg/m^3)	Specific Heat (J/kg K)	Thermal Conductivity (W/mK)	Ratio
Air	1.16	1005	0.024	1
Epoxy (dielectric)	1500	1000	0.23	9.6
Epoxy (conductive)	10500	1195	0.35	14.6
Polyimide	1413	1100	0.33	13.8
FR4	1500	1000	0.30	12.5
Water	1000	4200	0.59	24.6
Thermal grease	—	—	1.10	46
Alumina	3864	834	22.0	916
Aluminum	2700	900	150	6250
Silicon	2330	770	120	5000
Copper	8800	380	390	16,250
Gold	19300	129	300	12,500
Diamond	3500	51	2000	83,330



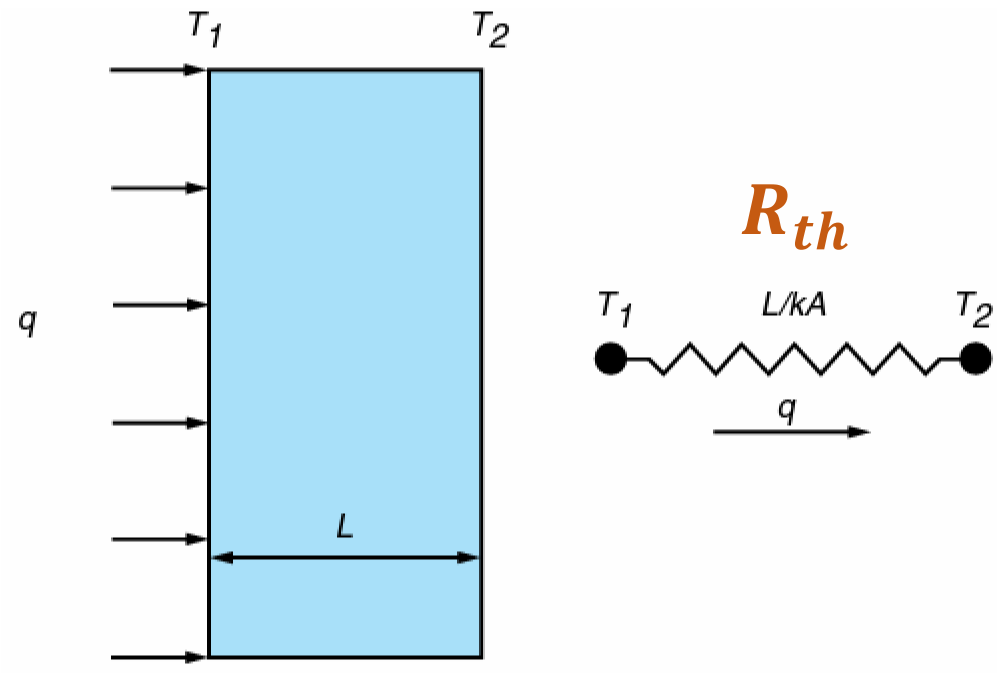
R_{th}



$$T_1 - T_2 = \frac{qL}{kA_c} \rightarrow T_1 - T_2 = qR_{th}$$, where $$R_{th} = \frac{L}{kA_c}$$

Thermal Resistance R_{th}

- Fourier's Law is analogous to Ohm's Law:
  - Heat q $\rightarrow$ current I
  - Temperature drop ΔT $\rightarrow$ voltage drop ΔV
  - Thermal resistance R_{th} $\rightarrow$ electrical resistance R



Thermal:

$$\Delta T = qR_{th} \rightarrow R_{th} = \frac{\Delta T}{q} \quad \left[\frac{\mathrm{K}}{\mathrm{W}}\right]$$

Electrical:

$$\Delta V = IR \rightarrow R = \frac{\Delta V}{I} \quad [\Omega]$$

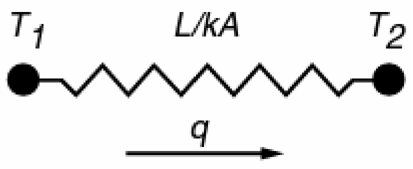
Thermal and Electrical Conduction

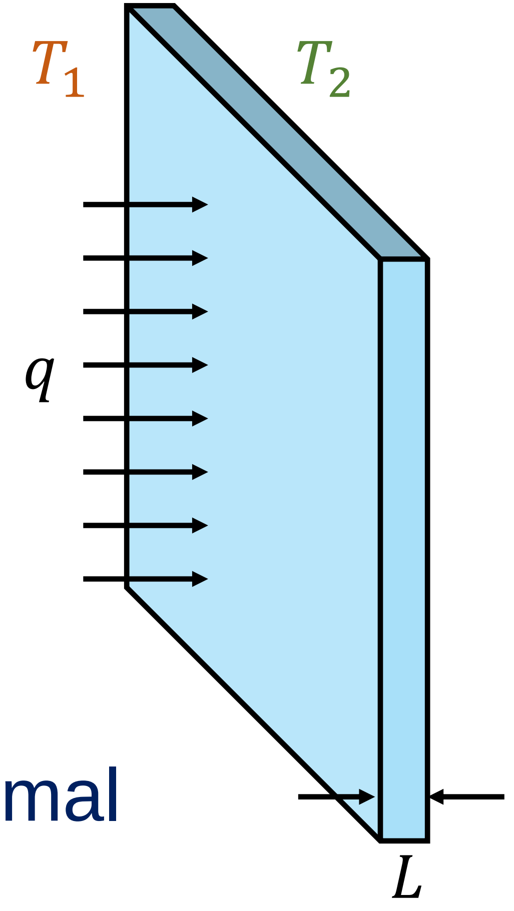
Thermal Conduction	Electrical Conduction
$q = \dfrac{kA_c\Delta T}{L}$ [W]	$I = \dfrac{\sigma A_c \Delta V}{L}$ [A]
k is a material property	σ is a material property
$R_{th} = \dfrac{L}{kA_c}$ [K/W]	$R = \dfrac{L}{\sigma A_c}$ [Ω]
Depends on: Material (k) Length (L) Cross-sectional Area (A_c)	Depends on: Material (σ) Length (L) Cross-sectional Area (A_c)
Series: algebraic sum Parallel: sum of inverses	Series: algebraic sum Parallel: sum of inverses

Example: Heat Conduction

Calculate the temperature difference across a 1-mm-thick layer of thermal grease with $k = 1$ W/(m·K). Assume a 1 W heat source spread *uniformly* over a 1 cm^2 area.

$$T_1 - T_2 = \frac{qL}{kA_c}$$

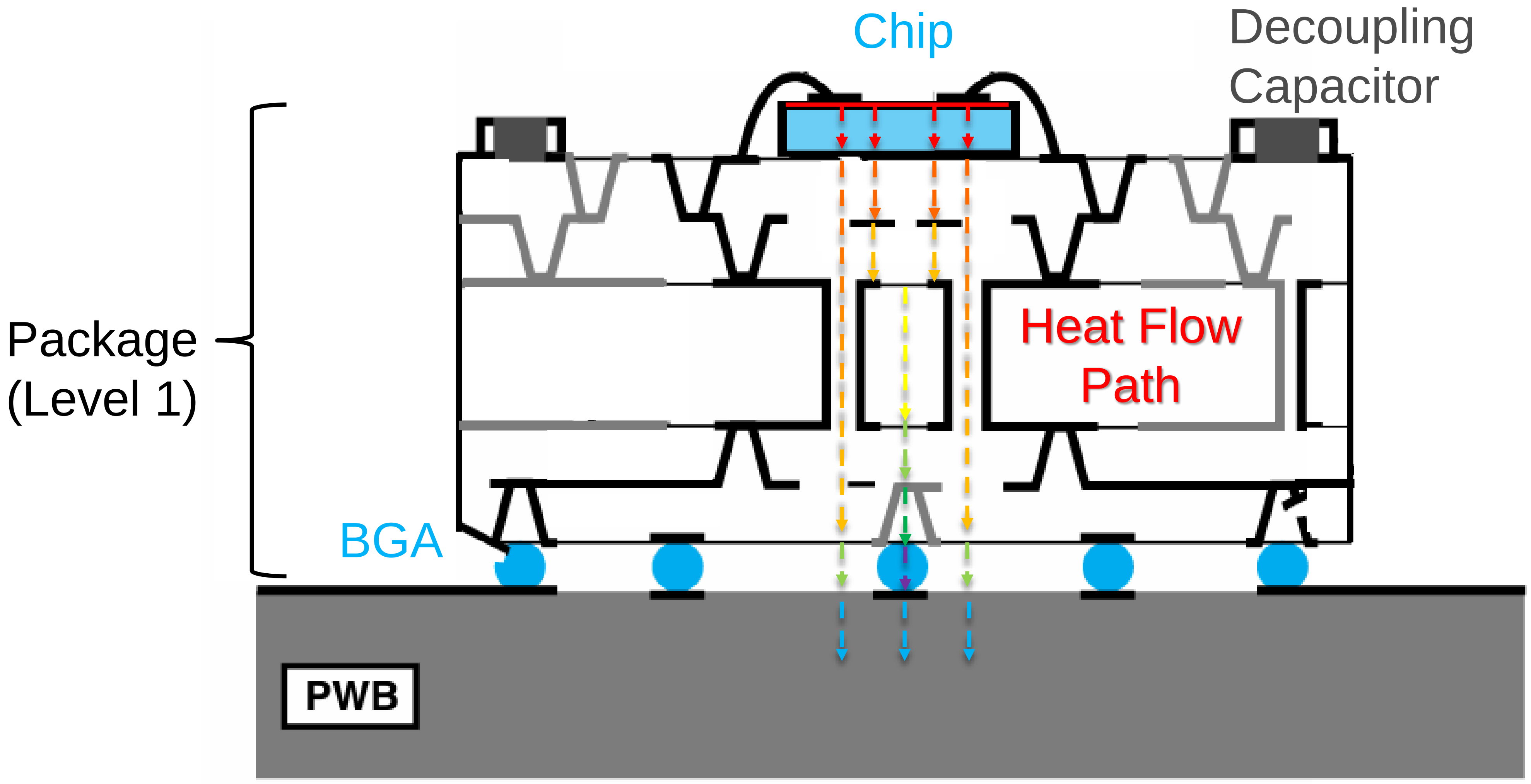




- $q = 1$ W
- $L = t_{TG} = 1$ mm = 0.001 m
- $k_{TG} = 1$ W/(m·K)
- $A_c = 1$ cm^2 = 1 x 10^{-4} m^2
- $T_1 - T_2 = \frac{qL}{kA_c} = \frac{(1\ \mathrm{W})(0.001\mathrm{m})}{\left(1\frac{\mathrm{W}}{\mathrm{m\cdot K}}\right)(1\times10^{-4}\mathrm{m}^2)} = \mathbf{10°C}$

➢ T_2 is 10°C lower than T_1 due to the high R_{th} of the thermal grease

Package Heat Flow

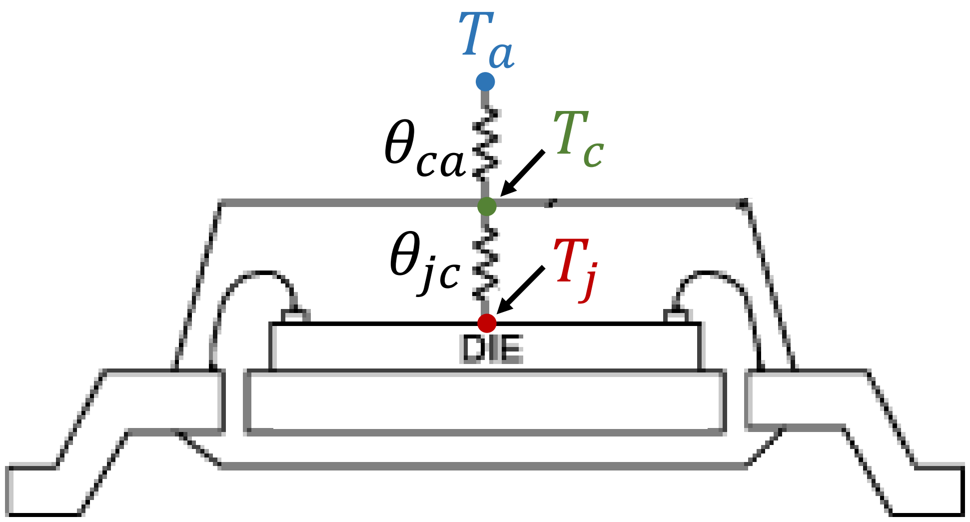


Package Thermal Resistance

- Packages are characterized by an overall junction-to-ambient thermal resistance, $R_{th,ja}$ or θ_{ja}

$$\theta_{ja} = \frac{T_j - T_a}{q}$$

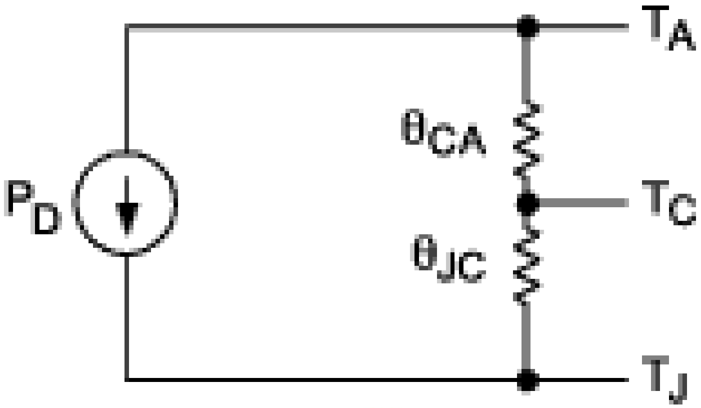
- T_j = junction temperature (°C)
- T_a = ambient temperature (°C)
- q = power dissipation (W)
- "j" = junction
- "a" = ambient
- "c" = case

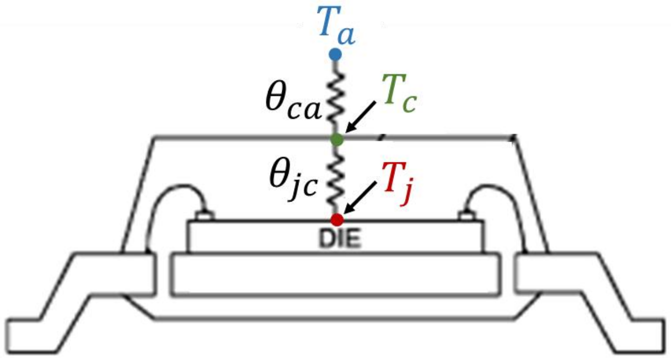


Package Thermal Resistance

- θ_{ja} can be separated into two parts:
  - Junction-to-case, θ_{jc}
  - Case-to-ambient, θ_{ca}

$$\boxed{\theta_{ja} = \theta_{jc} + \theta_{ca}}$$



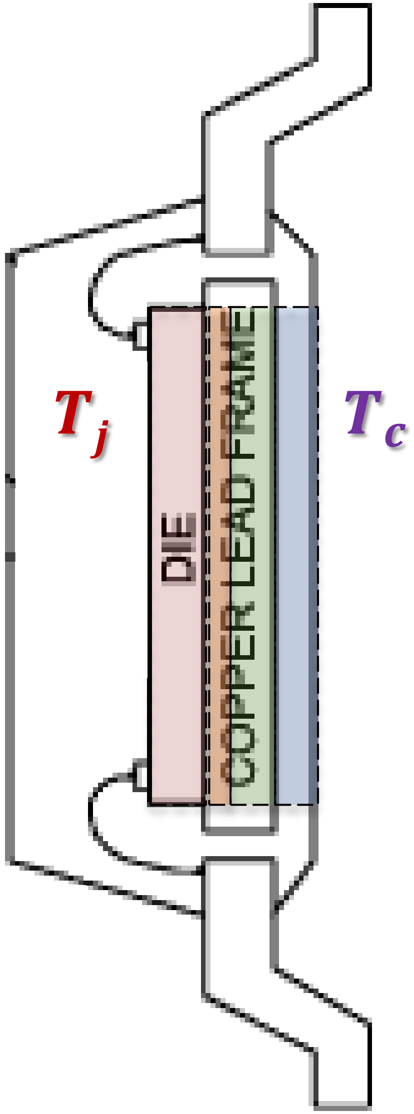


- Junction-to-case, θ_{jc}
  - Depends on the internal construction of the package
  - Depends on length, cross-sectional area, and k
- Case-to-ambient, θ_{ca}
  - Depends on the mounting and cooling techniques
  - Depends on wetted surface area and h

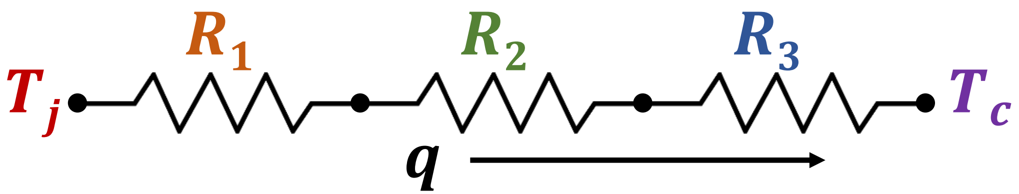
Example: Package Thermal Resistance

Find the junction temperature, T_j, of the die if it dissipates 1 W of heat and has the below specifications.

- $T_c = 50$ °C
- $A_c = 10$ x 10 mm^2 (for all components)
- Solder die attach: $k_1 = 50$ W/(m·K), $L_1 = 0.1$ mm
- Cu lead frame: $k_2 = 390$ W/(m·K), $L_2 = 1$ mm
- EMC: $k_3 = 0.23$ W/(m·K), $L_3 = 1$ mm
- Assume other sides are thermally insulated, that the die is at a uniform temperature, and neglect heat spreading.

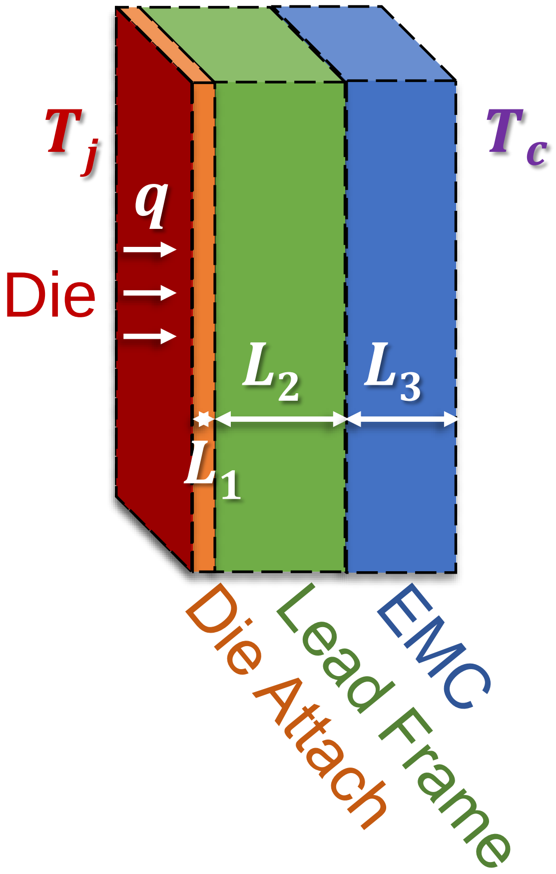


Example: Package Thermal Resistance



$$R_{th,cond} = \frac{L}{kA}$$

- $T_j - T_c = qR_{th,j-c}$
- $R_{th,j-c} = R_1 + R_2 + R_3$
- $R_1 = \frac{L_1}{k_1 A} = \frac{100\times10^{-6}\mathrm{m}}{\left(50\frac{\mathrm{W}}{\mathrm{mK}}\right)(1\times10^{-4}\mathrm{m}^2)} = 0.02\ \mathrm{K/W}$
- $R_2 = \frac{L_2}{k_2 A} = \frac{1\times10^{-3}\mathrm{m}}{\left(390\frac{\mathrm{W}}{\mathrm{mK}}\right)(1\times10^{-4}\mathrm{m}^2)} = 0.03\ \mathrm{K/W}$
- $R_3 = \frac{L_3}{k_3 A} = \frac{1\times10^{-3}\mathrm{m}}{\left(0.23\frac{\mathrm{W}}{\mathrm{mK}}\right)(1\times10^{-4}\mathrm{m}^2)} = \mathbf{43\ K/W}$

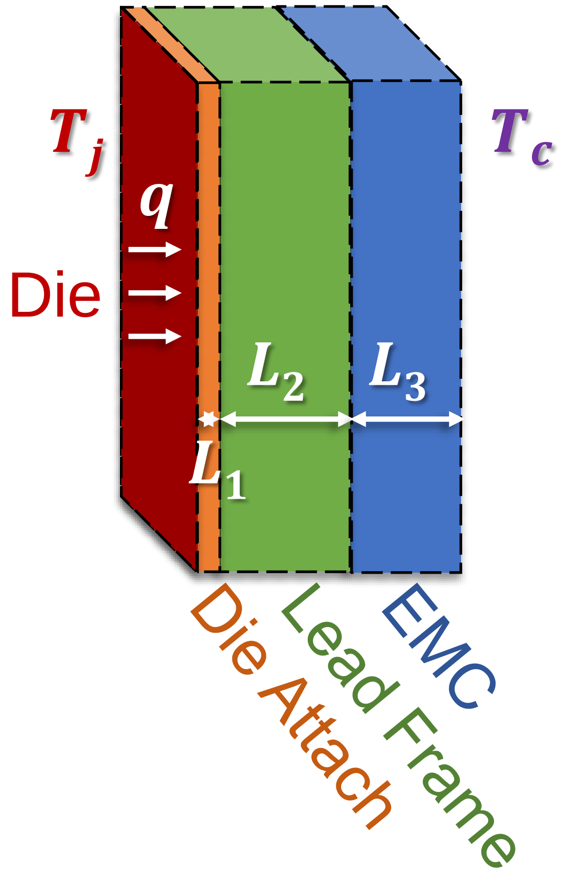


Example: Package Thermal Resistance

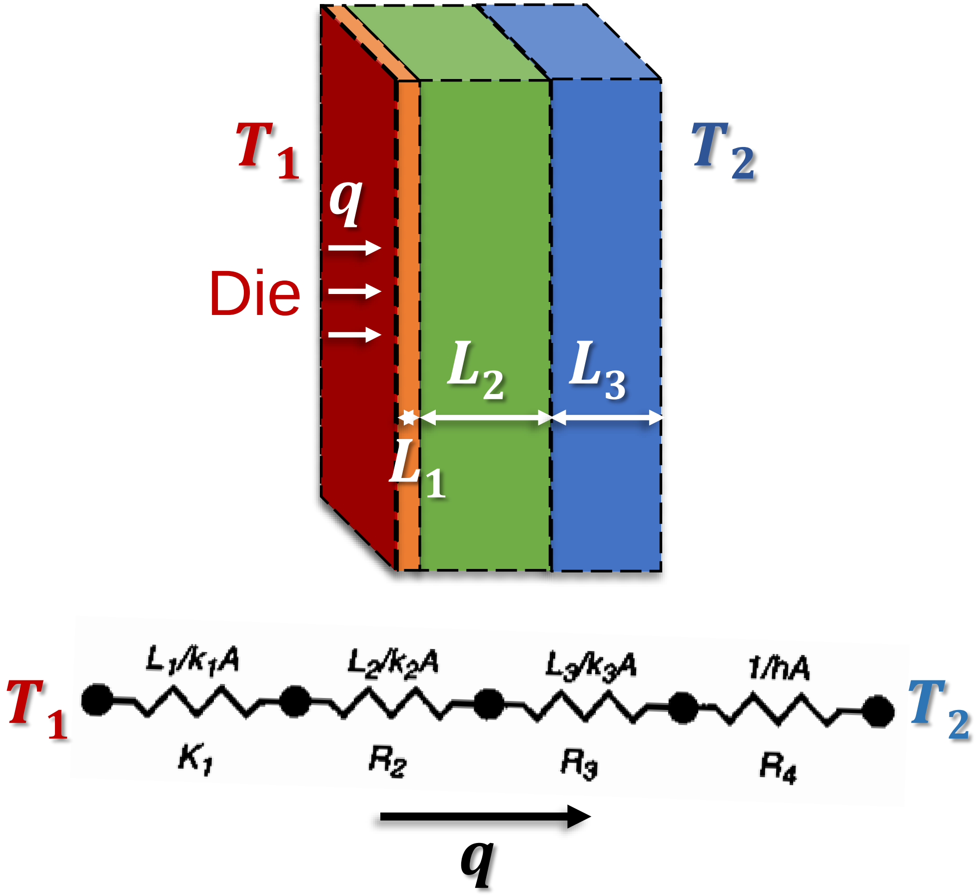
$$R_{th,cond} = \frac{L}{kA}$$

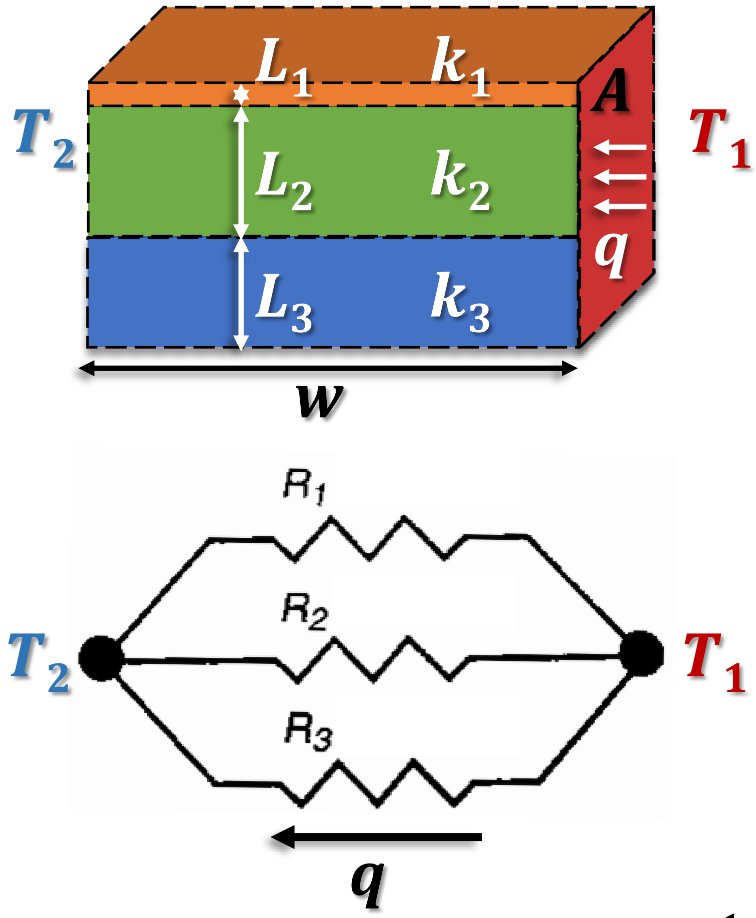
- Find T_j
- $R_{th,j-c} = R_1 + R_2 + R_3$
- $R_{th,j-c} = 0.02\ \mathrm{K/W} + 0.03\ \mathrm{K/W}$
  $+ 43\frac{\mathrm{K}}{\mathrm{W}} = \mathbf{43.05\ K/W}$
- $T_j = qR_{th,j-c} + T_c$
- $T_j = (1\mathrm{W})\left(43\frac{°\mathrm{C}}{\mathrm{W}}\right) + 50°\mathrm{C} = \mathbf{93°C}$

➢ Conduction through the EMC is the greatest contributor to the $R_{th,j-c}$



Thermal Resistances in Series and Parallel

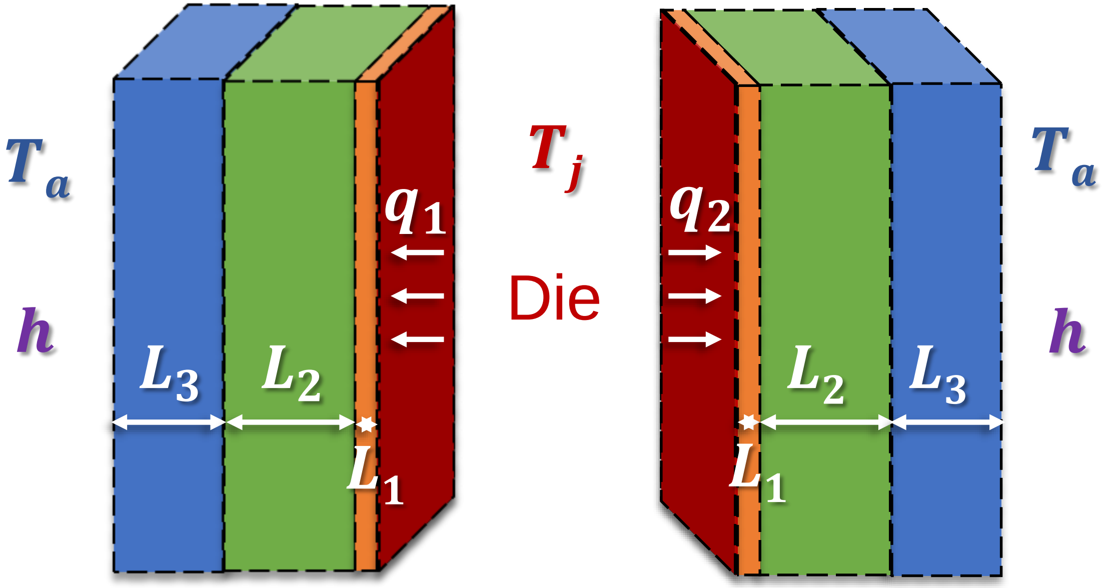


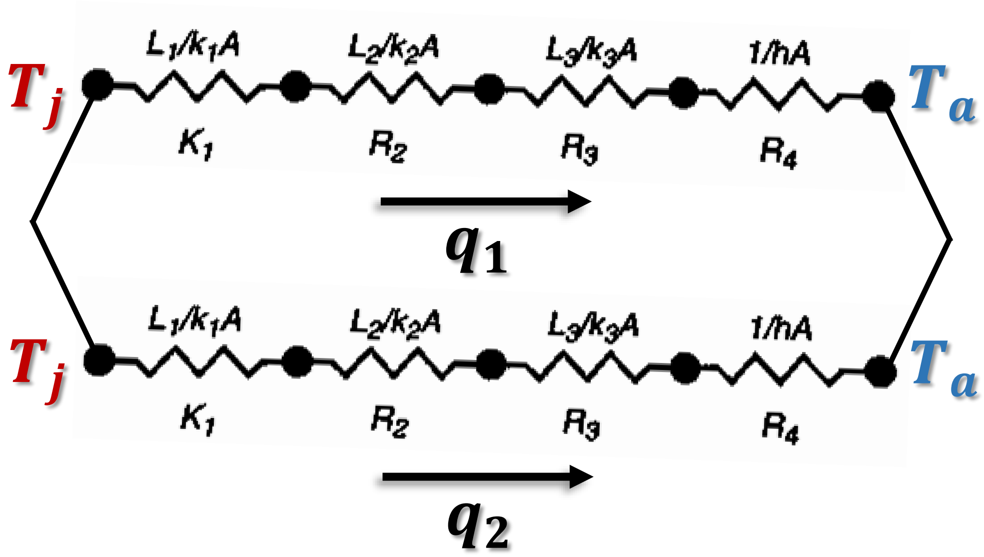


$$R_{th,1-2} = R_1 + R_2 + R_3 + R_4$$

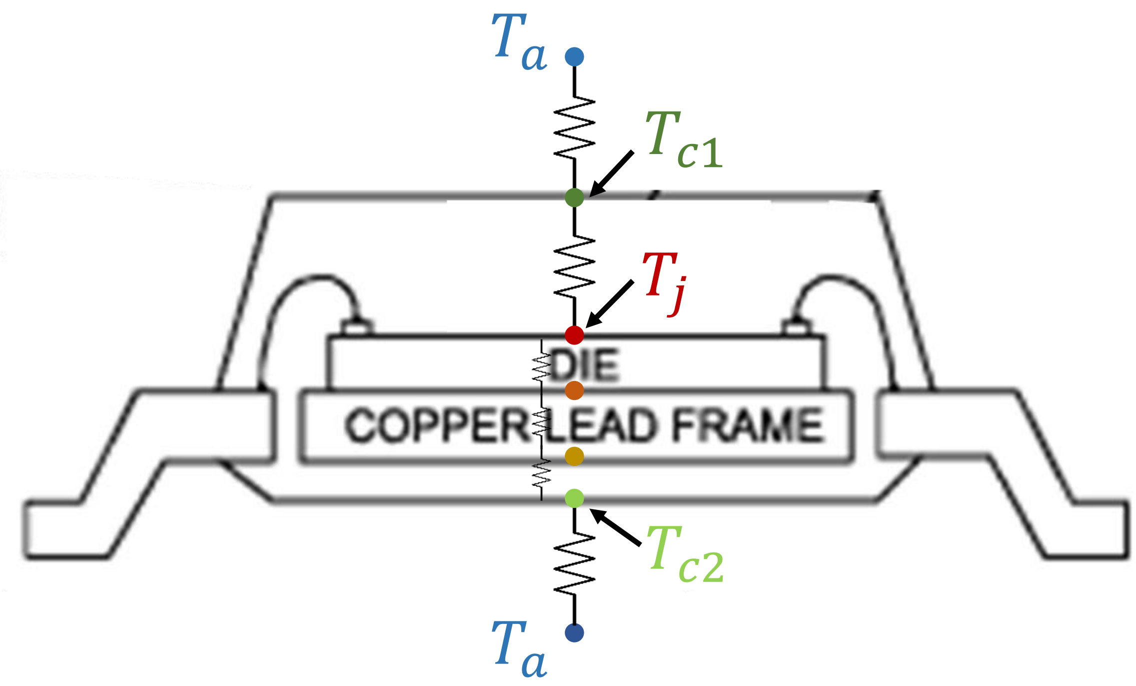
$$R_{th,1-2} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)^{-1}$$

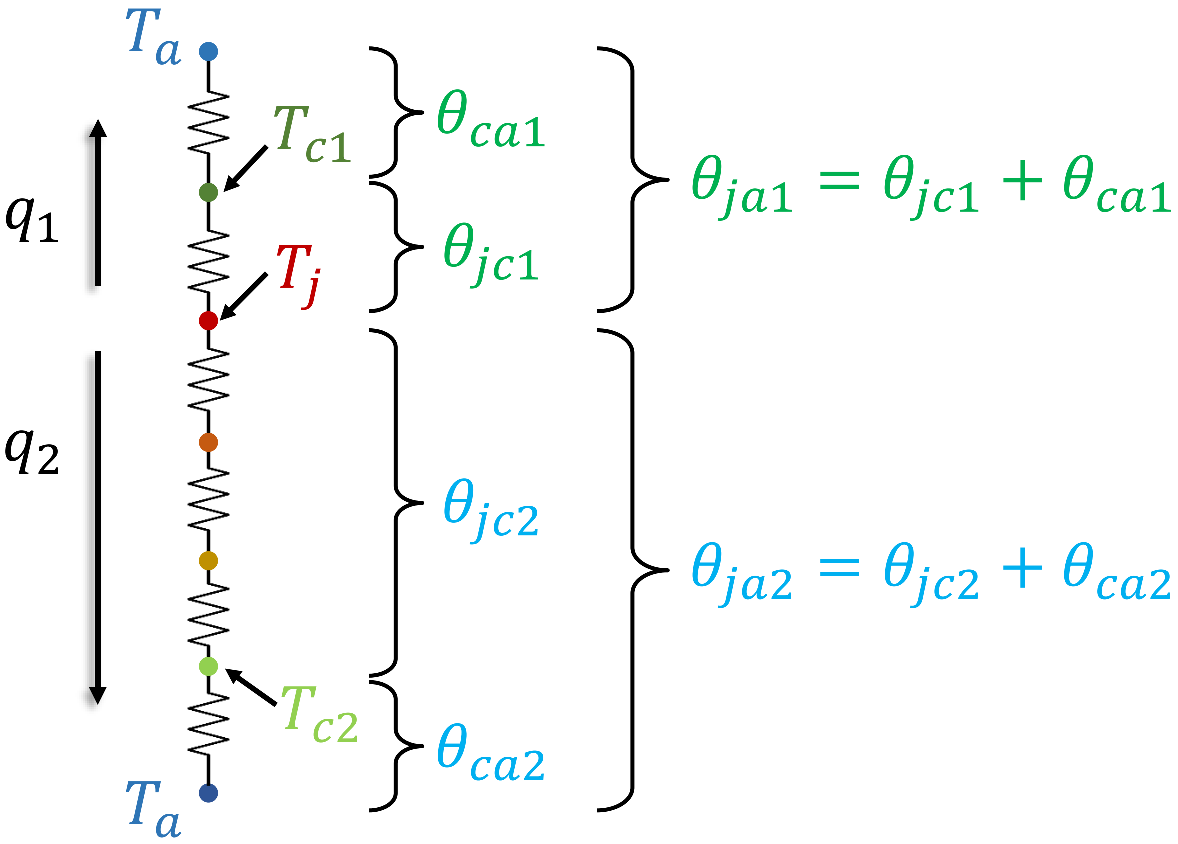
Thermal Resistances in Series and Parallel





Thermal Resistances in Series and Parallel





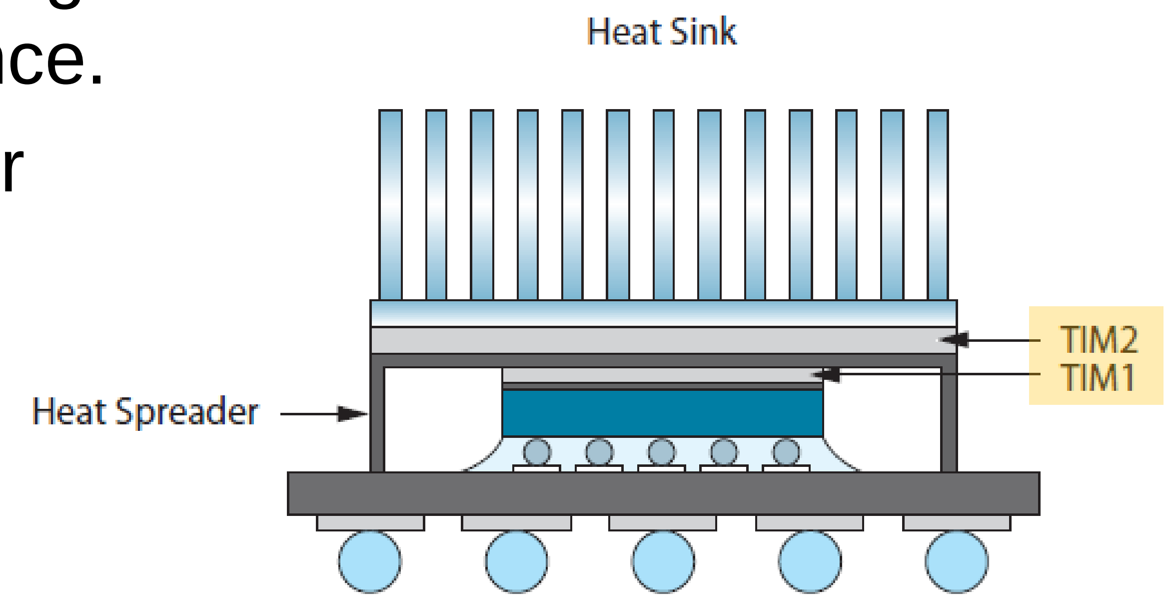
Total junction-to-ambient thermal resistance:

$$\theta_{ja} = \frac{\theta_{ja1}\theta_{ja2}}{\theta_{ja1} + \theta_{ja2}} = \frac{(\theta_{jc1} + \theta_{ca1})(\theta_{jc2} + \theta_{ca2})}{(\theta_{jc1} + \theta_{ca1}) + (\theta_{jc2} + \theta_{ca2})}$$

Contact Resistance

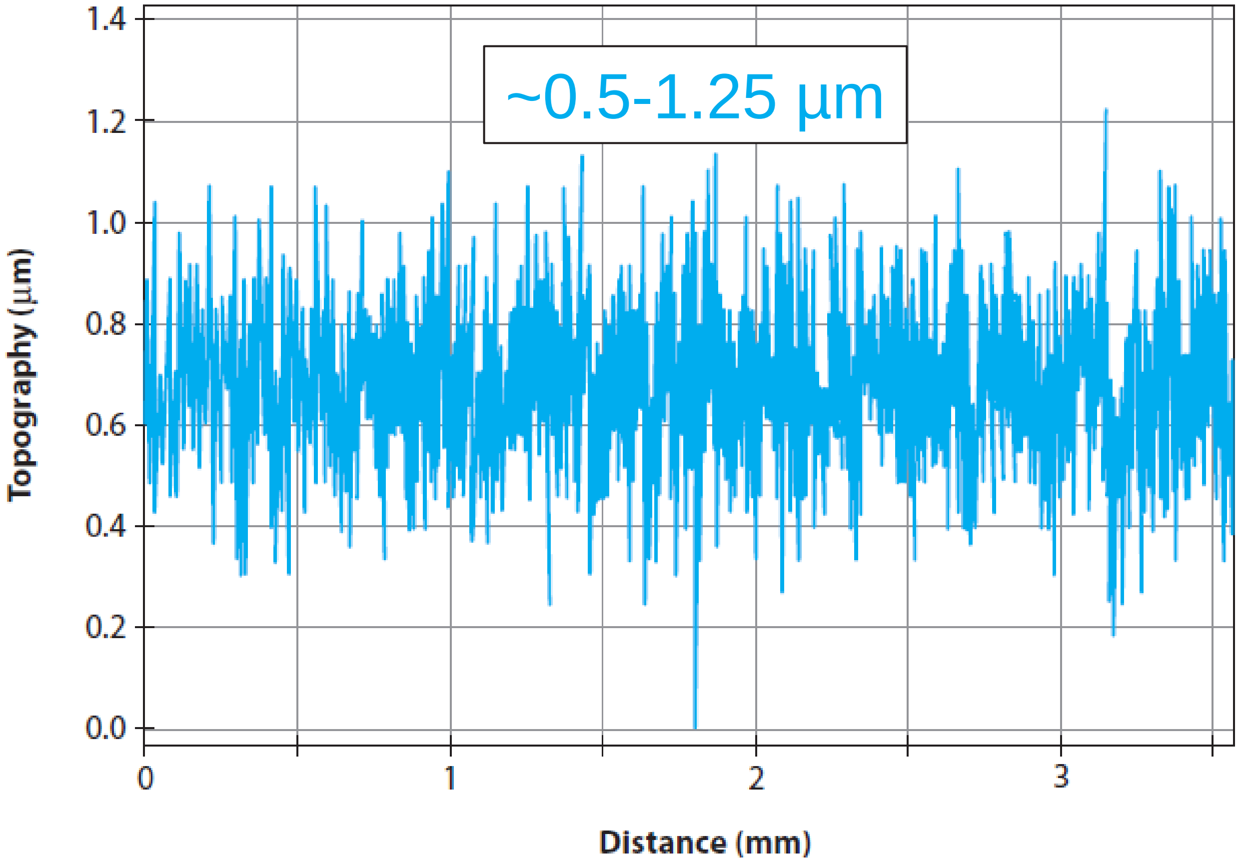
- **Contact resistance** is the thermal resistance that occurs between two adjacent solid bodies as a result of surface imperfections and non-uniformities.

- **Thermal interface materials (TIM)** are used to fill the interface between mating surfaces to decrease contact resistance.
  - Higher thermal conductivity than air
  - Examples of interfaces include: between the chip and package lid/heat spreader, or between the heat spreader and the heat sink

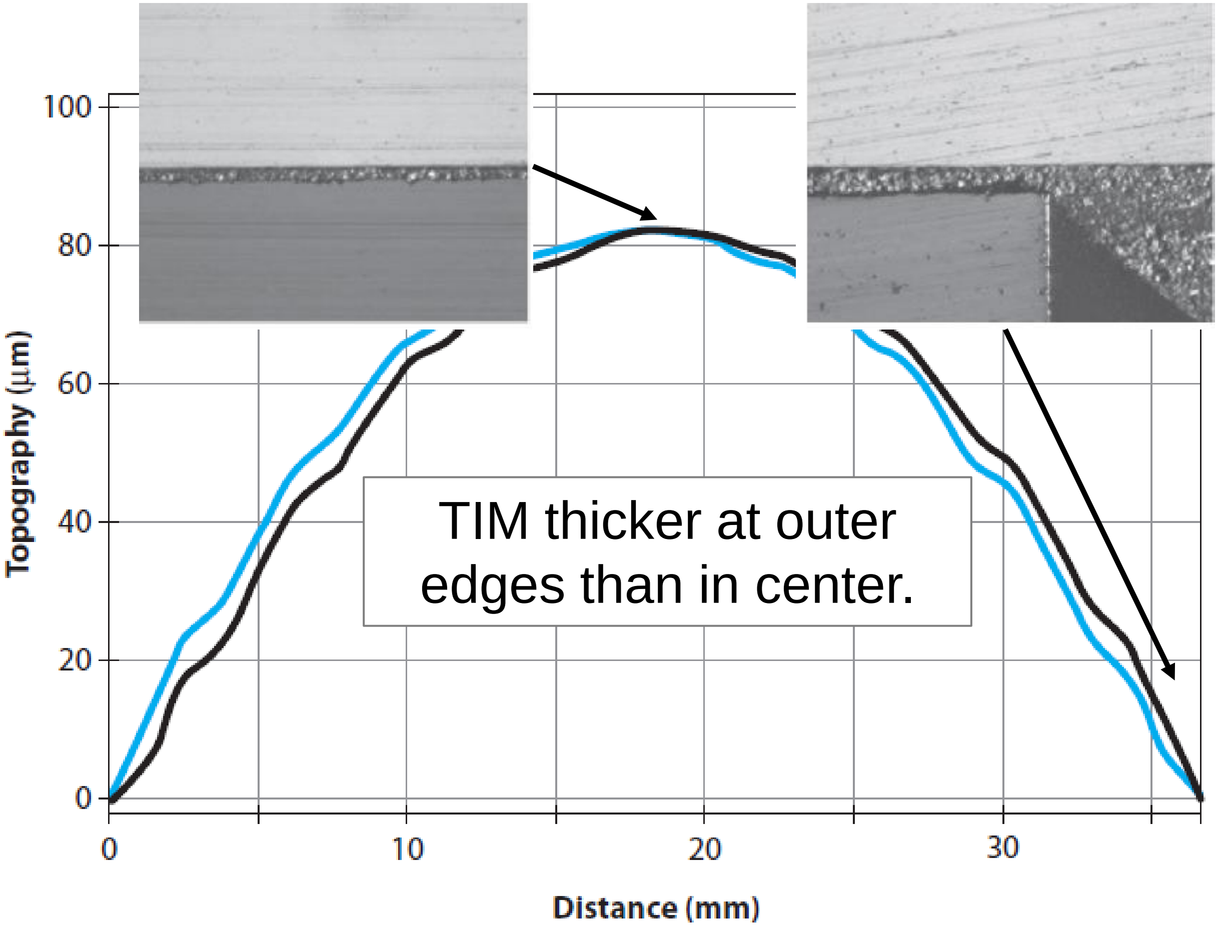


Surface Roughness and Flatness

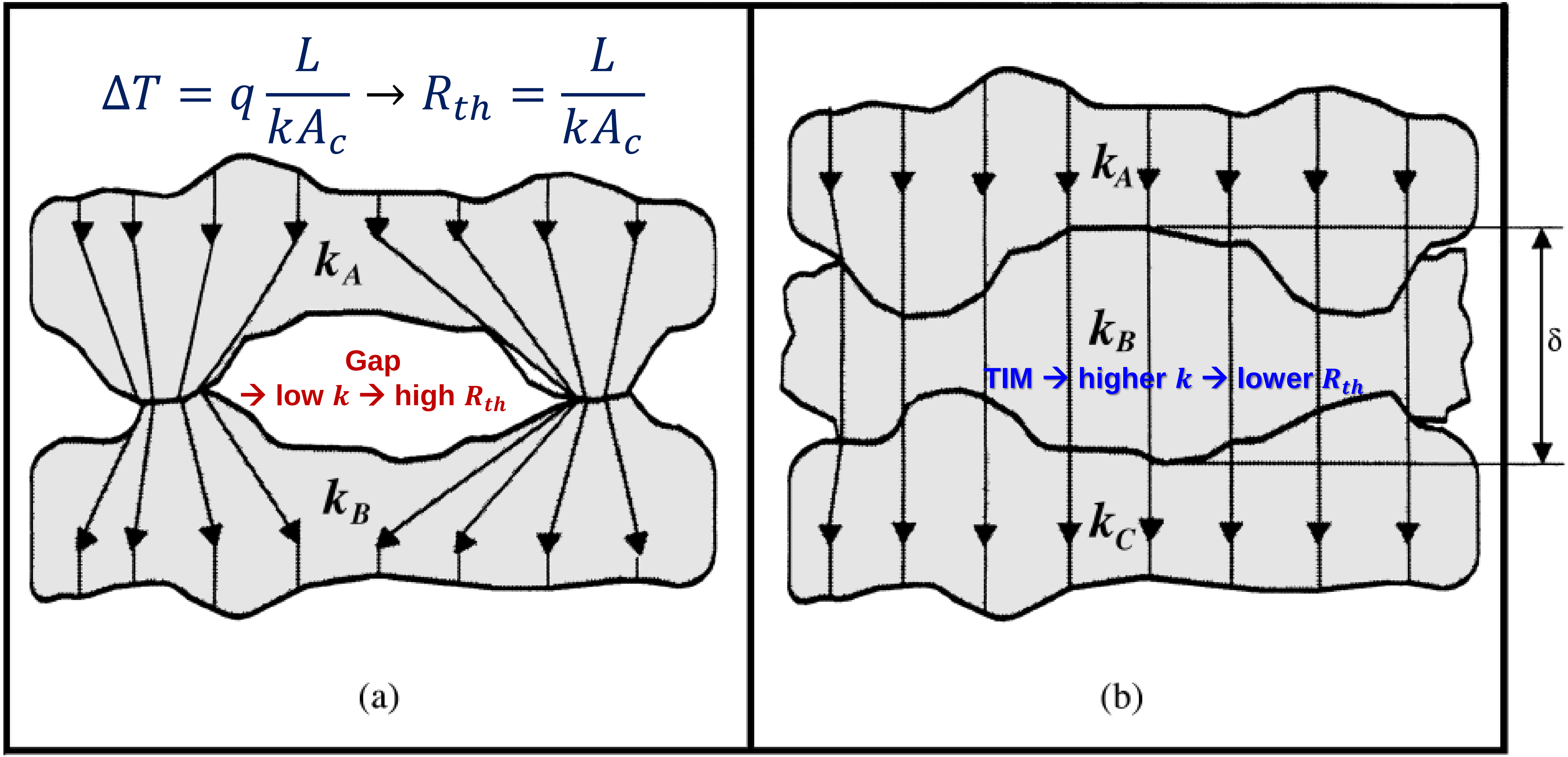
Copper Lid Surface Roughness



Chip Flatness Along Diagonal Axes

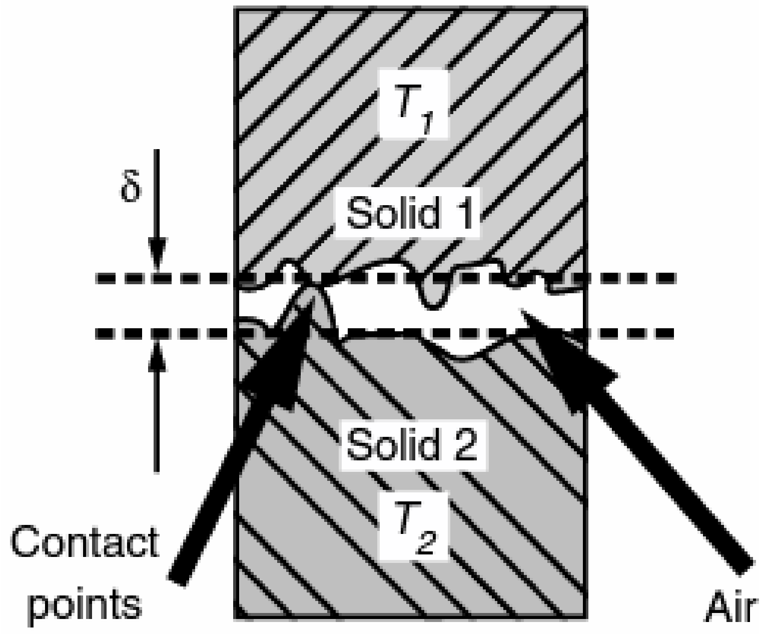


Interface Thermal Resistance



Example: Interface Thermal Resistance

Consider a lightly loaded, 10 cm^2 alumina-to-silicon interface with an actual contact percentage of 0.5 % and δ = 25 µm.



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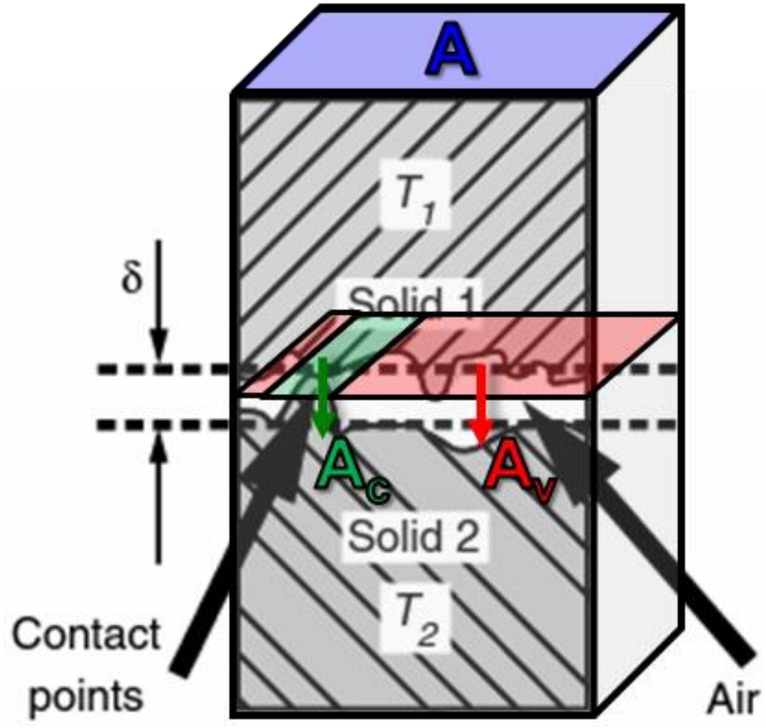

A = Total area of interface = 10 cm^2

A_c = Contact area between solid 1 and solid 2

= 0.005 · A = 0.05 cm^2

A_v = Void area between solid 1 and solid 2

= A – 0.005 · A = 10 cm^2 – 0.05 cm^2 = 9.95 cm^2

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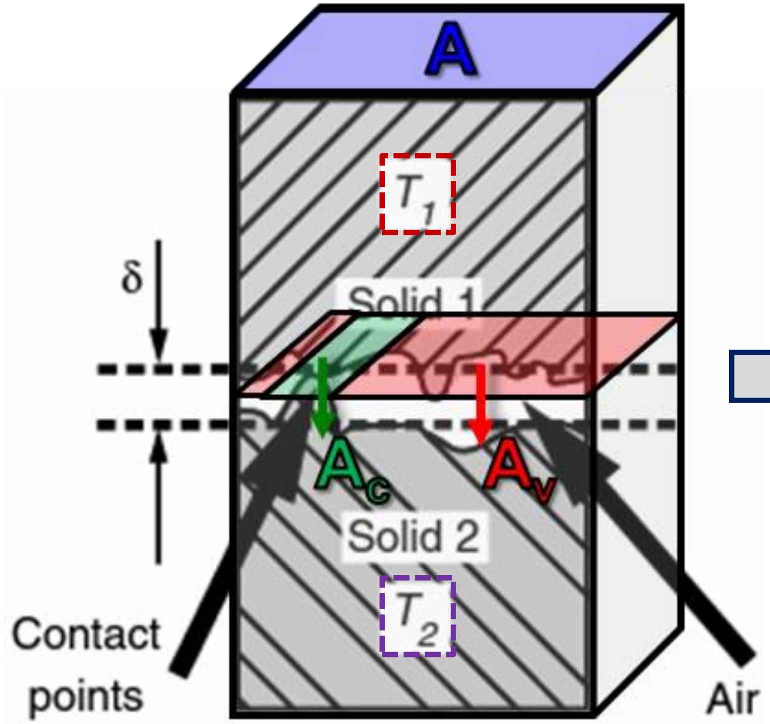
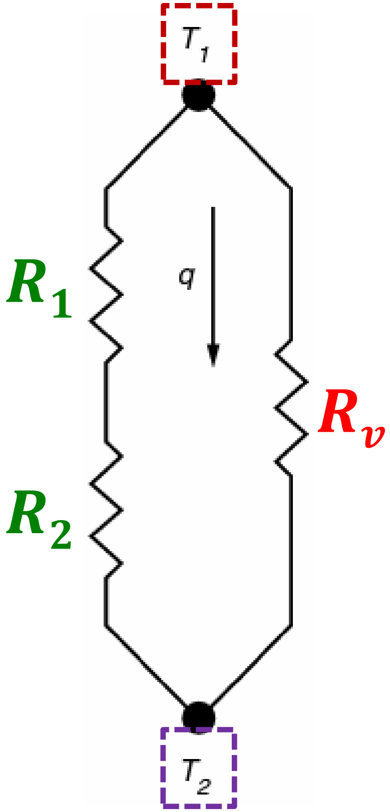




$$R_1 = \frac{L}{k_1 A_c} = \frac{\delta}{2k_1 A_c}$$

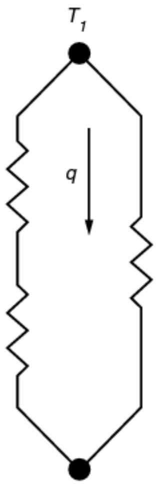
$$R_2 = \frac{L}{k_2 A_c} = \frac{\delta}{2k_2 A_c}$$

$$R_v = \frac{L}{k_f A_v} = \frac{\delta}{k_f A_v}$$

$$\boldsymbol{R_{int}} = (R_1 + R_2) \parallel R_v = \left(\frac{1}{R_1 + R_2} + \frac{1}{R_v}\right)^{-1}$$

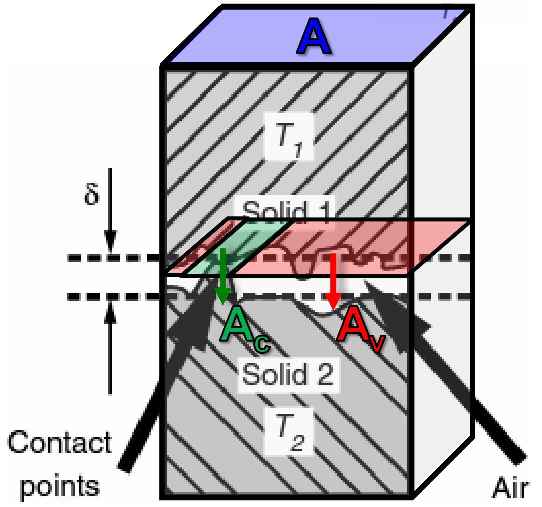
k_1= thermal conductivity of solid 1
k_2= thermal conductivity of solid 2
k_f= thermal conductivity of fluid in void
A_c= contact area between solid 1 and 2
A_v= area of void
δ = length of interface

Example: Interface Thermal Resistance



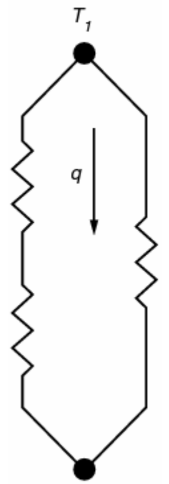
Consider a lightly loaded, 10 cm^2 alumina-to-silicon interface with an actual contact percentage of 0.5 % and δ = 25 µm.

If the interfacial gaps are filled with air, calculate the heat flow for a 5 °C temperature difference across the interface.



- $R = \frac{L}{kA}$
- $q = \left(\frac{kA}{L}\right)\Delta T = \left(\frac{1}{R}\right)\Delta T$
- $q = \left(\frac{1}{R_{int}}\right)\Delta T = \Delta T\left(\frac{1}{R_1+R_2} + \frac{1}{R_v}\right) = \Delta T\left(\frac{1}{\frac{\delta}{2k_1A_c}+\frac{\delta}{2k_2A_c}} + \frac{1}{\frac{\delta}{k_fA_v}}\right)$

Example: Interface Thermal Resistance



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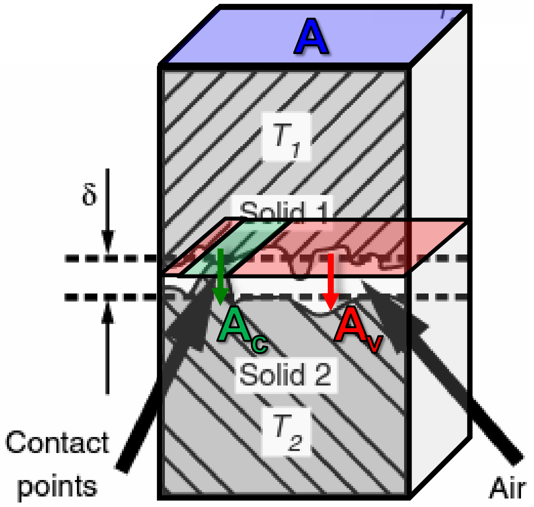


$$q = \frac{T_1 - T_2}{\delta/(2k_1A_c) + \delta/(2k_2A_c)} + \frac{T_1 - T_2}{\delta/(k_fA_v)}$$

$$q = \frac{5}{[25 \times 10^{-6}/(2 \times 22 \times 0.05 \times 10^{-4})] + [25 \times 10^{-6}/(2 \times 120 \times \underbrace{0.05 \times 10^{-4}}_{A_c = (0.005)A})]} + \frac{5}{[25 \times 10^{-6}/(0.0261 \times \underbrace{9.95 \times 10^{-4}}_{A_v = A - A_c})]}$$

$$= \frac{5}{0.116 + 0.021} + \frac{5}{0.963}$$

$$= 42.4 \text{ W}$$

$k_1 = k_{Al2O3}$ = 22 W/mK

$k_2 = k_{Si}$ = 120 W/mK

$k_f = k_{air}$ = 0.026 W/mK

Thermal Interface Materials

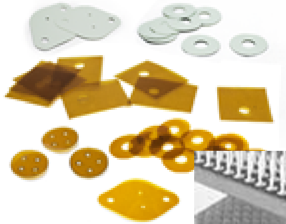
Material	Thermal Conductivity (W/mK)	Ratio
Air	0.024	1
Epoxy (dielectric)	0.23	9.6
Epoxy (conductive)	0.35	14.6
Polyimide	0.33	13.8
FR4	0.30	12.5
Water	0.59	24.6
Thermal grease	1.10	46
Alumina	22.0	916
Aluminum	150	6250
Silicon	120	5000
Copper	390	16,250
Gold	300	12,500
Diamond	2000	83,330

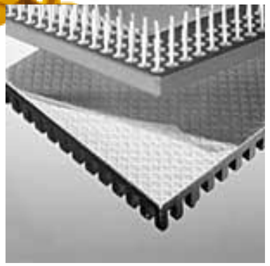
Electrically NON-Isolating

Thermal Greases
Sil-Free™
Ther-O-Link
Ultrastick
Thermalcote™

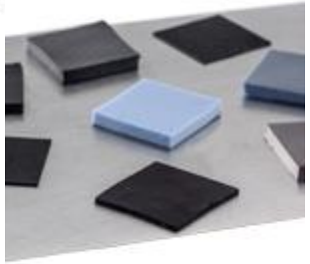
Double Sided Tapes
Ther-A-Grip 1070/T405R
Ther-A-Grip 1090/T412
T410R/T411

Thin Films
Kon Dux
Grafoil™





Electrically Isolating



Gap Fillers
A-Pli™

Double Sided Tapes
Ther-A-Grip 1050 T404

Pads
In-Sil-8
T-gard™500
Thermalsil™ III

Insulating Films
Thermalfilm™
Thermalfilm™MT

Thermal Adhesives
Ther-O-Bond 1500
Ther-O-Bond 1600
Ther-O-Bond 2000
Thermalbond™

https://www.boydcorp.com/thermal/thermal-interface-materials.html