# Lecture 12

# Thermal Design

## *Heat Spreading & Thermal Vias*

March 4, 2025

# Reminders and Announcements

- Homework #2 solutions posted to Canvas
- Homework #3 due Thursday, March $6^{th}$, by 11:59pm
- Office Hours: Wednesday 3:30pm-5:00pm
- Please put the course number in the subject line in emails to the instructor and TA (this helps us filter our inboxes so we don’t miss your messages)
- Uploaded “ANSYS Q3D – Reduce Matrix Feature” to Canvas Course Gallery, which shows how to simulate different nets in series and parallel configurations

# Midterm: Thursday, March 20th, 5:00pm-6:15pm

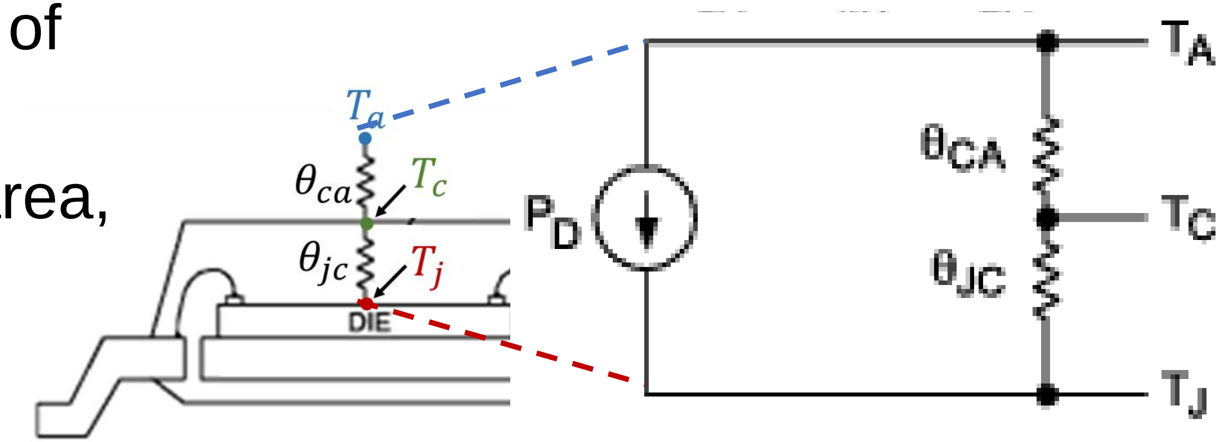
- If you are located in Blacksburg, then you should take the exam in-person in TORG 1050, even if you are enrolled in the virtual section of the course
- If you are enrolled in the *virtual campus*, please email me by March 5th indicating if you will take the exam virtually or in-person in Arlington or Blacksburg
- Will cover the topics in lectures 1-6 (packaging overview and electrical design) and 9-13 (transmission lines and thermal design)
- The lecture on March 18th will be a review session → come ready with questions or topics you would like to cover
- You will <u>not</u> be asked to do any simulations for the midterm
- The problems will be a mix of conceptual short response and calculation problems
- Things to bring to the exam: writing utensils & *non-programmable* calculator
- An equation/reference sheet and extra paper will be provided by the proctor
- The reference sheet will be uploaded to Canvas next week; you do <u>not</u> need to print out the reference sheet

# Package Thermal Resistance

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

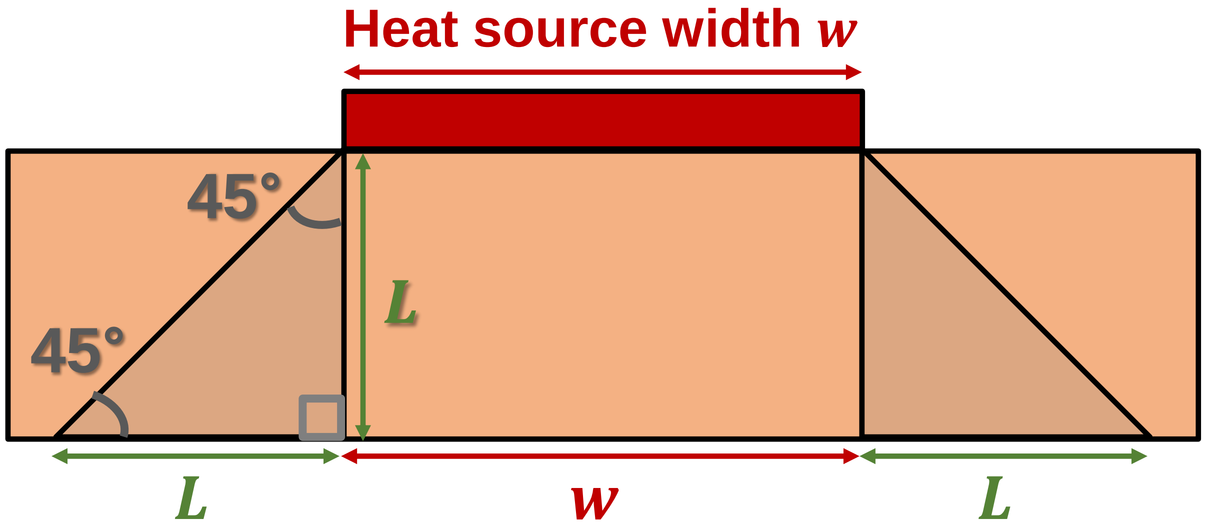
$$\boxed{\theta_{ja} = \theta_{jc} + \theta_{ca}}$$

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

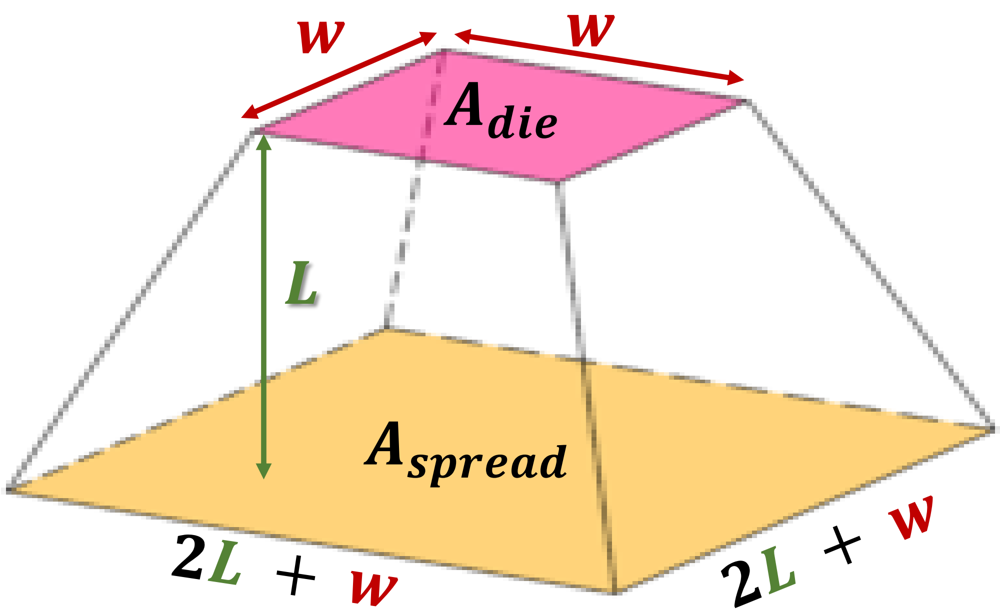


# Heat Spreading Approximation

- The effective area $A_{eff}$ for the heat flow through this layer can be approximated by averaging the heat source area $A_{die}$ and the base area $A_{spread}$:

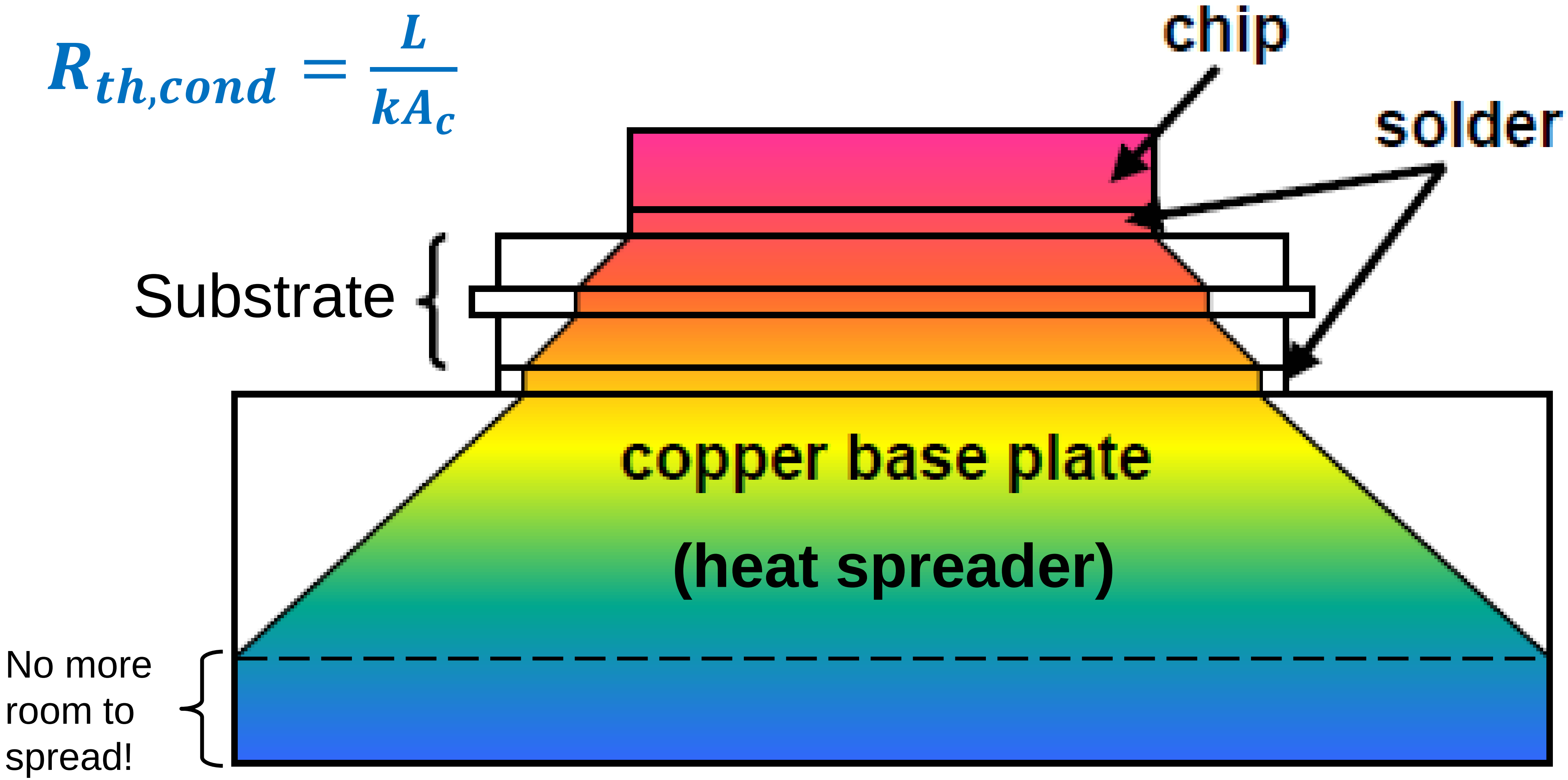



$$\boldsymbol{A_{eff} = (A_{spread} + A_{die}) / 2}$$
$$\boldsymbol{= [(2L + w)(2L + w) + (w \times w)] / 2}$$



# Lateral Heat Spreading

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

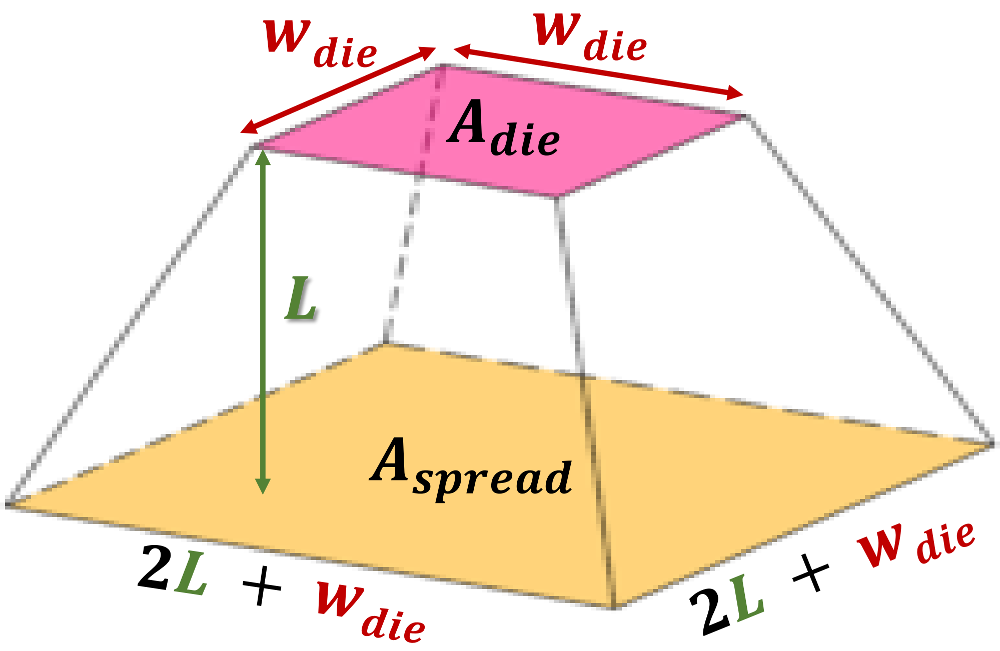



➢ Choose base plate width & thickness such that the base plate width ≈ heat spreading width at the base

# Example: Heat Spreading

Find the thermal resistance of a copper base plate with dimensions of 15 x 15 x 4 mm³. The dimensions of the heat-generating component (die) on top of the base plate are 5 x 5 x 1 mm³. Assume a heat spreading angle of 45°.

- $w_{die}$ = 5 mm
- $A_{die}$ = 5 mm x 5 mm = 25 mm²
- $L_{BP}$ = 4 mm
- $w_{BP}$ = 15 mm




Check that $w_{spread} \leq w_{BP}$ :

- $w_{spread} = (2L + w_{die})$ = 2(4mm) + 5mm = **11 mm** < 15 mm

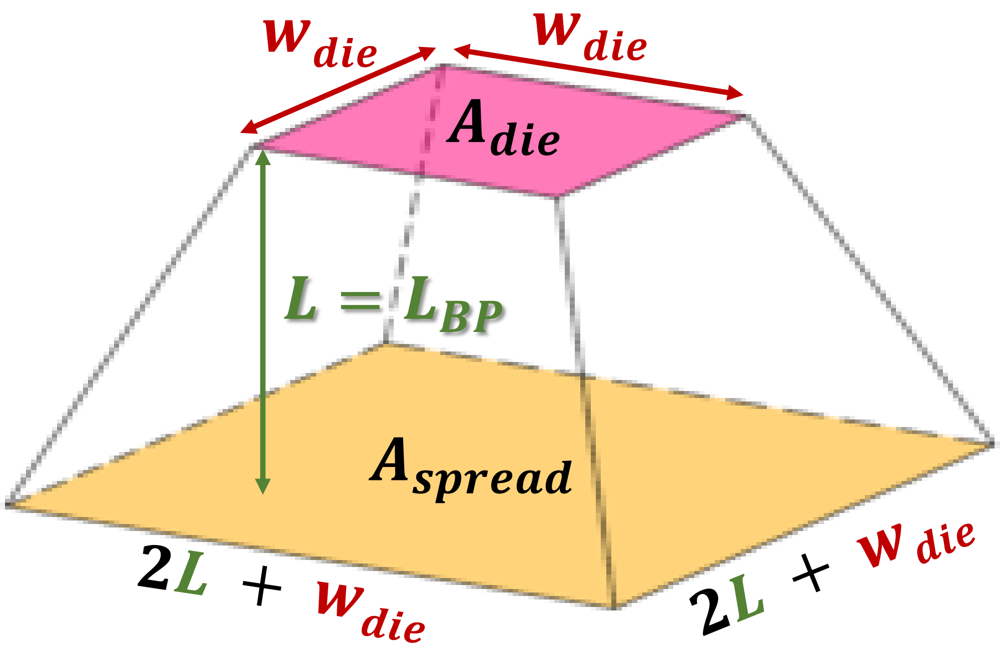
# Example: Heat Spreading

Find the thermal resistance of a copper base plate with dimensions of 15 x 15 x 4 mm$^3$. The dimensions of the heat-generating component (die) on top of the base plate are 5 x 5 x 1 mm$^3$. Assume a heat spreading angle of 45°.

- $w_{die}$ = 5 mm
- $A_{die}$ = 5 mm x 5 mm = 25 mm$^2$
- $L = L_{BP}$ = 4 mm
- $A_{spread} = (2L_{BP} + w_{die})(2L_{BP} + w_{die})$

$= (2(4\text{mm}) + 5\text{mm})(2(4\text{mm}) + 5\text{mm})$

$=$ **169 mm$^2$**



# Example: Heat Spreading

Find the thermal resistance of a copper base plate with dimensions of 15 x 15 x 4 mm$^3$. The dimensions of the heat-generating component (die) on top of the base plate are 5 x 5 x 1 mm$^3$. Assume a heat spreading angle of 45°.

- $A_{eff} = (A_{spread} + A_{die})$ / 2

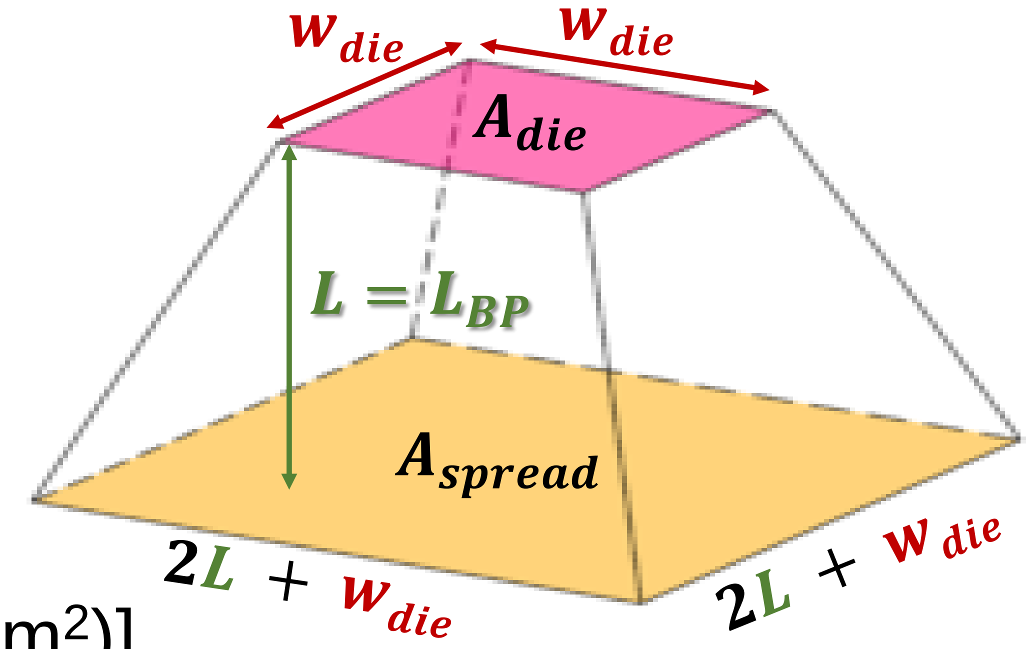
  = (169 mm$^2$ + 25 mm$^2$) / 2

  = 97 mm$^2$ = 0.000097 m$^2$

- $R_{th,BP} = L_{BP}$ / $(k_{BP}\, A_{eff})$

  = 0.004 m / [(390 W/(mK))(9.7e-5 m$^2$)]

  = **0.106 K/W**



# Example: Smaller Base Plate Area

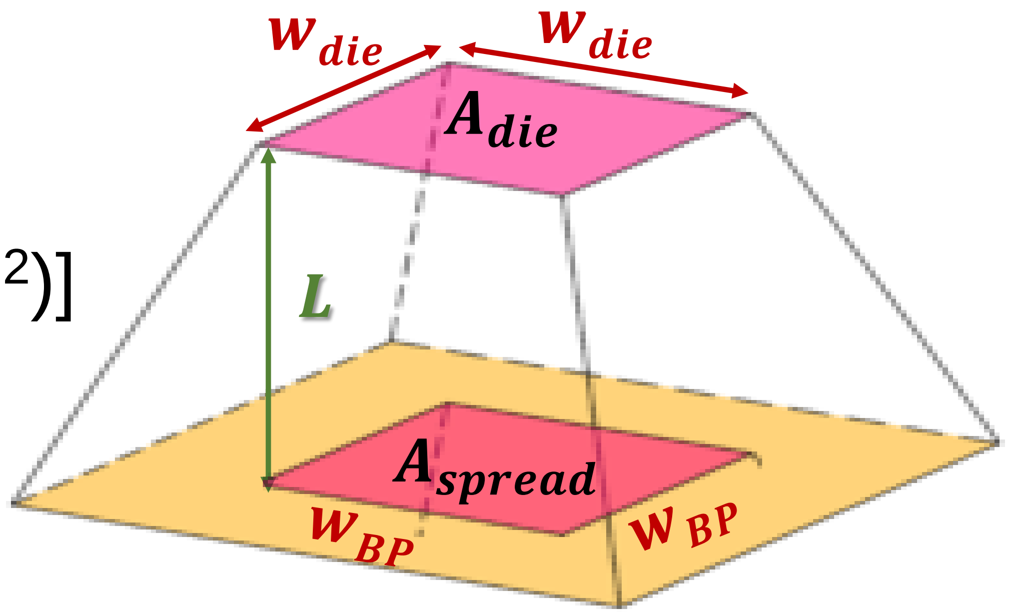
- Silicon die: 5 x 5 x 1 mm
- Copper baseplate: *5* x *5* x 4 mm
- Find the thermal resistance of the base plate.

- $A_{spread} = A_{BP} = A_{die}$

- $R_{th,BP} = \ L_{BP}\ /\ (k_{BP}\ A_{BP})$

  $= 0.004$ m / [(390 W/(mK))(*2.5e-5* m$^2$)]

  $=$ **0.410 K/W**




➢ $R_{th,BP}$ increases by **4x** because there is no room for heat spreading ($A_{BP}$ is smaller)

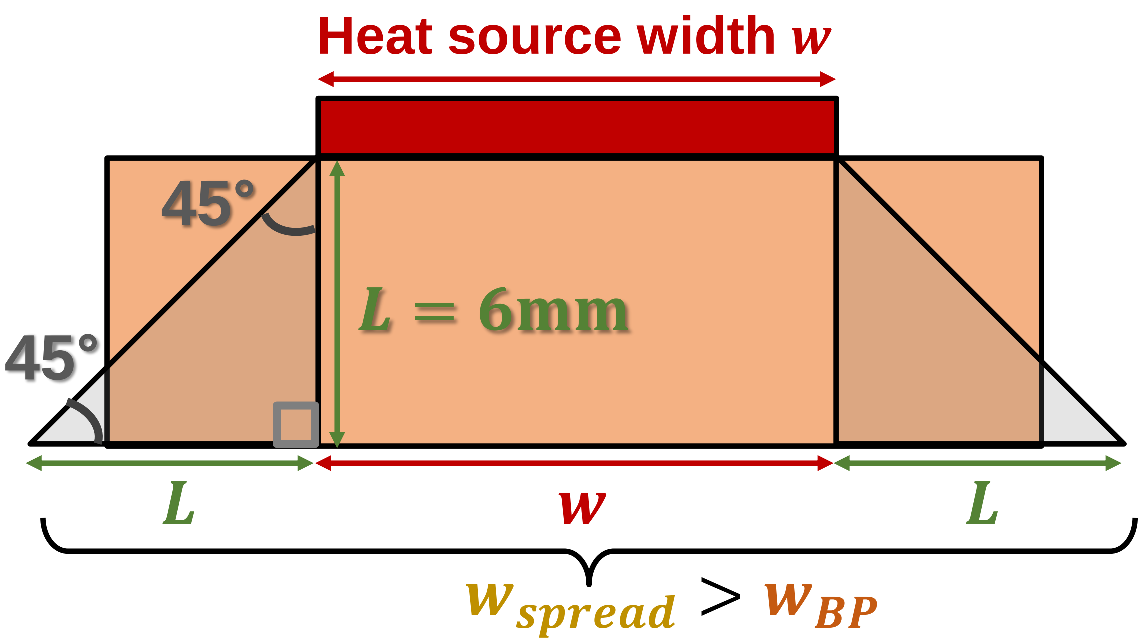
# Example: Thicker Base Plate Area

- Silicon die: 5 x 5 x 1 mm
- Copper baseplate: 15 x 15 x *6* mm

Check that $w_{spread} \leq w_{BP}$ :

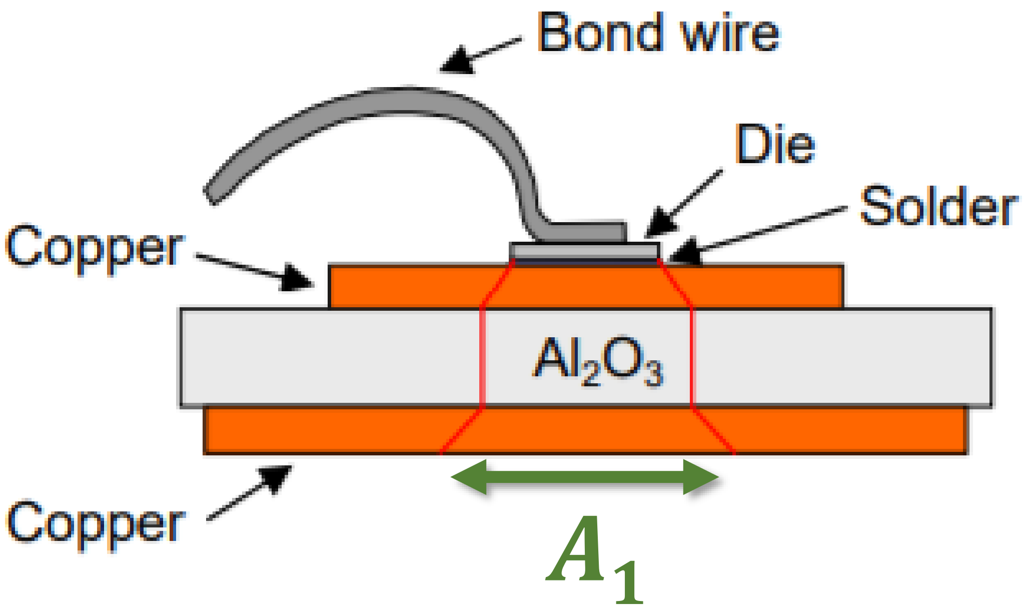
- $w_{spread} = (2L + w_{die})$ = 2(6mm) + 5mm = **17 mm** > 15 mm !

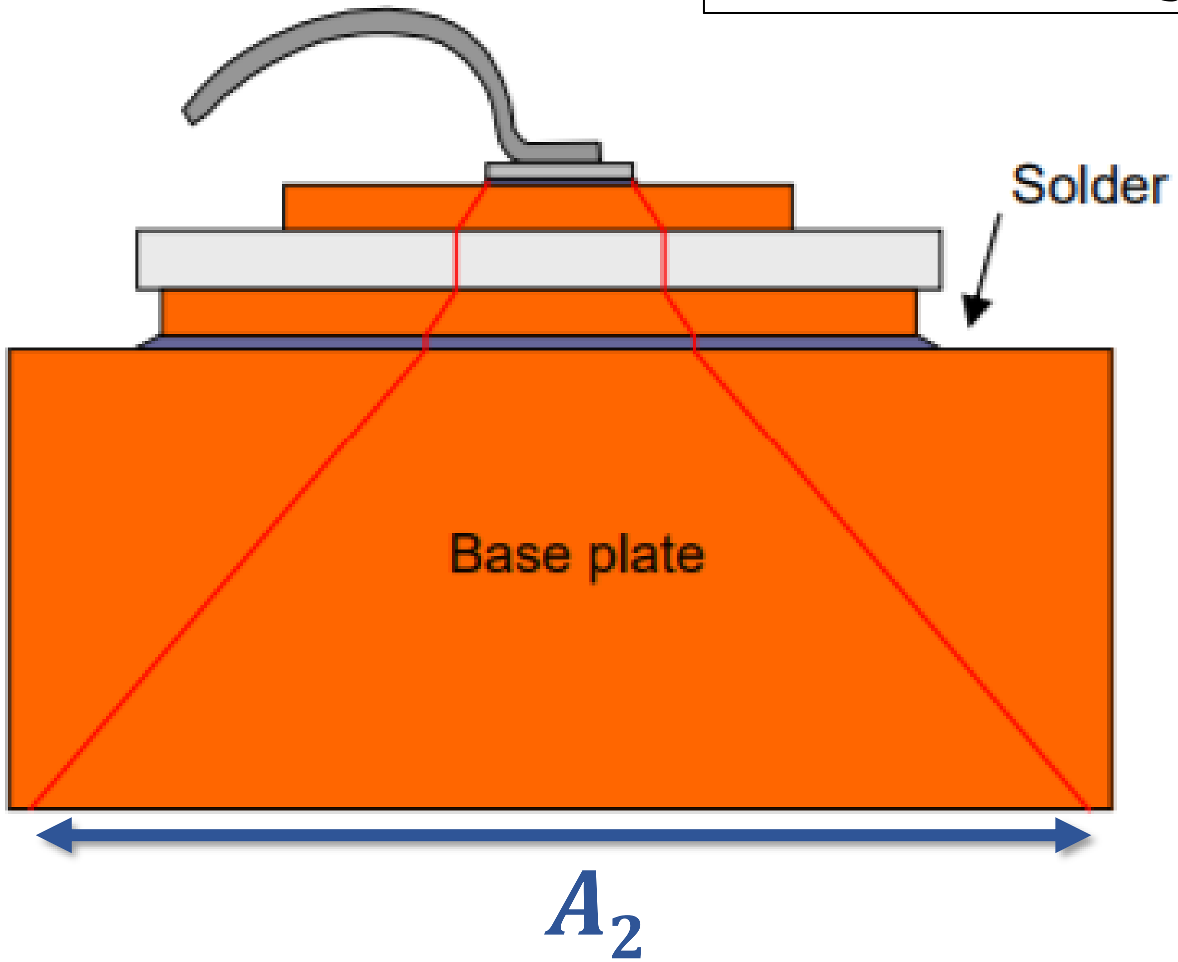
- The bottom of the base plate is not helping with the heat spreading



# Base Plate/Heat Spreader

$$R_{th,conv} = \frac{1}{hA_s}$$




For the same $h$,

$$R_{th,convA_1} > R_{th,convA_2}$$

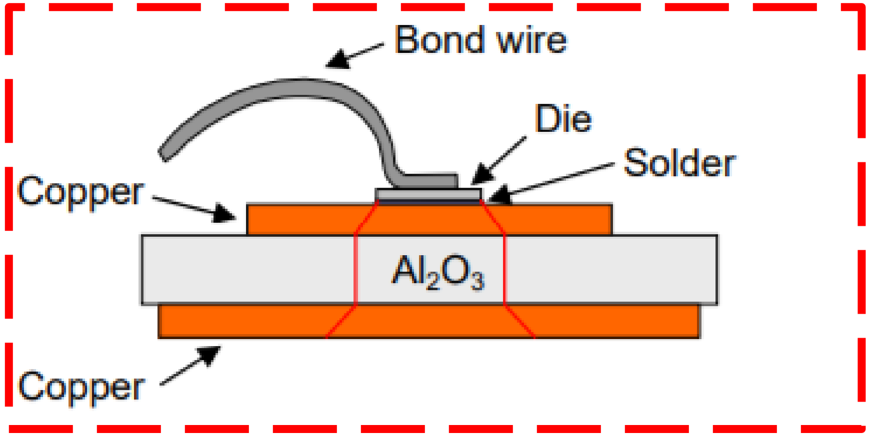
*note: if $h$ is high, then Z heat flow > X,Y heat flow, so heat spreading is low and the baseplate becomes less effective.

https://www.power-mag.com/pdf/feature_pdf/1319729749_Vincotech_Layout_1.pdf

# Impact of Base Plate/Heat Spreader

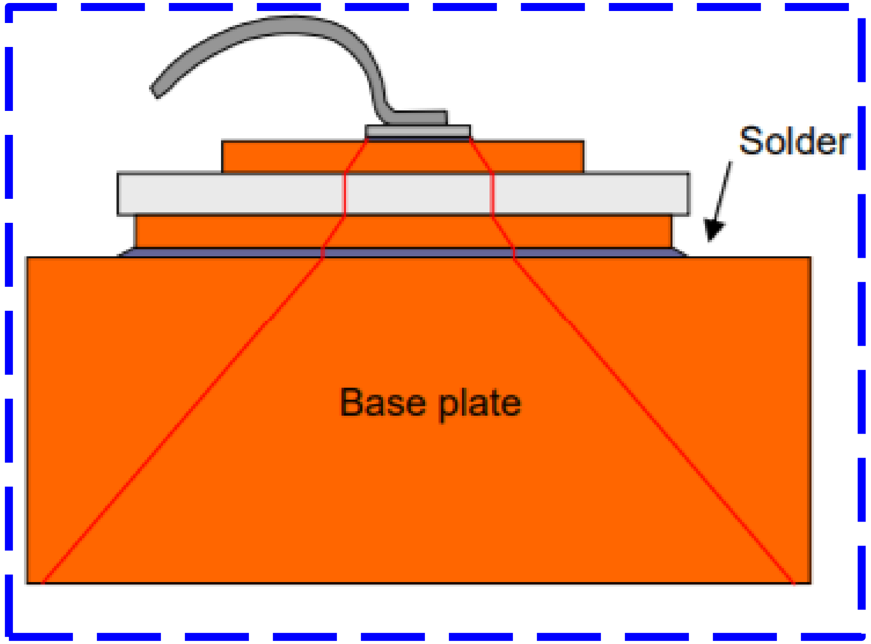
## Thermal Conductivities

| Part | DBC module | | Baseplate modules | |
|---|---|---|---|---|
| Die [W/mK] | Silicon [148] | | Silicon [148] | |
| Solder [W/mK] | SnAg [62] | | SnAg [62] | |
| DBC [W/mK] | $Al_2O_3$ [25] | AlN [155] | $Al_2O_3$ [25] | AlN [155] |
| Solder [W/mK] | | | SnAg [62] | |
| Baseplate [W/mK] | | | Cu [401] | AlSiC [180] |




## Coefficients of Thermal Expansion (CTE)

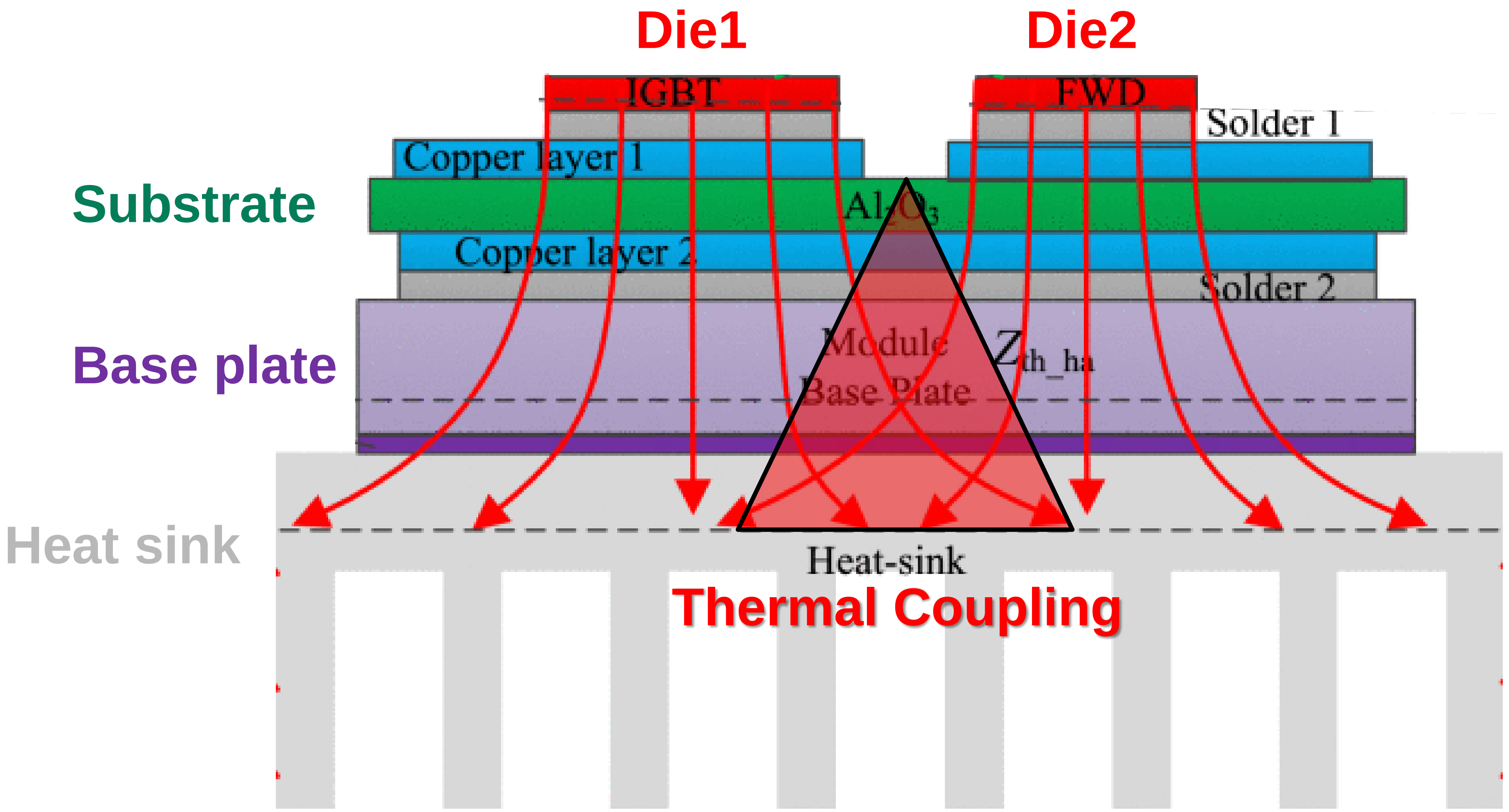
| Part | DBC module | | Baseplate modules | |
|---|---|---|---|---|
| Die [$10^{-6}$/K] | Silicon [2.8] | | Silicon [2.8] | |
| Solder [$10^{-6}$/K] | SnAg [22.1] | | SnAg [22.1] | |
| DBC [$10^{-6}$/K] | $Al_2O_3$ [8.2] | AlN [4.5] | $Al_2O_3$ [8.2] | AlN [4.5] |
| Solder [$10^{-6}$/K] | | | SnAg [22.1] | |
| Baseplate [$10^{-6}$/K] | | | Cu [16.5] | AlSiC [8.4] |




***Reliability trade-off: baseplate reduces $T_j$, but increases CTE mismatch***

https://www.power-mag.com/pdf/feature_pdf/1319729749_Vincotech_Layout_1.pdf

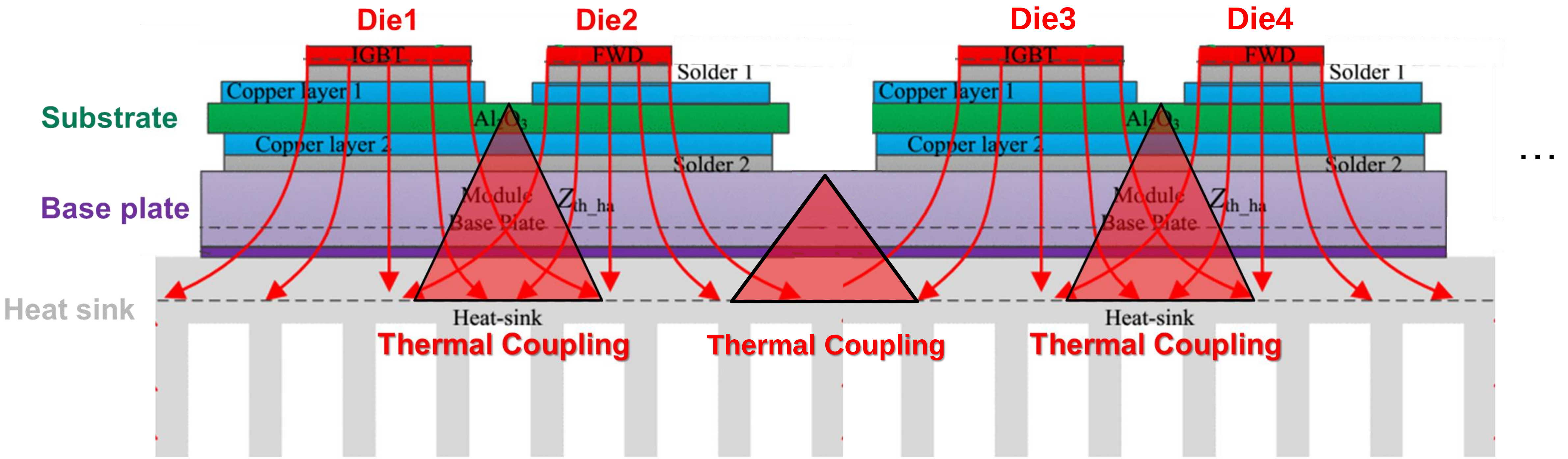
# Heat Spreading in MCM = Thermal Coupling: Common Substrate




https://ieeexplore.ieee.org/abstract/document/7581086

MCM = Multi-Chip Module

# Heat Spreading in MCM = Thermal Coupling: Common Base Plate

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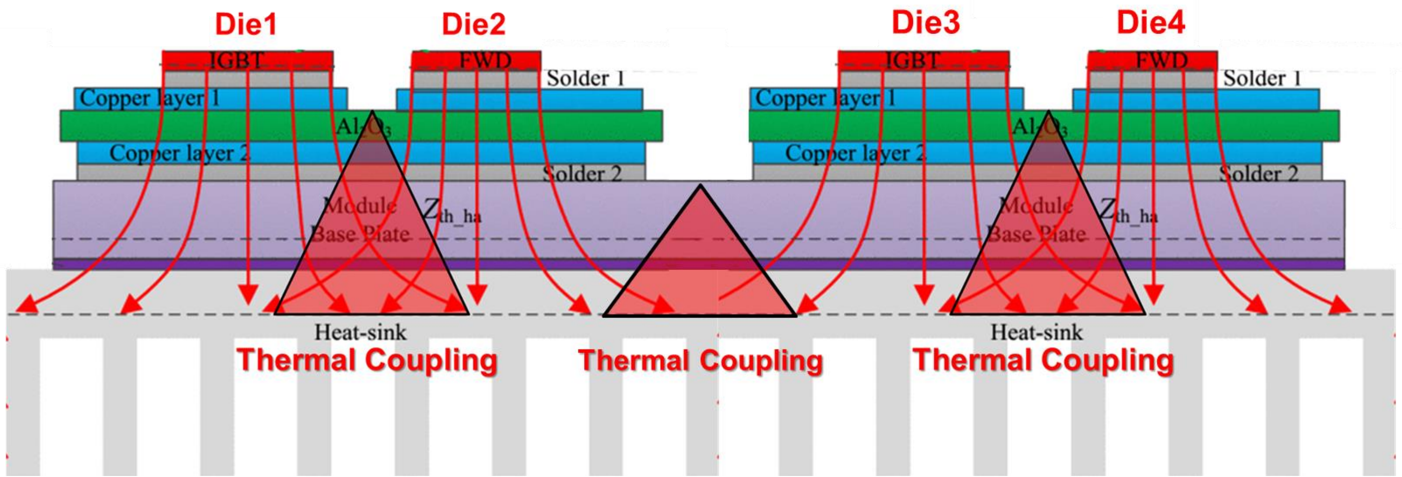
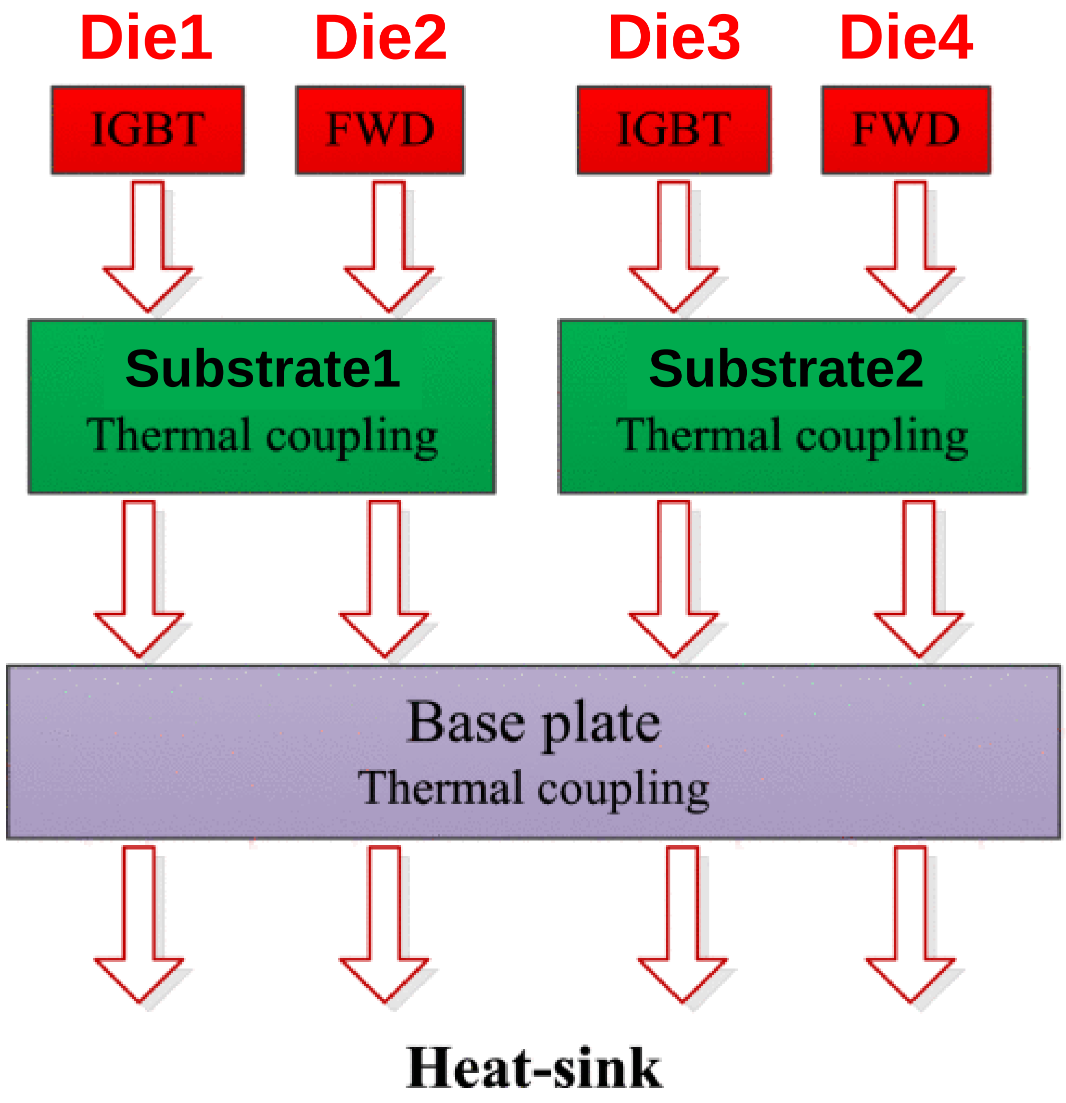
MCM = Multi-Chip Module

# Simplified Heat Flow Path

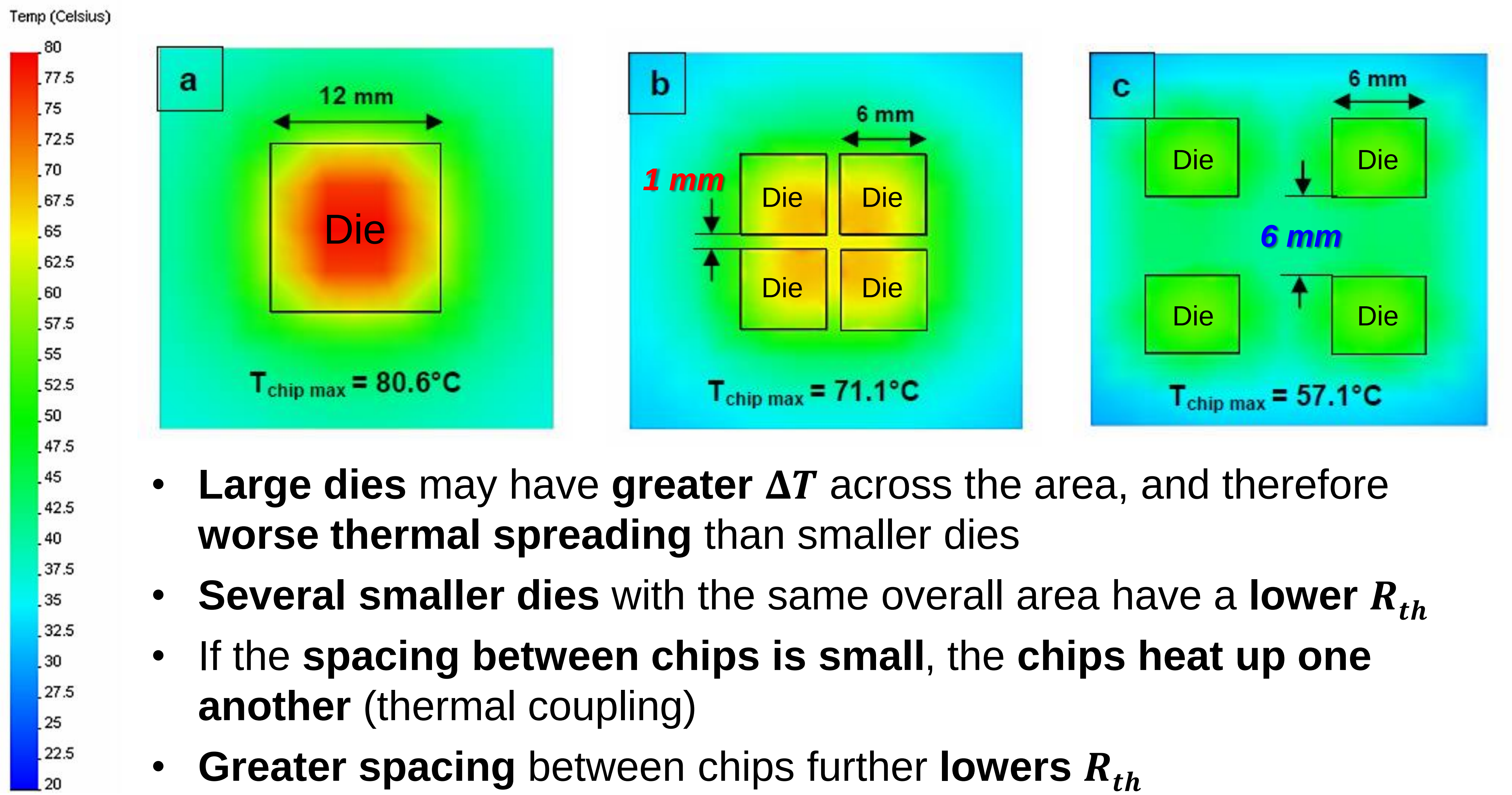



- Thermal coupling at substrate level due to multiple dies
- Thermal coupling at base plate level due to multiple substrates

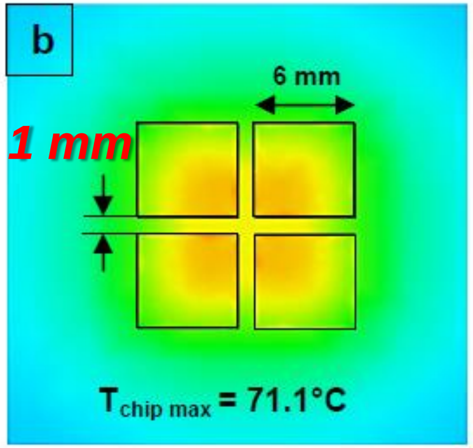
https://ieeexplore.ieee.org/abstract/document/7581086

# Impact of Thermal Coupling

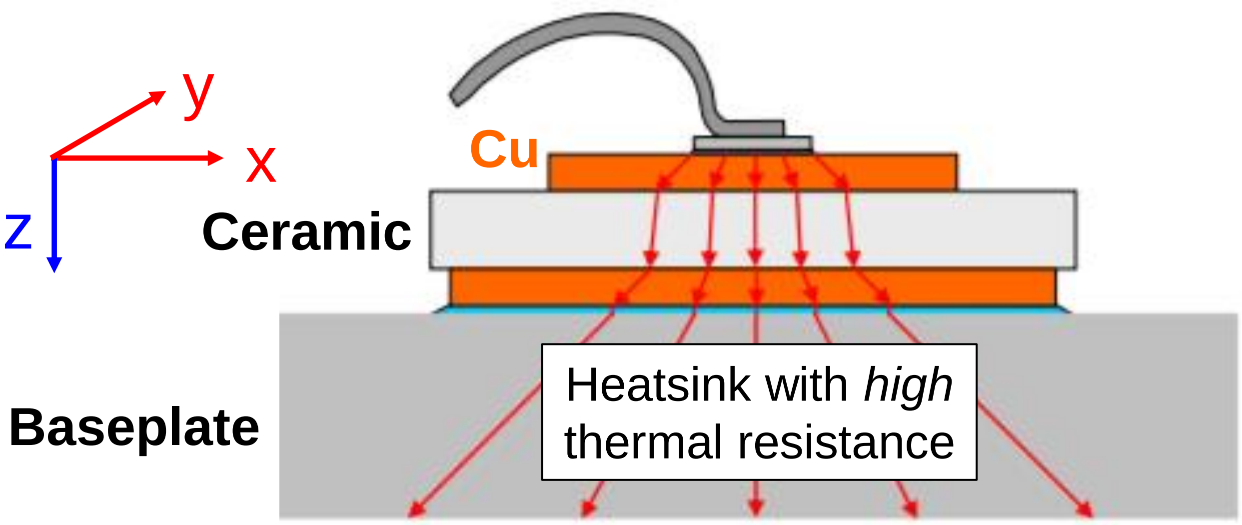


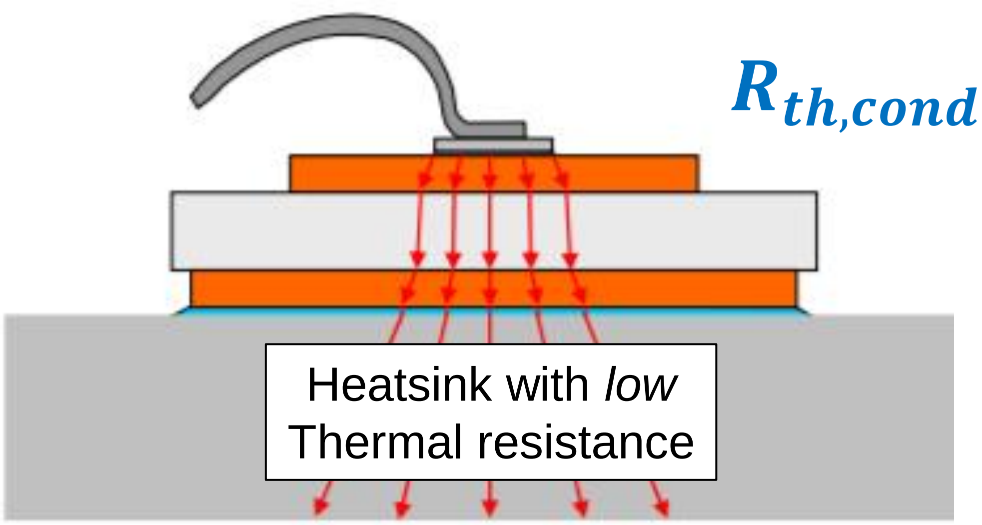

- **Large dies** may have **greater $\Delta T$** across the area, and therefore **worse thermal spreading** than smaller dies
- **Several smaller dies** with the same overall area have a **lower $R_{th}$**
- If the **spacing between chips is small**, the **chips heat up one another** (thermal coupling)
- **Greater spacing** between chips further **lowers $R_{th}$**

# Heat Spreading Summary




- Heat spreading occurs when:
  - Heat flow in X, Y > heat flow in Z
  - $k$ and/or $h$ of downward layer is low (high $R_{th}$, low $q$)
- 45° heat spreading angle is a good approximation for high-$k$ materials
  - Use to find effective heat transfer area through the spreading layer
- Close spacing of chips can increase $T_j$ due to thermal coupling




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

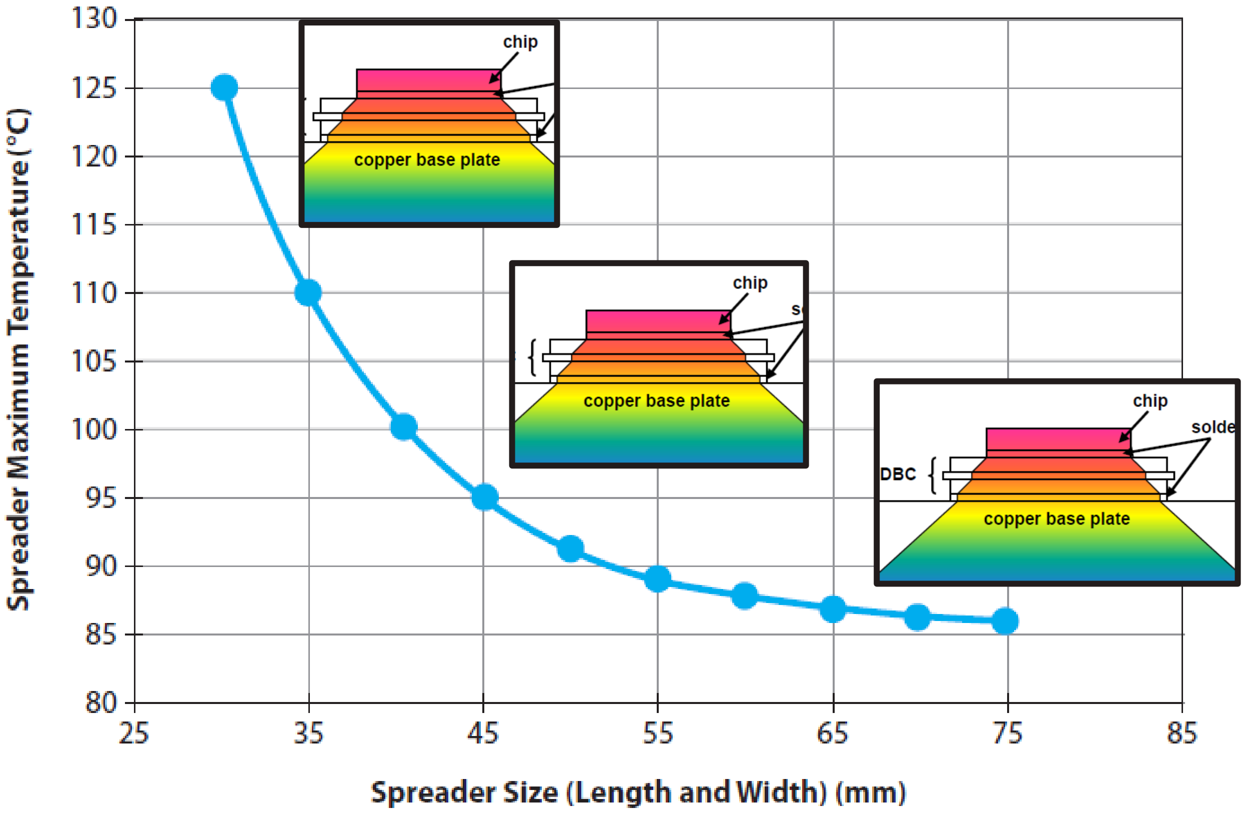
# Biot Number (Bi)

- Compares convective heat transfer to conductive heat transfer
- Dimensionless quantity
- $Bi = hL/k$
  - $h$ is the convective or interfacial heat transfer coefficient (W/m$^2$K)
  - $L$ is a characteristic length (m) (e.g., heat spreader thickness)
  - $k$ is the thermal conductivity of the solid (W/mK)
- For $Bi \ll 1$
  - Strong heat spreading, high convective $R_{th}$
- For $Bi \gg 1$
  - Weak heat spreading and high temperature gradient inside the solid due to high conductive $R_{th}$

Tummala, 3.3.

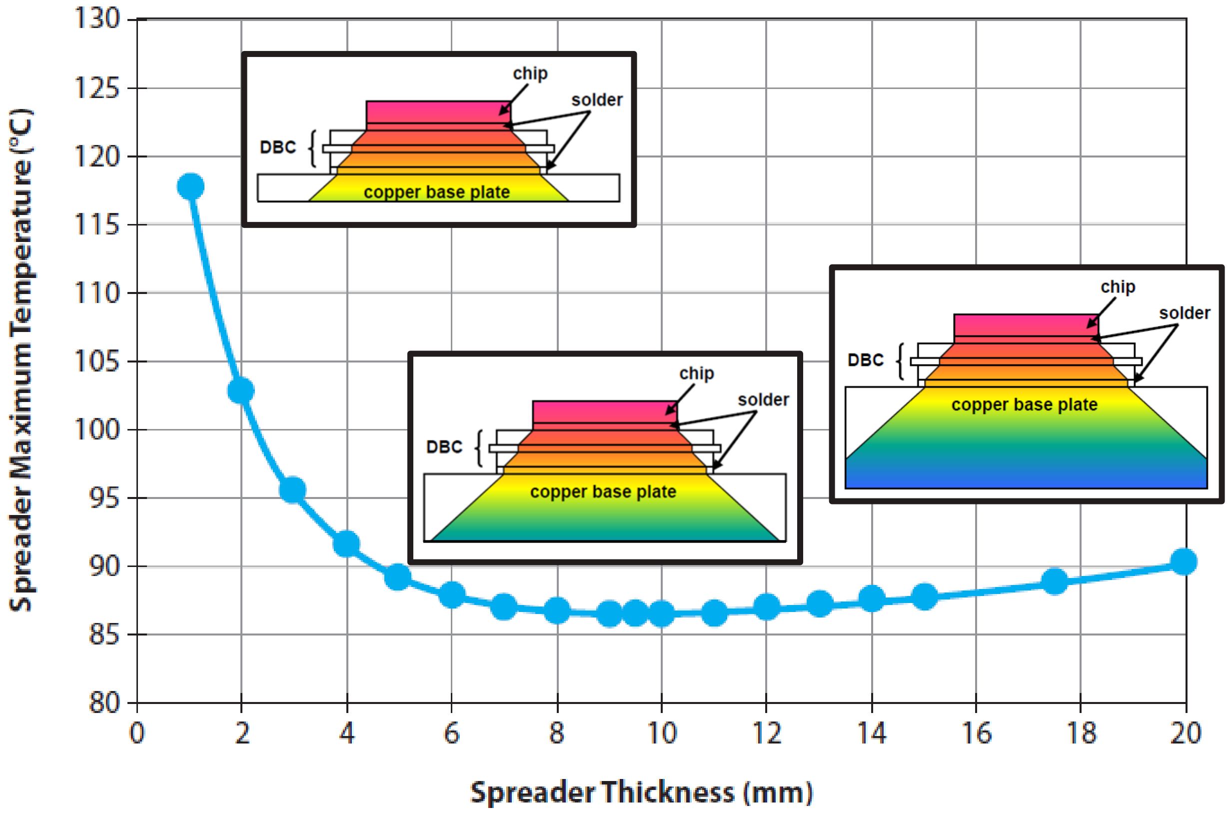
# Impact of Heat Spreader Area and Thickness

## Heat Spreader Temp. vs. Size*




*heat spreader thickness is fixed

## Heat Spreader Temp. vs. Thickness**




**heat spreader width = length and are fixed

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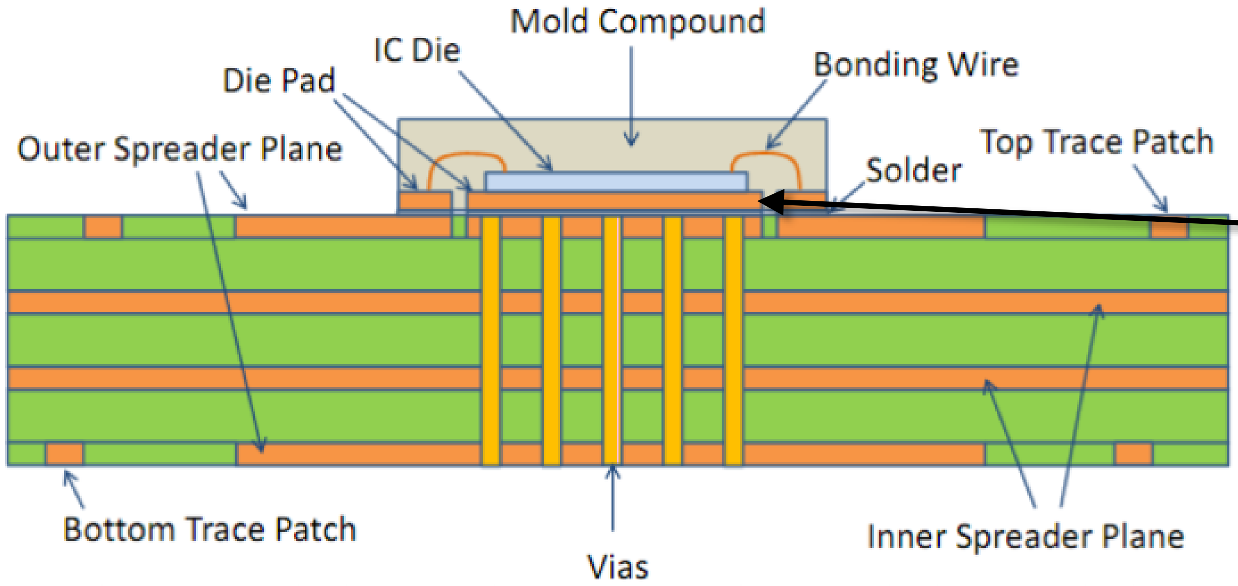
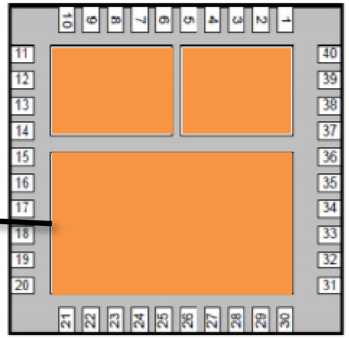
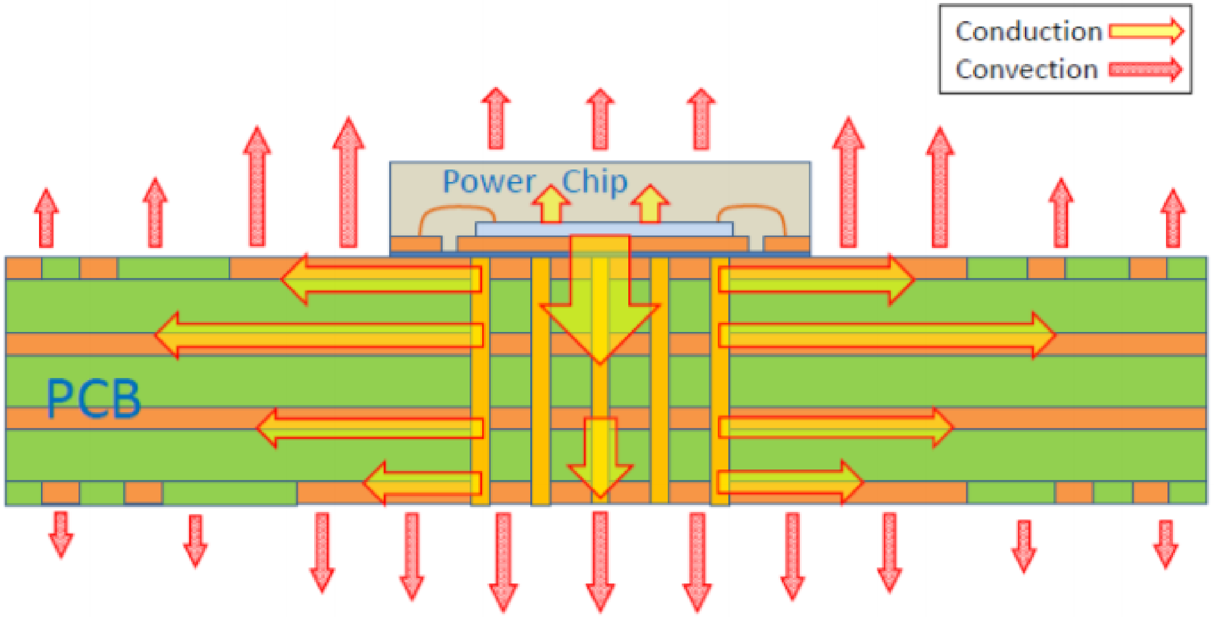
# Thermal Vias & Metal Planes



Exposed metal pad




| Material | Thermal Conductivity (W/mK) |
|---|---|
| Silicon | 145 |
| Mold Compound | 0.7 |
| Lead Frame | 277 |
| Die Attach Epoxy | 2.4 |
| Copper | 388 |
| FR4 PCB | 0.35 |
| SnAgCu Solder | 57.3 |
| 63Sn37Pb Colder | 50 |

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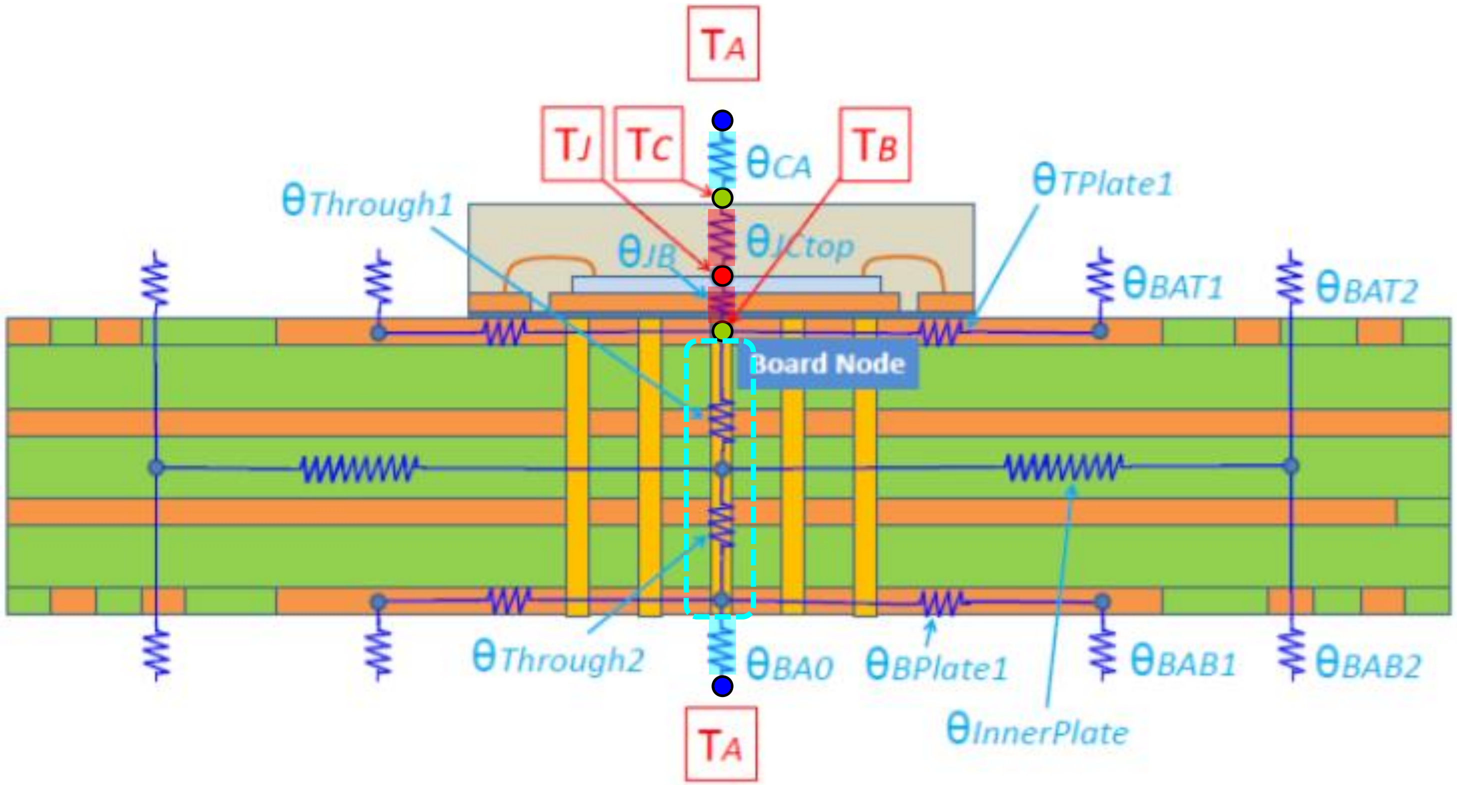
# Thermal Vias

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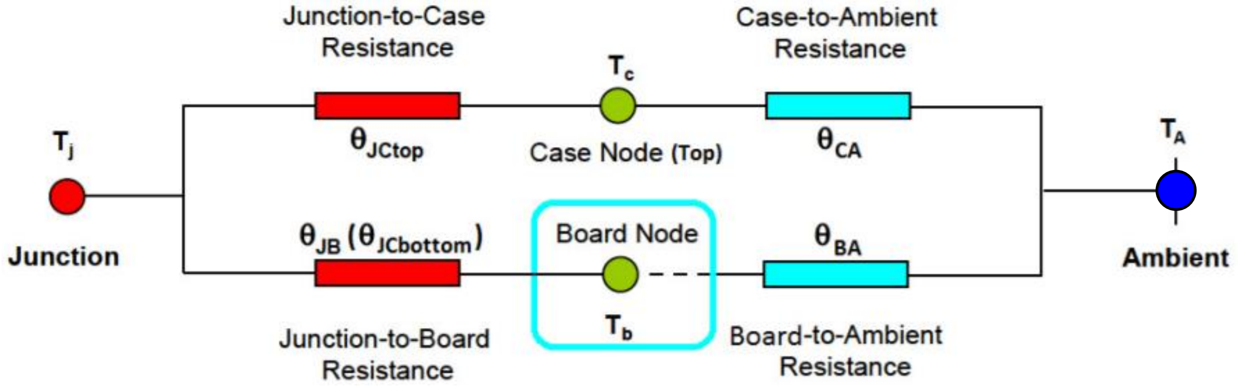

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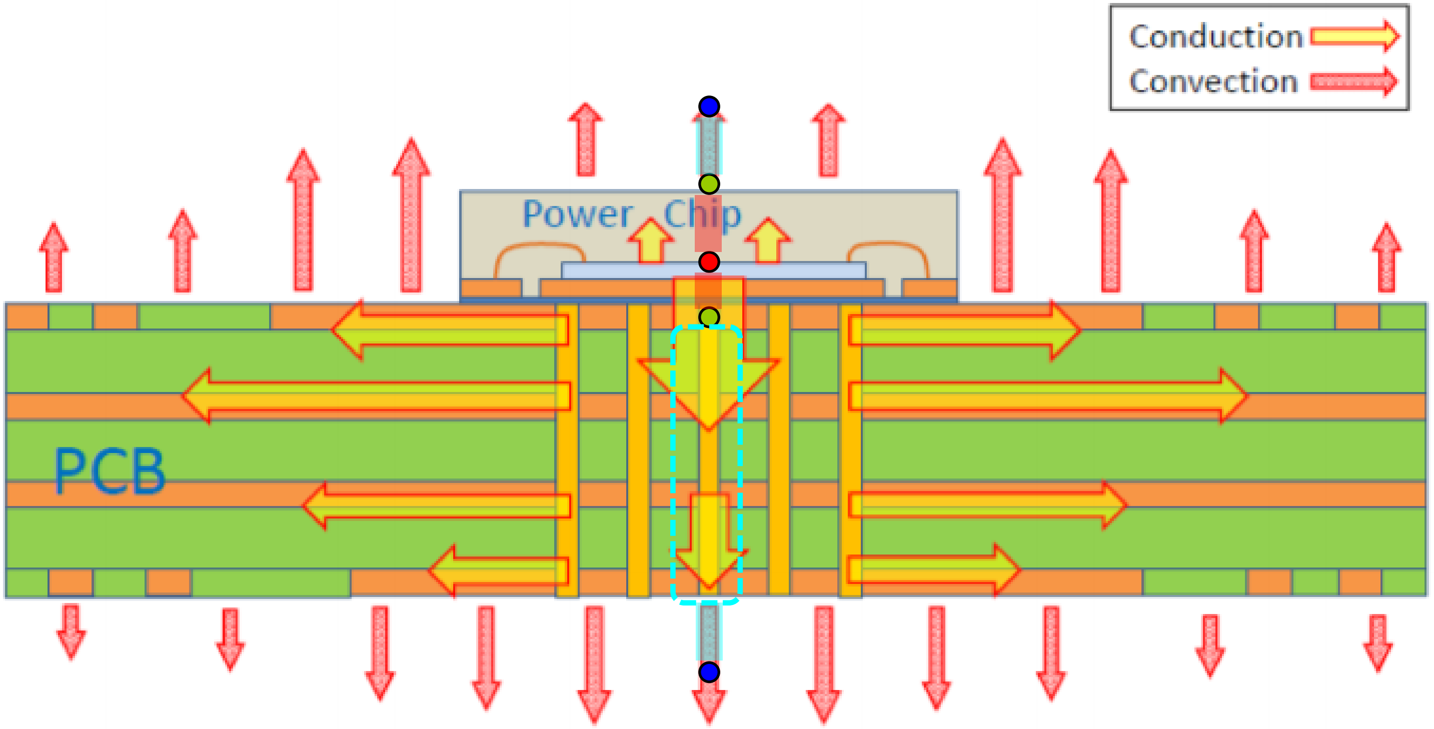
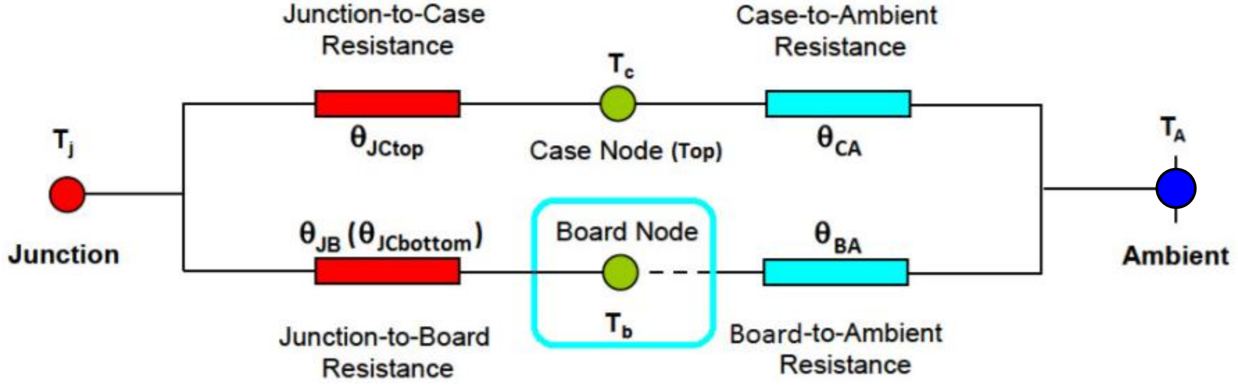
# Thermal Vias

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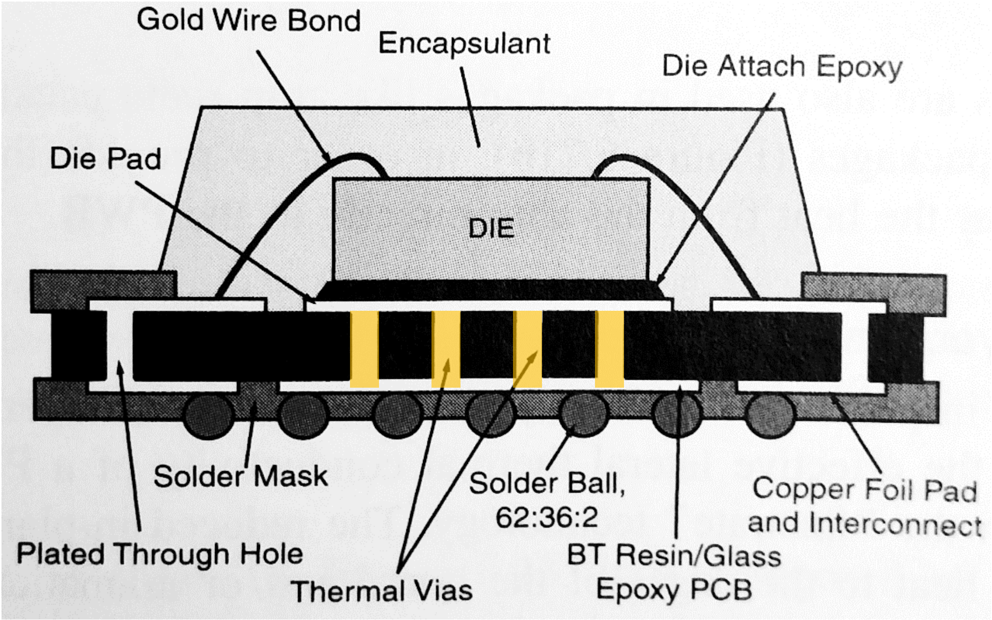
# Thermal Vias

- Vias can reduce the vertical $R_{th}$
- The equivalent vertical (Z-direction) thermal conductivity is:

$$k_{zz} = k_m a_m + k_i(1 - a_m)$$

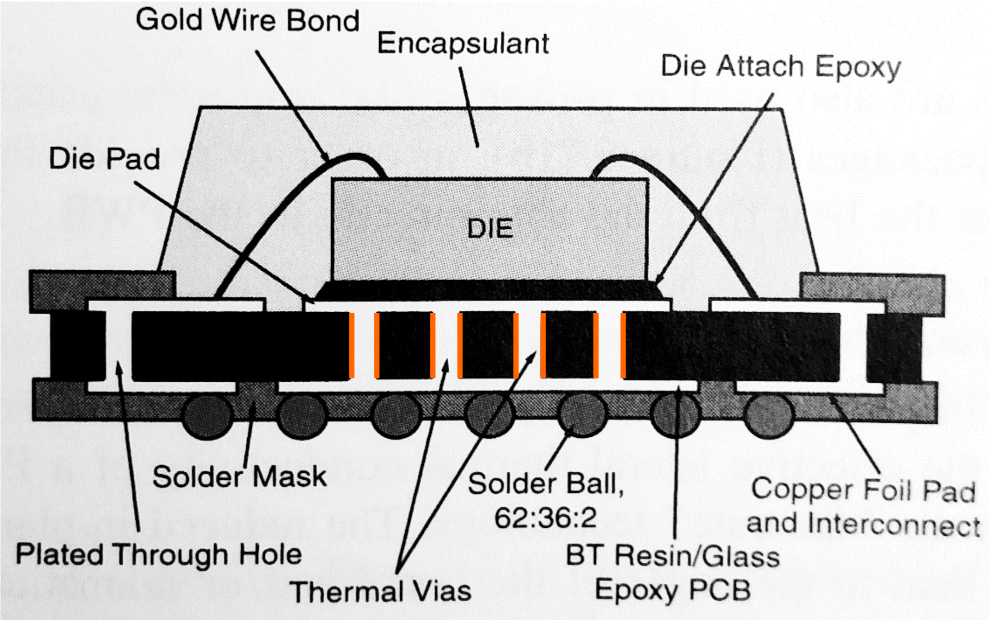
where

- $k_m = k$ of metal
- $a_m =$ fraction of the *cross-sectional area* occupied by the metal vias
- $k_i = k$ of the insulator



# Example: Thermal Vias

PCB has a through-hole via density of 25 per cm$^2$ of board area. The via hole diameter is 0.43 mm, and its inner surface is plated with 15-µm-thick copper. Calculate the equivalent thermal conductivity value $k_{zz}$ for this PCB. Use $k_{Cu} = 390$ W/(m·K) and $k_i = 0.2$ W/(m·K).



Tummala, 1st Ed.

# Example: Thermal Vias

- Equivalent thermal conductivity in Z direction:

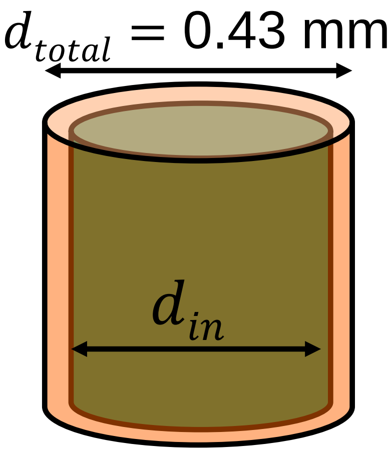
$$k_{zz} = k_m a_m + k_i(1 - a_m)$$

- Need $a_m$ (fraction of the cross-sectional area occupied by the via metal)
- To find $a_m$, need the effective conducting area for each via
  - Via hole diameter = 0.43 mm
  - Via copper plating = 0.015 mm
  - Effective via conducting area = Total via area – non-conductive via area

$$A_{cond} = \pi\left(\frac{0.43\text{mm}}{2}\right)^2 - \pi(0.43\text{mm}/2 - 0.015\text{mm})^2 = 0.01956\text{mm}^2$$

– $a_m = 25\,\frac{\text{vias}}{\text{cm}^2} \times 0.0001956\text{cm}^2 = 0.004889$

- $k_{zz} = 390\,\frac{\text{W}}{\text{m}\cdot\text{K}}(0.004889) + 0.2\,\frac{\text{W}}{\text{m}\cdot\text{K}}(1 - 0.004889) = \mathbf{2.11}\,\frac{\mathbf{W}}{\mathbf{m\cdot K}}$




$d_{in}$ = 0.43 mm – 2(0.015 mm)

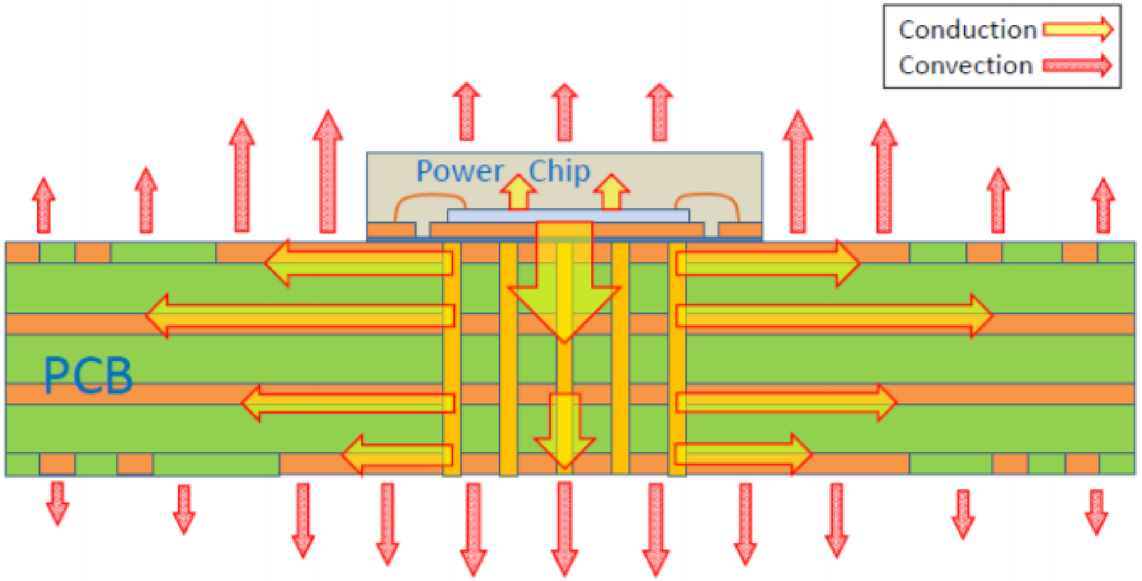
# Metal Planes

- Metal planes can reduce the lateral $R_{th}$ by increasing the effective thermal conductivity in the XY plane:

$$k_{xy} = k_m t_m + k_i(1 - t_m)$$

where

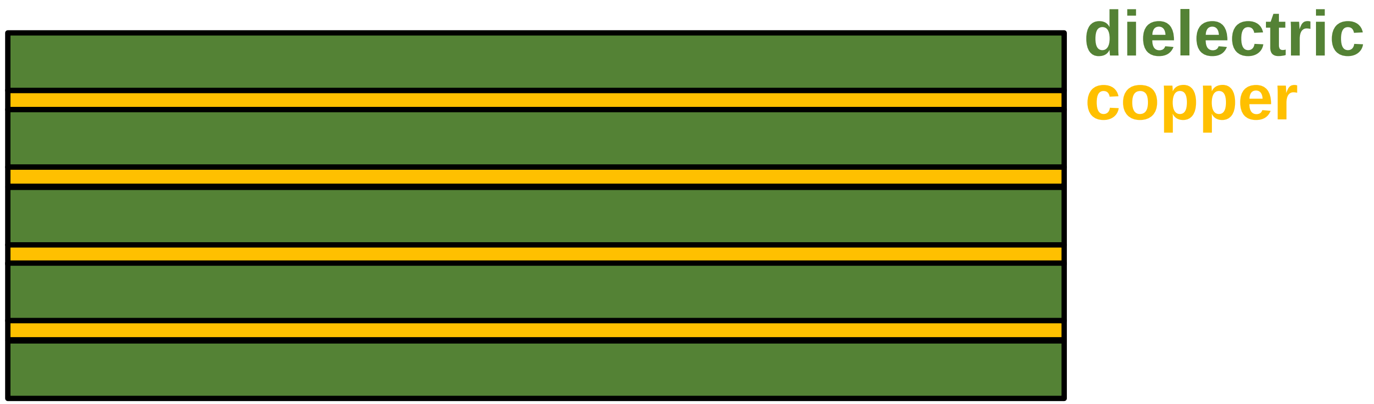
- $k_m = k$ of metal
- $t_m =$ fraction of the *thickness* occupied by the metal planes
- $k_i = k$ of the insulator



Tummala, 1st Ed.

# Example: Metal Planes

A PCB has two power layers and two ground layers, each with a 50-µm-thick copper plane. The power and ground layers are separated by 200-µm-thick dielectric (insulator) layers. Calculate the equivalent thermal conductivity value $k_{xy}$ for this PCB. Use $k_{Cu} = 390$ W/(m·K) and $k_i = 0.2$ W/(m·K).



# Example: Metal Planes

- Equivalent thermal conductivity in XY direction:

$$k_{xy} = k_m t_m + k_i(1 - t_m)$$

- Need $t_m$ (fraction of the thickness area occupied by the metal planes)
  - Total metal thickness = 50 μm/layer x 4 layers = 200 μm
  - Total insulator thickness = 200 μm/layer x 5 layers = 1000 μm
  - $t_m = \frac{200\mu\text{m}}{1000\mu\text{m}+200\mu\text{m}} = 0.167$
- $k_{xy} = 390\frac{\text{W}}{\text{m}\cdot\text{K}}(0.167) + 0.2\frac{\text{W}}{\text{m}\cdot\text{K}}(1 - 0.167) = \mathbf{65.17}\,\frac{\mathbf{W}}{\mathbf{m\cdot K}}$

- Note: if there are unfilled vias cutting through the plane, the XY thermal conductivity will be reduced

# Example: Metal Planes

- If $L = w$ for the PCB, the equivalent thermal resistance in XY direction:

$$R_{th,xy} = \frac{L}{k_{xy}A} = \frac{1}{\left(65.17\,\frac{\mathrm{W}}{\mathrm{m\cdot K}}\right)(0.0012\mathrm{m})} = \mathbf{12.8\ K/W}$$

- Alternatively, could find the thermal resistance of the copper layer in XY and the insulator layer in XY and then use the parallel rule:

- $R_{th,xy,Cu} = \frac{L}{k_{Cu}A} = \frac{1}{\left(390\frac{\mathrm{W}}{\mathrm{m\cdot K}}\right)(0.00005\mathrm{m})} = 51.2\,\frac{\mathrm{K}}{\mathrm{W}}$ per layer → $\div\, 4 = \mathbf{12.8}\,\frac{\mathbf{K}}{\mathbf{W}}$

- $R_{th,xy,i} = \frac{L}{k_{xy}A} = \frac{1}{\left(0.2\frac{\mathrm{W}}{\mathrm{m\cdot K}}\right)(0.0002\mathrm{m})} = 25000\,\frac{\mathrm{K}}{\mathrm{W}}$ per layer → $\div\, 5 = \mathbf{5000}\,\frac{\mathbf{K}}{\mathbf{W}}$

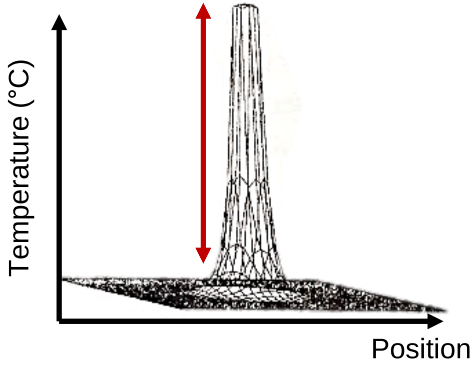
- $R_{th,xy,Cu} \parallel R_{th,xy,i} = \left(\frac{1}{12.8\mathrm{K/W}} + \frac{1}{5000\mathrm{K/W}}\right)^{-1} = \mathbf{12.8\ K/W}$

# Metal Planes

- Metal planes spread heat laterally, which reduces local temperature rises
- FEA simulation of 7.5 mm$^2$ chip dissipating 1 W on different PCBs
  - Adding a plane of **1 oz** copper reduces the maximum $\Delta T$ by **86 %**
  - **1 oz** → **2 oz** reduces $\Delta T_{max}$ by **35 %**
  - **2 oz** → **4 oz** reduces $\Delta T_{max}$ by **35 %**

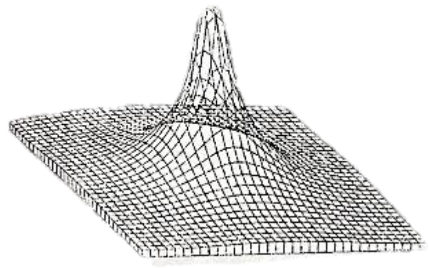
**No Metal:**

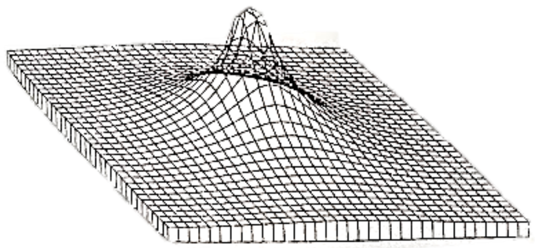
$\Delta T_{max} = 160\ °C$




**1 oz Copper:**

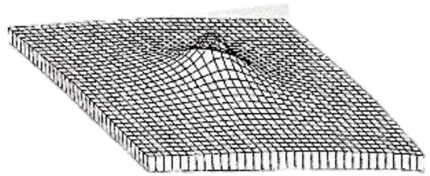
$\Delta T_{max} = 22\ °C$





**2 oz Copper:**

$\Delta T_{max} = 14\ °C$



**4 oz Copper:**

$\Delta T_{max} = 9\ °C$

Tummala, 3.2.

# Convection

- Transfer of heat between the surface of a body and a fluid in motion
- Newton's Law of Cooling:

$$\boldsymbol{q = hA_s(T_s - T_f)}$$

- $q$ = heat (W)
- $h$ = convective heat transfer coefficient (W/(m$^2$K))
- $A_s$ = wetted surface area (m$^2$)
- $T_s$ = surface temperature (°C)
- $T_f$ = bulk temperature of fluid (°C)
- Rearranging the above equation:

$$\frac{1}{hA_s} = \frac{(T_s - T_f)}{q} \quad \rightarrow \quad R_{th,conv} = \frac{1}{hA_s}$$

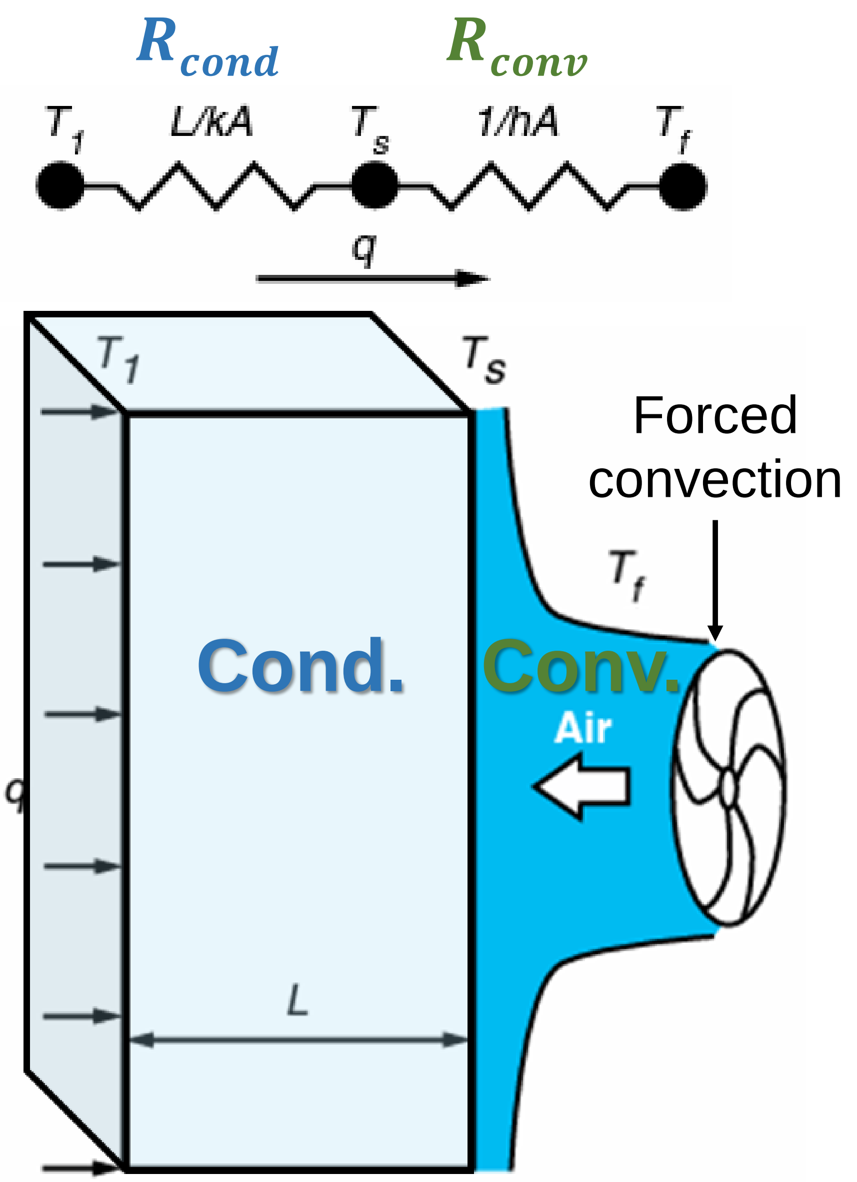
# Conduction & Convection Thermal Resistances

$$q = \frac{kA_c(T_h - T_c)}{L} \qquad R_{th,cond} = \frac{L}{kA_c}$$

$q$ = heat (W)
$k$ = thermal conductivity (W/(m·K))
$A_c$ = cross-sectional area (m²)
$L$ = length $q$ needs to travel (m)
$T_h$ = hot temperature (°C)
$T_c$ = cold temperature (°C)

$$q = hA_s\left(T_s - T_f\right) \qquad R_{th,conv} = \frac{1}{hA_s}$$

$h$ = heat transfer coefficient (W/(m²K))
$A_s$ = wetted surface area (m²)
$T_s$ = surface temperature (°C)
$T_f$ = bulk temperature of fluid (°C)



Tummala, 3.2.

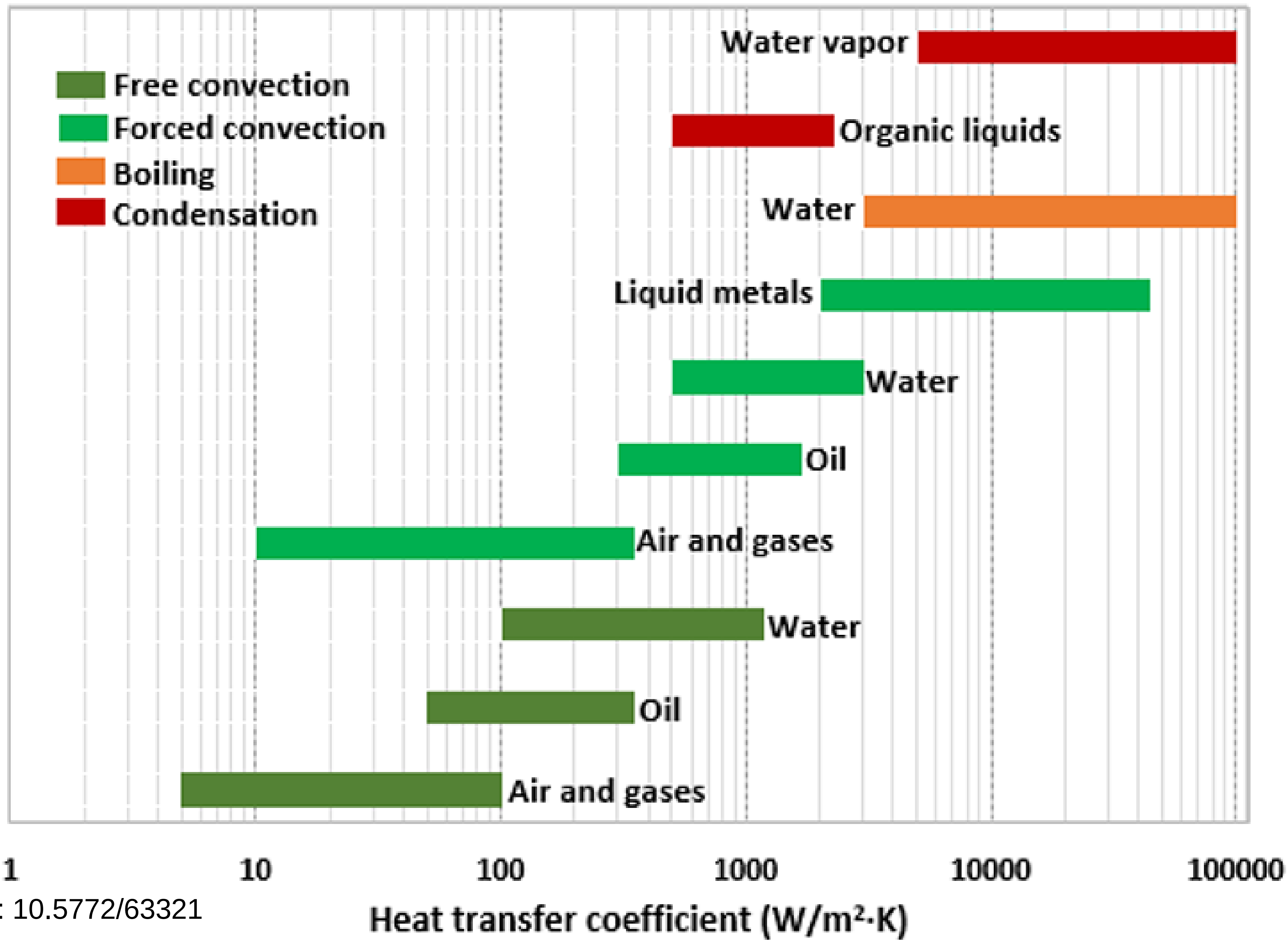
# Convection Heat Transfer Coefficient $h$

$$q = hA_s(T_s - T_f)$$

- $h$ depends on the properties of the fluid, the velocity of the fluid, and the surface geometry
- $h$ can be determined empirically or analytically

| **Cooling Method** | $h$ **(W/(m²K))** |
|---|---|
| Free (natural) convection | 5 – 25 |
| Forced convection, air | 25 – 250 |
| Forced convection, water | 100 – 10,000 |
| Boiling water | 1,000 – 50,000 |
| Condensing steam | 5,000 – 100,000 |

# Heat Transfer Coefficients

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# Types of Convection

- **Free** (or natural)
  - Occurs due to buoyancy effects: hotter fluid adjacent to a hot surface rises, leading to the transfer of heat from the hot surface
- **Forced**
  - Occurs when heat is transported from a hot surface by a fluid stream moved by an external stimulant (e.g., fan, pump)
- **Mixed** (combination of free and forced)
  - Occurs when the forced fluid velocity is low such that heat transfer due to free and forced convection are of similar magnitudes