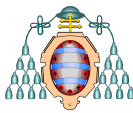# Thermal management in power semiconductor devices

Main ideas about heat transfer

Heat transfer occurs through three mechanisms:

- **Radiation.** ➡ *Only significant for space applications.*
- **Conduction.**
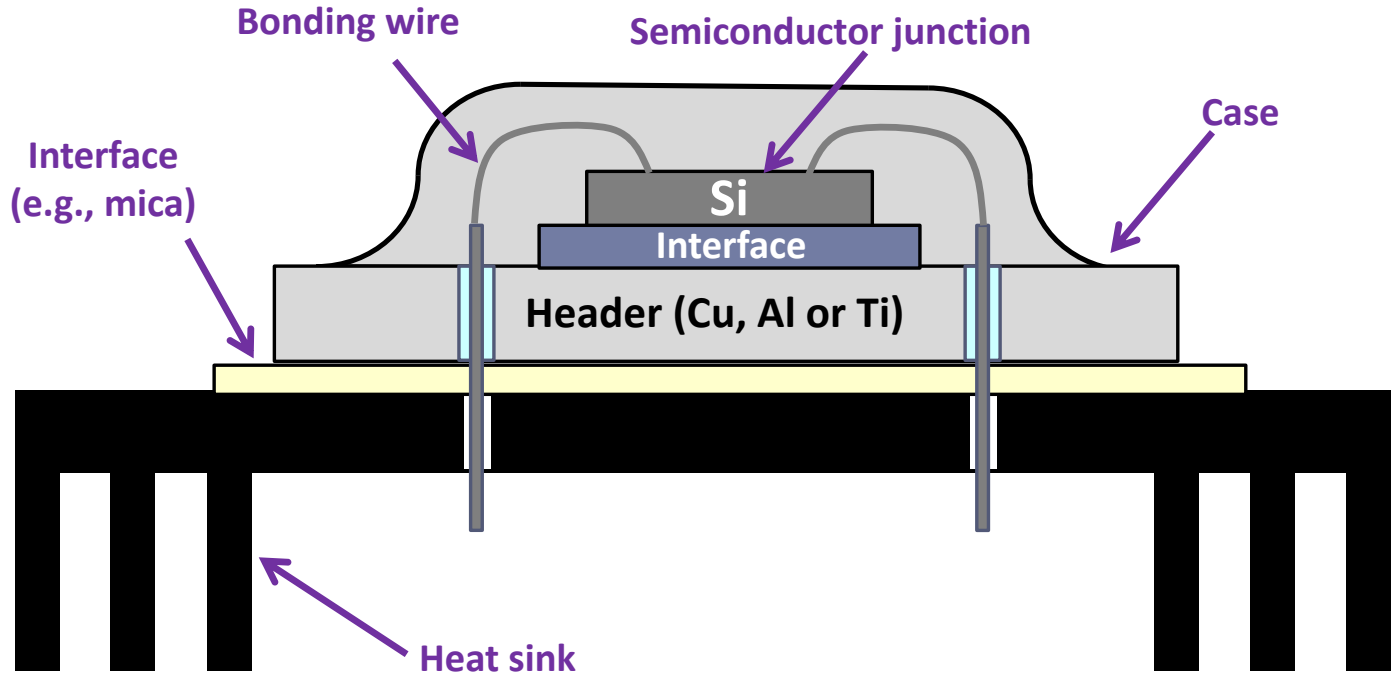- **Convection.** ➡ *Significant for general power applications.*

- **Conduction: the heat is transferred by the vibratory motion of atoms or molecules.**

- **Convection: the heat is transferred by mass movement of a fluid. It could be natural convection (without a fan) or forced convection (with a fan).**

- **In both cases, the heat transfer process can be approached using equivalent electric circuits.**

- **However, a detailed study of the heat transfer mechanisms is more complex and it is beyond the scope of this course.**
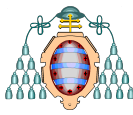
• **Typical mechanical structure used for mounting a power semiconductor device**
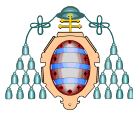
- **Example: an electronic device in TO-3 package over an HS02 heat sink**

TO-3

HS02

Semiconductor package (Case)

Insulating mica for TO-3 (Interface)
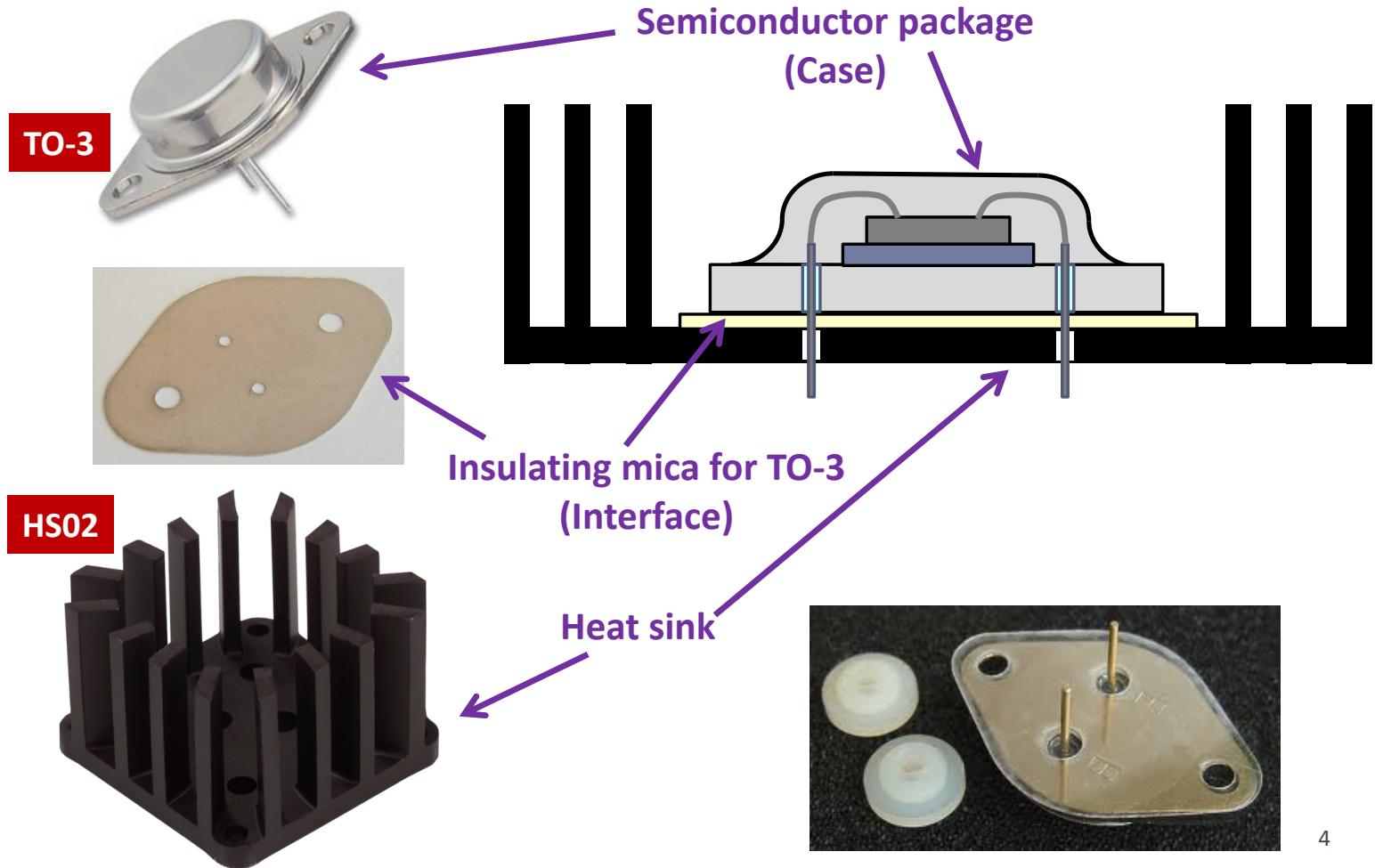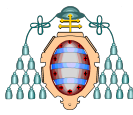
Heat sink

• **Examples of final assembly of electronic devices in TO-3 package over heat sinks**
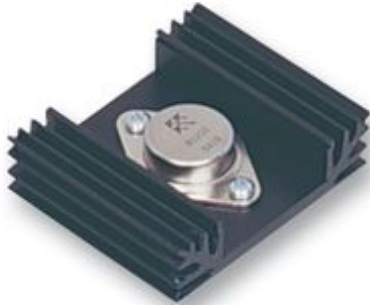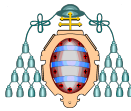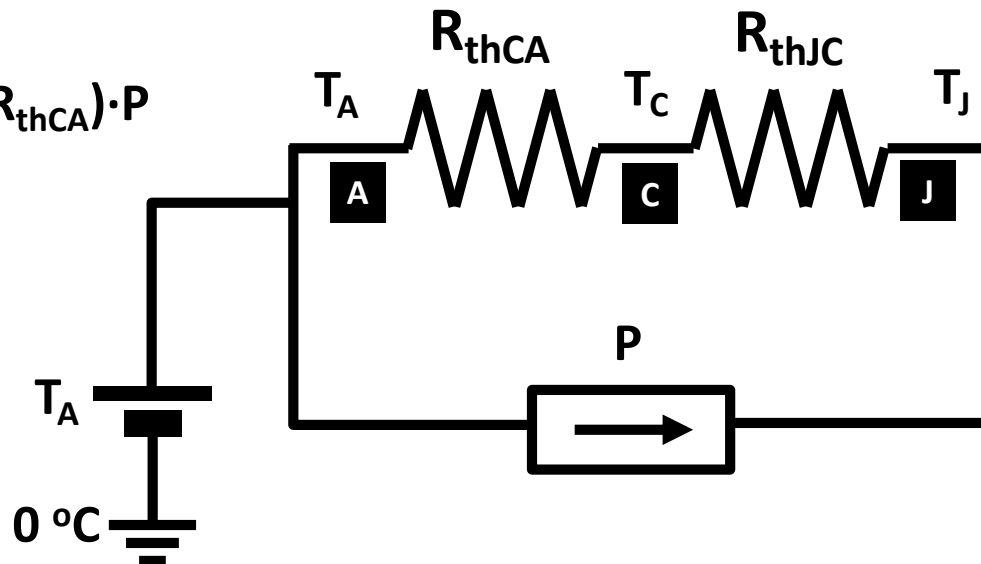
• **Thermal resistances without a heat sink**

Basic equations:

$$T_C = T_A + R_{thCA} \cdot P$$

$$T_J = T_C + R_{thJC} \cdot P$$

Therefore:

$$T_J = T_A + (R_{thJC} + R_{thCA}) \cdot P$$
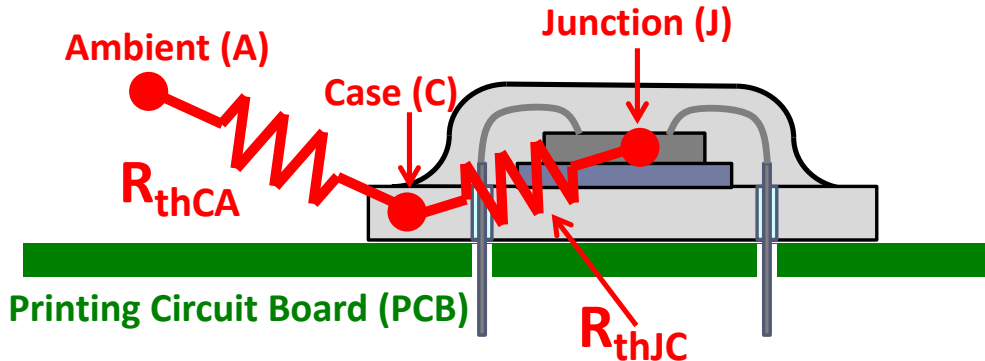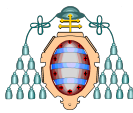
IMPEDANCIA TÉRMICA

- ESTÁTICA (R_{th})
- DINÁMICA (Z_{th})

$$\boxed{\Delta T = P \cdot R_{th}}$$

Z_{th}

	THERMAL		ELECTRICAL
	Temp	$\longrightarrow$	v
$\Delta T = P \cdot R_{th}$	Power Loss	$\longrightarrow$	i
	R_{th}	$\longrightarrow$	R

$\Delta v = i \cdot R$
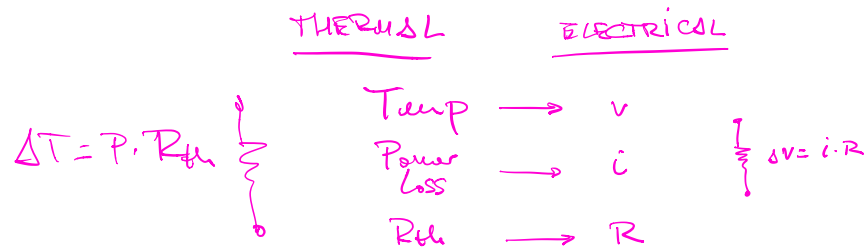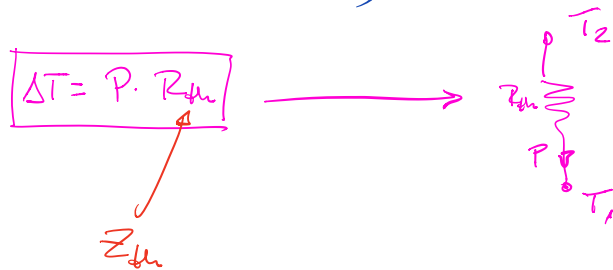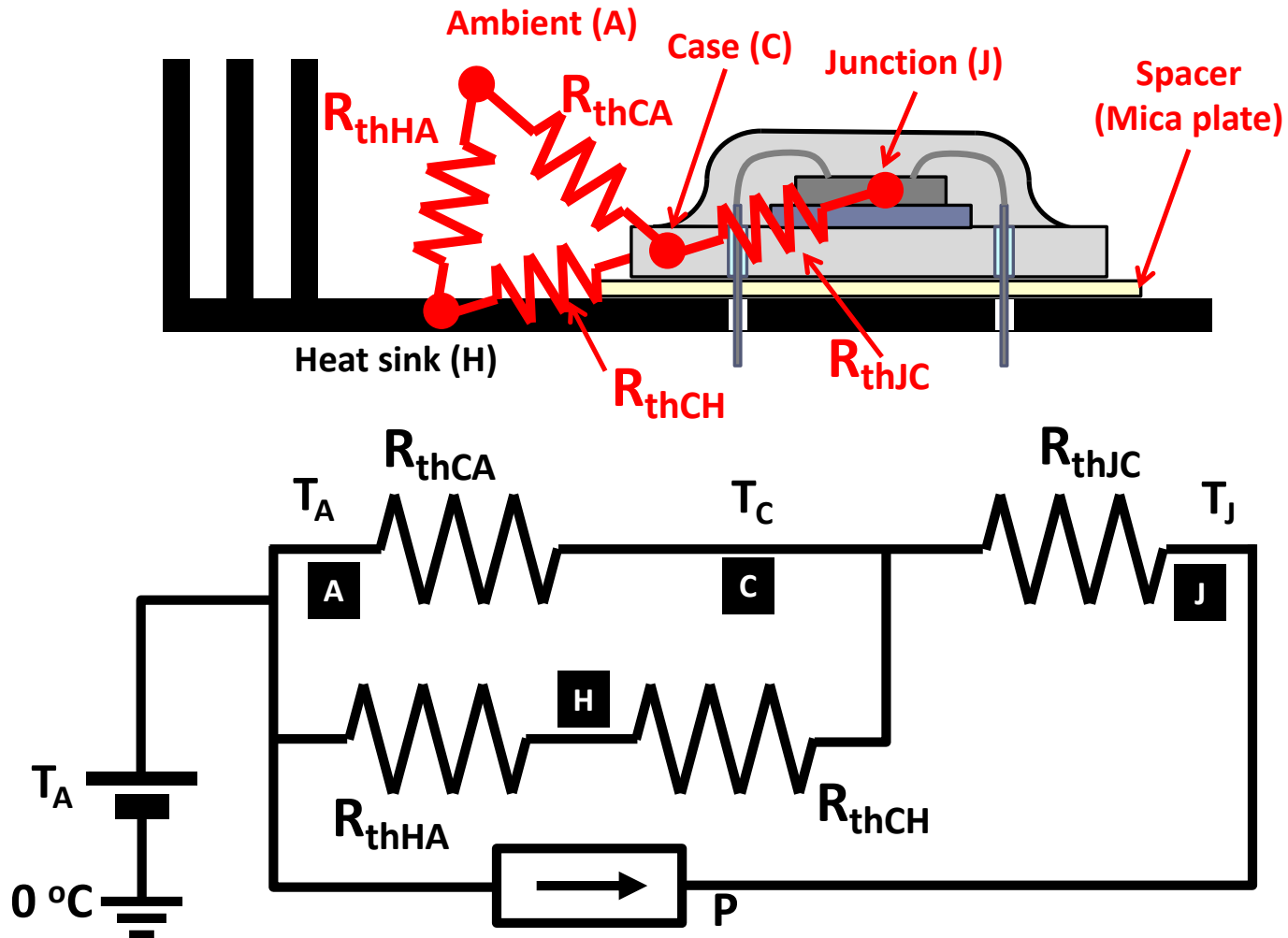
• **Thermal resistances with a heat sink (I)**

• **Thermal resistances with a heat sink (II)**
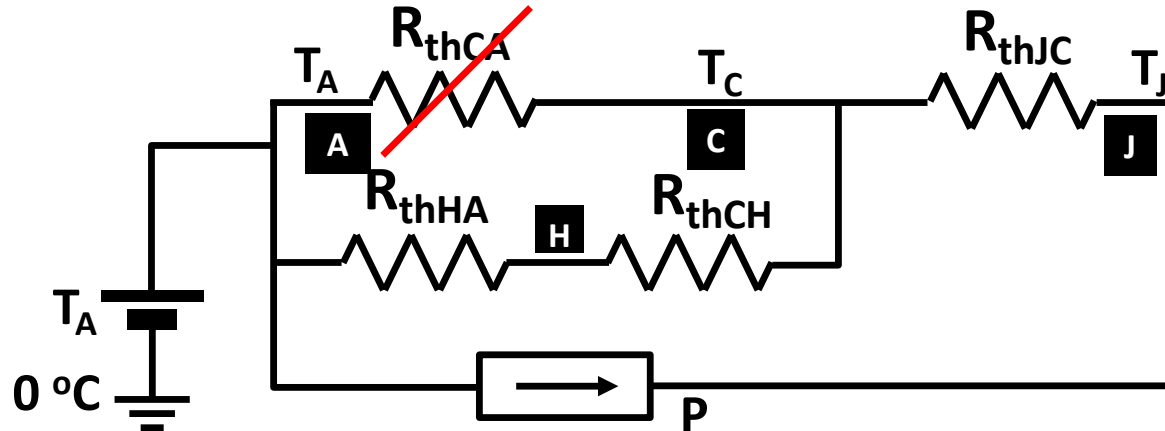
Basic equations:

$T_C = T_A + [R_{thCA} \cdot (R_{thHA} + R_{thCH})/(R_{thCA} + R_{thHA} + R_{thCH})] \cdot P$

$T_J = T_C + R_{thJC} \cdot P$

Therefore:

$T_J = T_A + [R_{thJC} + R_{thCA} \cdot (R_{thHA} + R_{thCH})/(R_{thCA} + R_{thHA} + R_{thCH})] \cdot P$

However, many times $R_{thCA} \gg (R_{thHA} + R_{thCH})$, and therefore:

$T_J \approx T_A + (R_{thJC} + R_{thHA} + R_{thCH}) \cdot P$

• Thermal resistances with a heat sink (III)
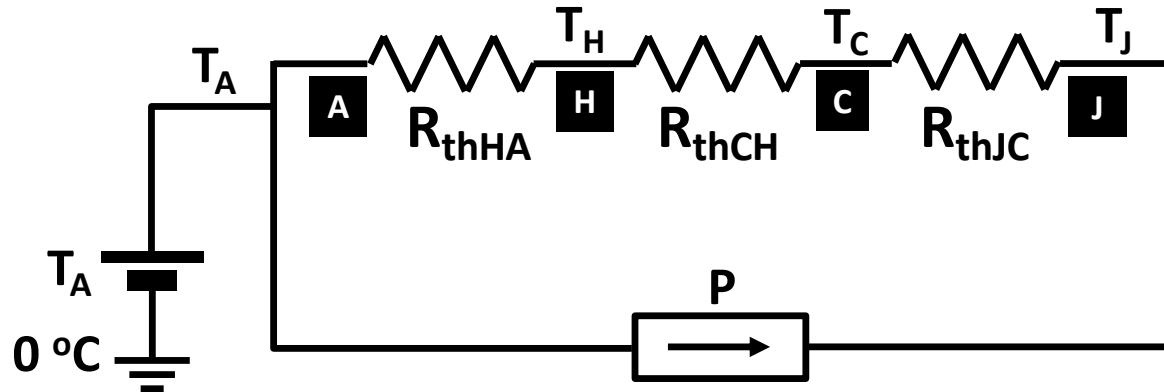
Basic equations:

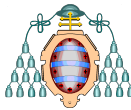$T_H = T_A + R_{thHA} \cdot P$

$T_C = T_H + R_{thCH} \cdot P$

$T_J = T_C + R_{thJC} \cdot P$

Therefore:

$T_J = T_A + (R_{thJC} + R_{thCH} + R_{thHA}) \cdot P$

• Main issue in thermal management:

➤ **The junction temperature must be below the limit specified by the manufacturer.**

➤ **For power silicon devices, this limit is about 150-200 ºC.**

- **Its value depends on the device.**
- **Examples corresponding to different devices in TO-3:**

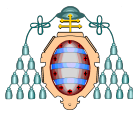- **MJ15003, NPN low-frequency power transistor for audio applications**

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	0.70	°C/W

- **LM350, adjustable voltage regulator**

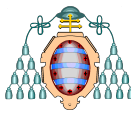| Parameter	Conditions	LM150			Units
		Min	Typ	Max	
Thermal Resistance, Junction to Case	K Package		1.2	1.5	°C/W

- **2N3055, NPN low-frequency power transistor for audio applications**

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	1.52	°C/W

10

- **The same device has different value of R_{thJC} for different packages.**
- **Examples corresponding to two devices:**
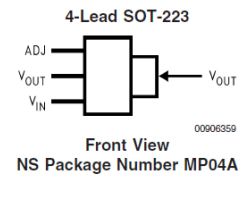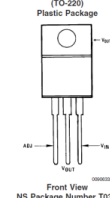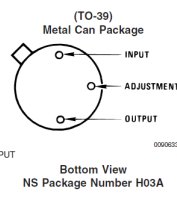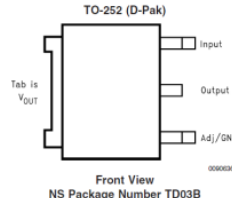
Table 2.   **Thermal parameters**   *ST* **STTH512**   *$I_{F(AV)}$ = 5A, V_{RRM} = 1200V*

Symbol	Parameter		Value	Unit
$R_{th(j-c)}$	Junction to case	TO-220AC / DPAK	2.5	°C/W
		TO-220FPAC	5.8	

National Semiconductor

LM117/LM317A/LM317
3-Terminal Adjustable Regulator

Parameter	Conditions	LM317A			LM317			Units
		Min	Typ	Max	Min	Typ	Max	
Thermal Resistance,	K Package					2.3	3	°C/W
Junction-to-Case	MDT Package					5		°C/W
	H Package		12	15		12	15	°C/W
	T Package		4	5		4		°C/W
	MP Package		23.5			23.5		°C/W

LM117 Series Packages

Part Number Suffix	Package	Design Load Current
K	TO-3	1.5A
H	TO-39	0.5A
T	TO-220	1.5A
E	LCC	0.5A
S	TO-263	1.5A
EMP	SOT-223	1A
MDT	TO-252	0.5A

11
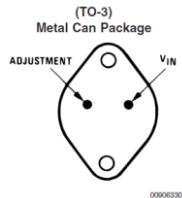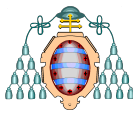
- **Its value depends on the case.**

- **Manufacturers give information about $R_{thJA} = R_{thJC} + R_{thCA}$.**

- **Therefore, $R_{thCA} = R_{thJA} - R_{thJC}$.**

- **This thermal resistance is important only for relative low-power devices.**

TO-3

- **IRF150, N-Channel power MOSFET in TO-3 package**

Thermal Resistance

	Parameter	Min	Typ	Max	Units	Test Conditions
R_{thJC}	Junction to Case	—	—	0.83	°C/W	
R_{thJA}	Junction to Ambient	—	—	30		Typical socket mount

TO-220

- **IRF540, N-Channel power MOSFET in TO-220 package**

THERMAL DATA

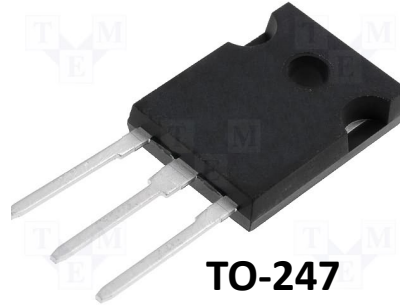| Rthj-case	Thermal Resistance Junction-case	Max	1.76	°C/W
Rthj-amb	Thermal Resistance Junction-ambient	Max	62.5	°C/W
T_l	Maximum Lead Temperature For Soldering Purpose	Typ	300	°C

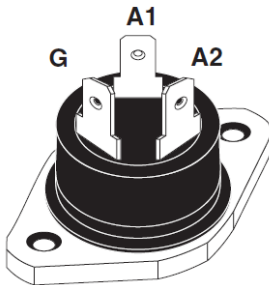# Other examples of packages for power semiconductor devices
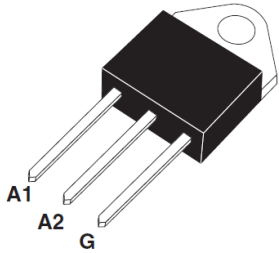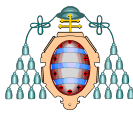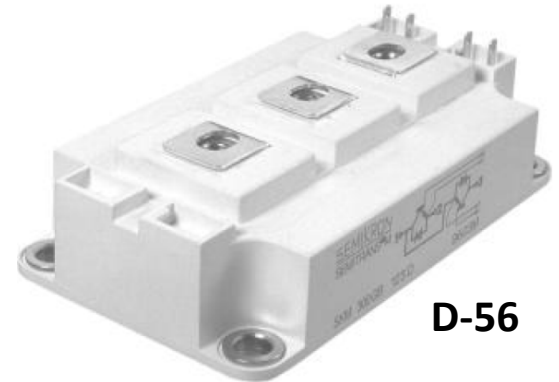

TOP3 insulated
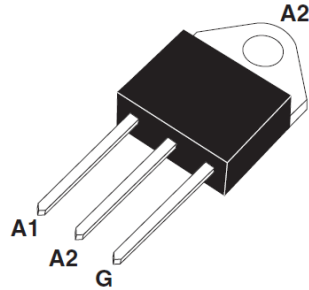
TOP3

TO-247

D-61-8

RD91 insulated

SOT-227

D-56
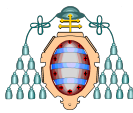
- **Its value depends on the interface material between semiconductor and heat sink.**

- **Examples of thermal pads for TO-3 package:**

Based on silicone: SP400-0.009-00-05

Description	THERMAL PAD TO-3 .009" SP400
Material	Silicone Based
Thermal Conductivity	0.9 W/m-K
Thermal Resistance	1.40 °C/W
Thickness	0.229 mm

Based on mica:

R_{th}=0.3 ºC/W)

- **Its value depends on the heat sink dimensions and shape and also on the convection mode (either natural or forced).**
- **Examples of heat sinks for TO-3 package:**

UP-T03-CB

Material	Aluminum
R_{th} @ natural	9 °C/W

HP1-TO3-CB

Material	Aluminum
R_{th} @ natural	5.4 °C/W

HS02

Material	Aluminum
R_{th} @ natural	4.5 °C/W

• Examples of heat sinks for general purpose
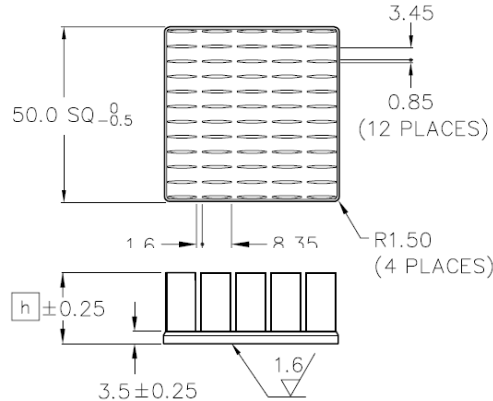
MATERIAL : A 6063
FINISH : BLACK ANODIZE

MODEL	HEIGHT h
LPD50−10B	10
LPD50−15B	15
LPD50−20B	20
LPD50−25B	25
LPD50−30B	30
LPD50−35B	35

Dimensions : mm

△ LPD50−10B
□ LPD50−15B
○ LPD50−20B
▲ LPD50−25B
■ LPD50−30B
⬤ LPD50−35B

THERMAL RESISTANCE °C/W

PRESSURE DROP mm H₂O
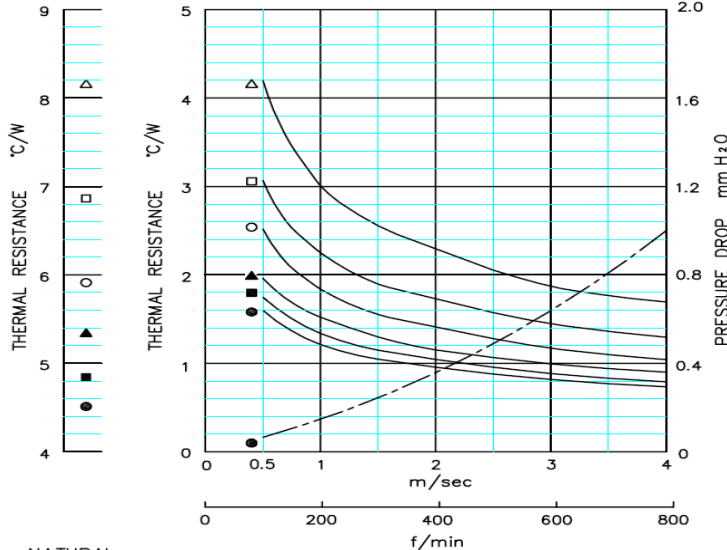
NATURAL CONVECTION

AIR VELOCITY: DUCTED CONDITION

16

• Heat sink profiles (I)
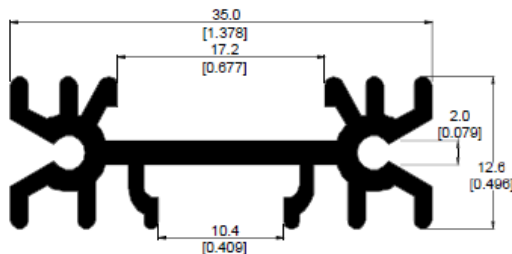
AAVID THERMALLOY

000SW

Wt: 0.43 Kg/m

R$_{th,n}$: 5.3°C/W

R$_{th,f}$: 1.87°C/W
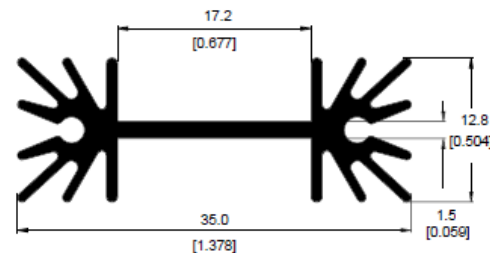
S.A.: 191 mm^2/mm

0S172

Wt: 0.4 Kg/m

R$_{th,n}$: 4.37°C/W

R$_{th,f}$: 1.52°C/W
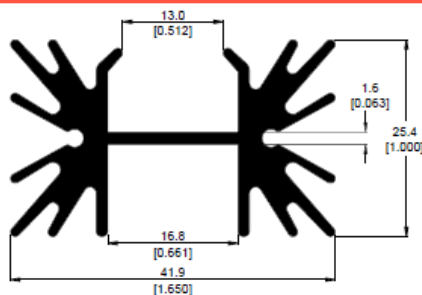
S.A.: 220 mm^2/mm

16372

Wt: 0.93 Kg/m

R$_{th,n}$: 3.4°C/W

R$_{th,f}$: 1.02°C/W
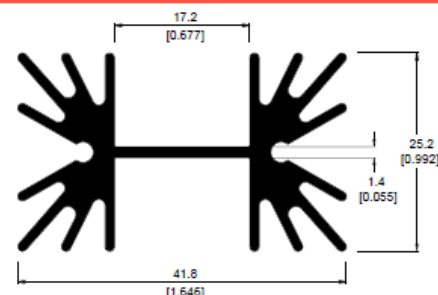
S.A.: 323 mm^2/mm

0S097

Wt: 0.88 Kg/m

R$_{th,n}$: 3.43°C/W

R$_{th,f}$: 1.16°C/W
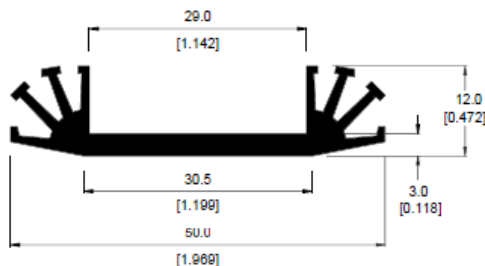
S.A.: 341 mm^2/mm

0S014

Wt: 0.60 Kg/m
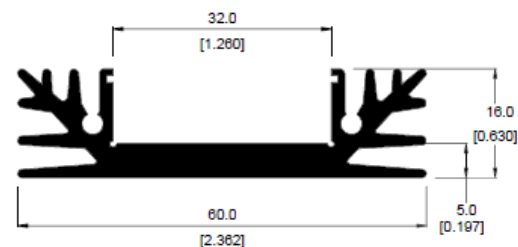
R$_{th,n}$: 5°C/W

R$_{th,f}$: 3.13°C/W

S.A.: 102 mm^2/mm
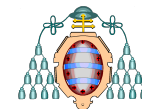
000YB

Wt: 1.08 Kg/m

R$_{th,n}$: 3.21°C/W

R$_{th,f}$: 1.15°C/W

S.A.: 305 mm^2/mm

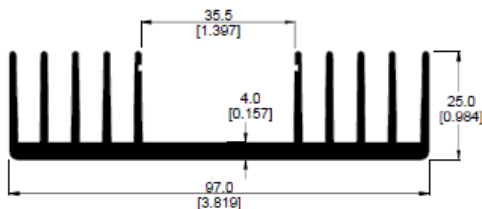## • Heat sink profiles (II)

AAVID THERMALLOY

000MA
Wt: 2.04 Kg/m
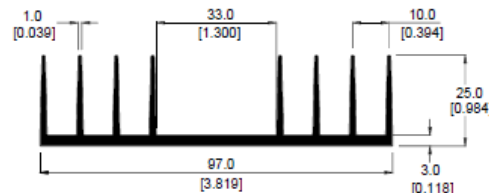$R_{th,n}$: 1.38°C/W
$R_{th,f}$: 0.56°C/W
S.A.: 612 mm²/mm

0S023*
Wt: 1.55 Kg/m
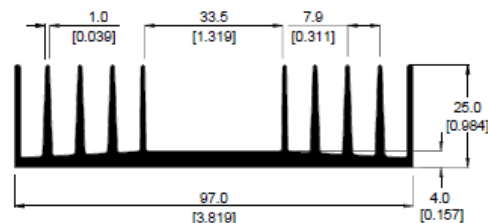$R_{th,n}$: 1.23°C/W
$R_{th,f}$: 0.62°C/W
S.A.: 555 mm²/mm

0S117
Wt: 1.84 Kg/m
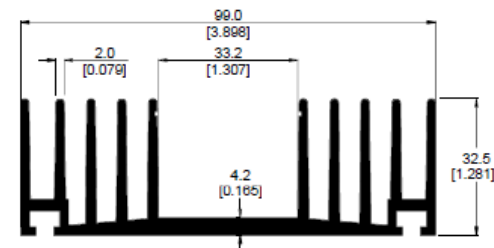$R_{th,n}$: 1.08°C/W
$R_{th,f}$: 0.51°C/W
S.A.: 617 mm²/mm

000MB
Wt: 2.72 Kg/m
$R_{th,n}$: 1.09°C/W
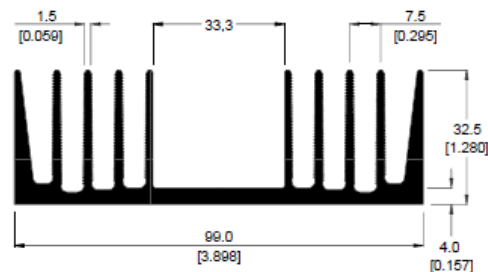$R_{th,f}$: 0.41°C/W
S.A.: 791 mm²/mm

000MK
Wt: 2.72 Kg/m
$R_{th,n}$: 1.07°C/W
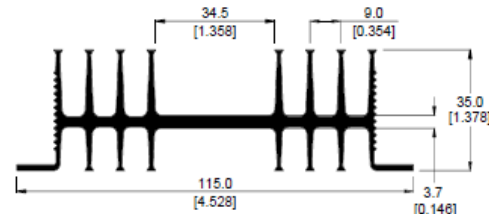$R_{th,f}$: 0.41°C/W
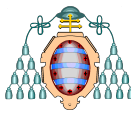S.A.: 852 mm²/mm

0S040
Wt: 2.42 Kg/m
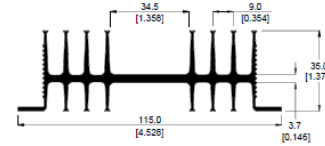$R_{th,n}$: 0.99°C/W
$R_{th,f}$: 0.72°C/W
S.A.: 802 mm²/mm

18

Thermal resistance heat sink to ambient, R_{thHA} (VII)

- **Examples**

0S040

$R_{th,n}$: 0.99°C/W
$R_{th,f}$: 0.72°C/W

THERMAL RESISTANCE vs LENGTH

$R_{th\_10cm} = 1.32 \cdot R_{th\_15cm}$
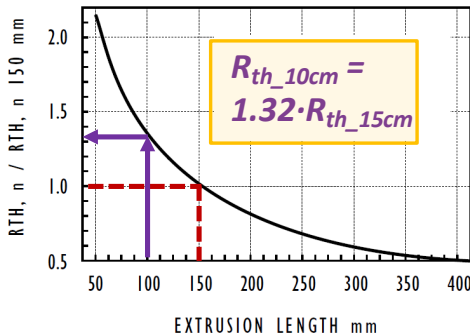
THERMAL RESISTANCE vs. AIR SPEED

$R_{th\_1m/s} = 1.41 \cdot R_{th\_2m/s}$
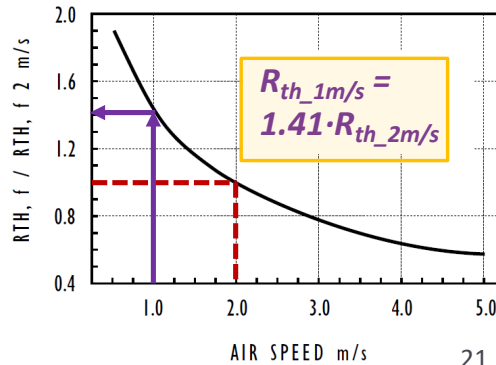
THERMAL RESISTANCE vs (Ts - Ta)

$R_{th\_50°C} = 1.15 \cdot R_{th\_75°C}$

21
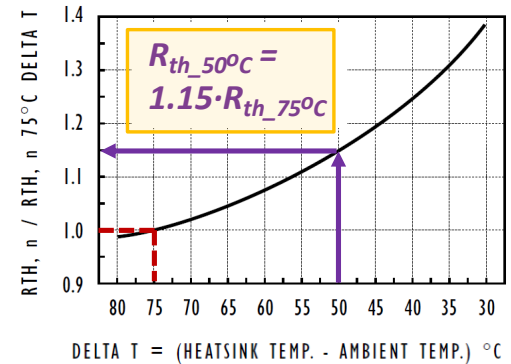
- R_{th} for 10 cm at $\Delta T = 50$ °C and natural convection = $0.99 \cdot 1.32 \cdot 1.15 = 1.5$ °C/W

- R_{th} for 10 cm and 2 m/s air speed = $0.72 \cdot 1.32 = 0.95$ °C/W

- R_{th} for 15 cm and 1 m/s air speed = $0.72 \cdot 1.41 = 1.01$ °C/W

- R_{th} for 10 cm and 1 m/s air speed = $0.72 \cdot 1.32 \cdot 1.41 = 1.34$ °C/W
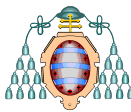
• **Transient thermal model for a star-up process, P being constant:**
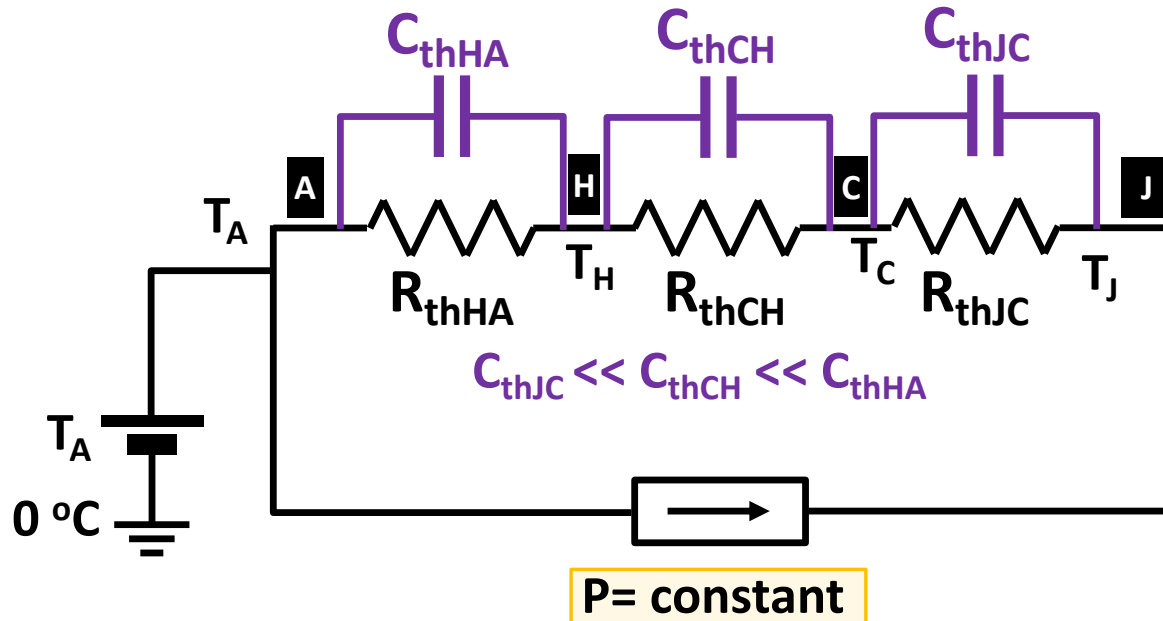
• **Under this condition, the junction temperature will be lower than the one predicted by static models, due to the fact that the total thermal impedance will be lower than the thermal resistance.**

• **Transient thermal model for pulsed-power operation in steady-state (I) (after the start-up process)**

$C_{thJC} \ll C_{thCH} \ll C_{thHA}$

C_{thHA} C_{thCH} C_{thJC}

A H C J

T_A T_H T_C T_J
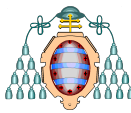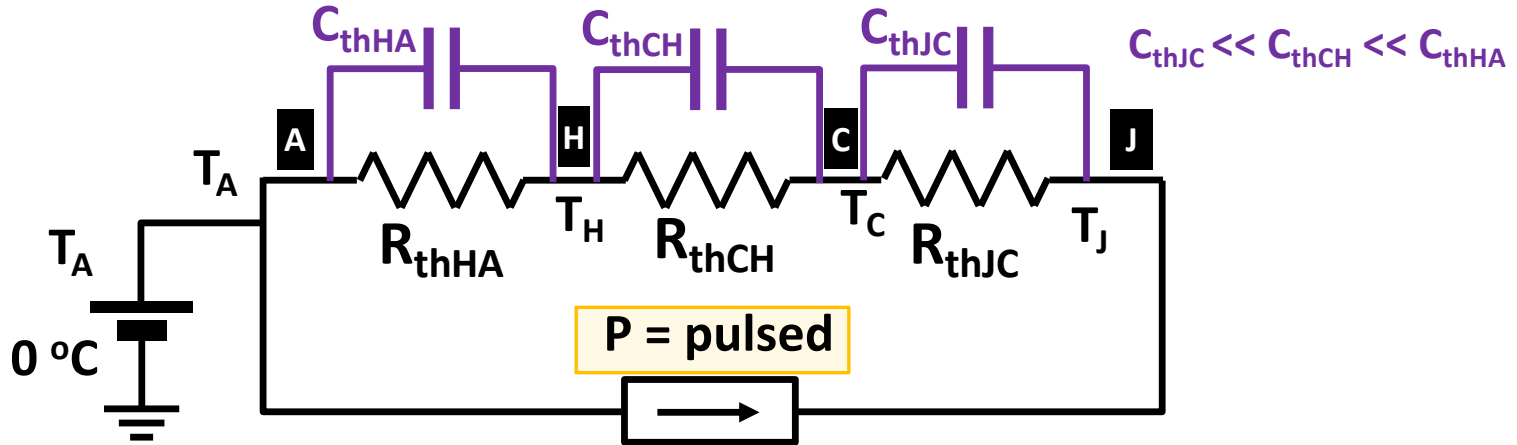
R_{thHA} R_{thCH} R_{thJC}

T_A

0 ºC

P = pulsed

• T_H and T_C can be computed from P_{avg}, because $R_{thHA} \cdot C_{thHA} \gg t_S$ and $R_{thCH} \cdot C_{thCH} \gg t_S$. Hence, the AC component of P can be removed and, therefore:

$$T_H = T_A + P_{avg} \cdot R_{thHA} \quad \text{and} \quad T_C = T_H + P_{avg} \cdot R_{thCH}$$

• **However, $R_{thHA} \cdot C_{thHA}$ may be lower than t_S and, therefore, T_J cannot be computed from R_{thJC} and P_{avg}.**
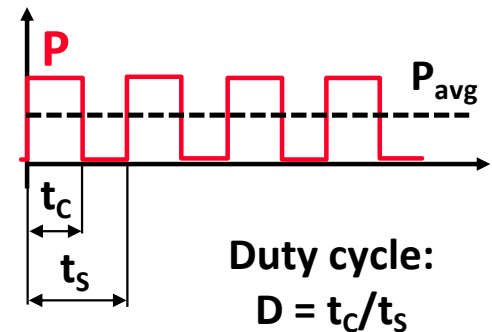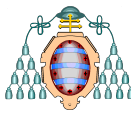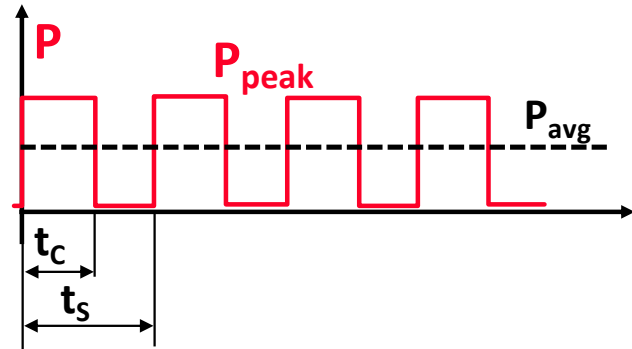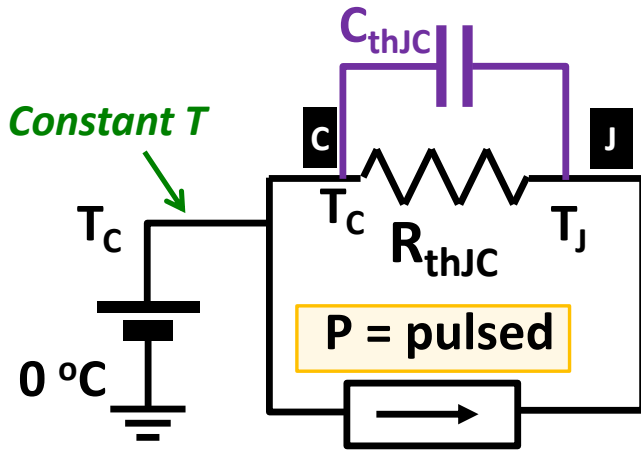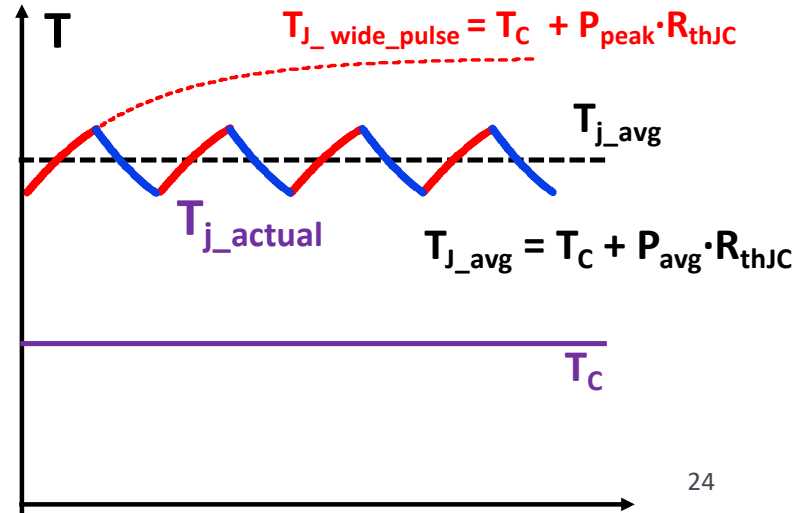
P

P_{avg}

t_C

t_S

Duty cycle:
$D = t_C / t_S$

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• **Transient thermal model for pulsed-power operation in steady-state (II) (after the start-up process)**

Constant T

T_C

$0\ ^oC$

C_{thJC}

C — T_C — R_{thJC} — J — T_J

P = pulsed

P

P_{peak}

P_{avg}

t_C

t_S

T

$T_{J\_wide\_pulse} = T_C + P_{peak} \cdot R_{thJC}$

T_{j_avg}

T_{j_actual}

$T_{J\_avg} = T_C + P_{avg} \cdot R_{thJC}$

T_C

• **The maximum value of the actual temperature is not as low as** $T_{J\_average}$.

•**The maximum value of the actual temperature is not as high as** $T_{J\_wide\_pulse}$.

• **How can we compute the maximum value of the actual temperature?** $\Rightarrow$ *Transient thermal impedance*.
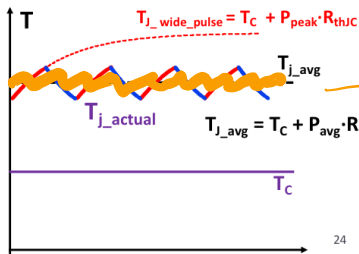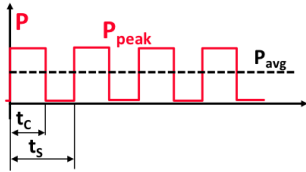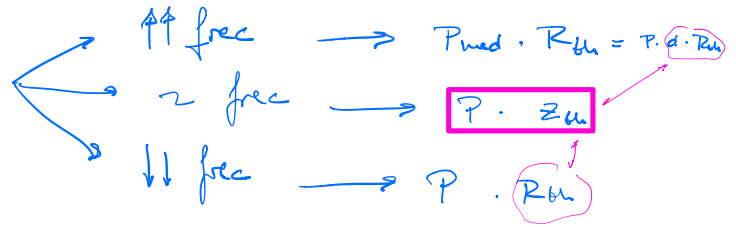
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3 CASOS POSIBLES

$\uparrow\uparrow$ frec $\longrightarrow$ $P_{med} \cdot R_{th} = P \cdot d \cdot R_{th}$

$\sim$ frec $\longrightarrow$ $\boxed{P \cdot Z_{th}}$

$\downarrow\downarrow$ frec $\longrightarrow$ $P \cdot R_{th}$
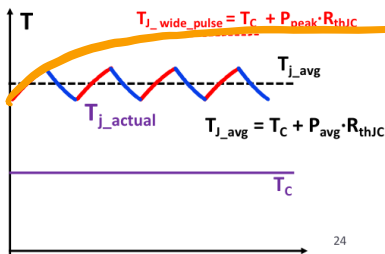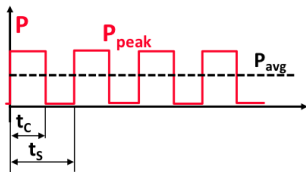
P

P_{peak}

P_{avg}

t_C
t_S

T

$T_{J\_wide\_pulse} = T_C + P_{peak} \cdot R_{thJC}$

T_{j_avg}

T_{j_actual}

$T_{J\_avg} = T_C + P_{avg} \cdot R_{thJC}$

T_C

$\Delta T_j = P_{med} \cdot R_{th} = P \cdot Z_{th}$

$\boxed{R_{th} \cdot d = Z}$

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$\uparrow\uparrow$ frec

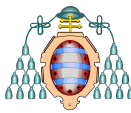Siempre: (Gráfica)

$$\Delta T = P \cdot Z_{th}$$

P

P_{peak}

P_{avg}

t_C
t_S

T

$T_{J\_wide\_pulse} = T_C + P_{peak} \cdot R_{thJC}$

T_{j_avg}

T_{j_actual}

$T_{J\_avg} = T_C + P_{avg} \cdot R_{thJC}$

T_C

24

$$\Delta T = P \cdot R_{th}$$

$f \downarrow\downarrow$
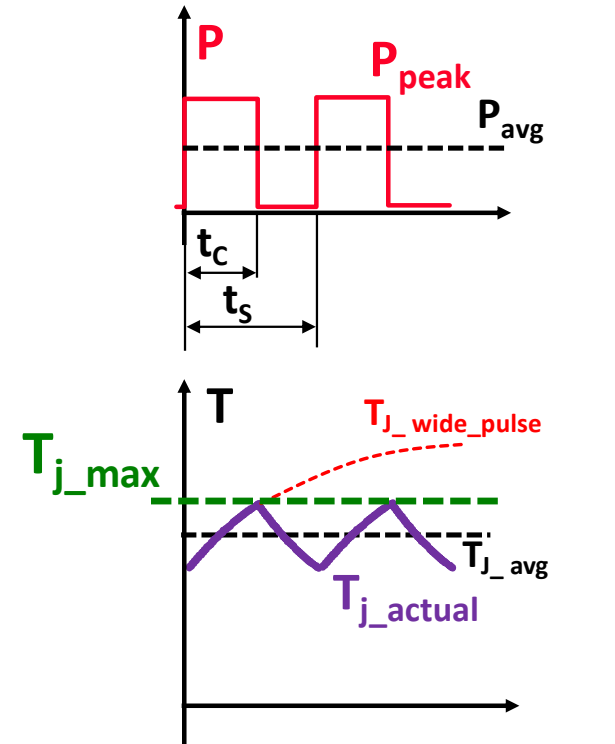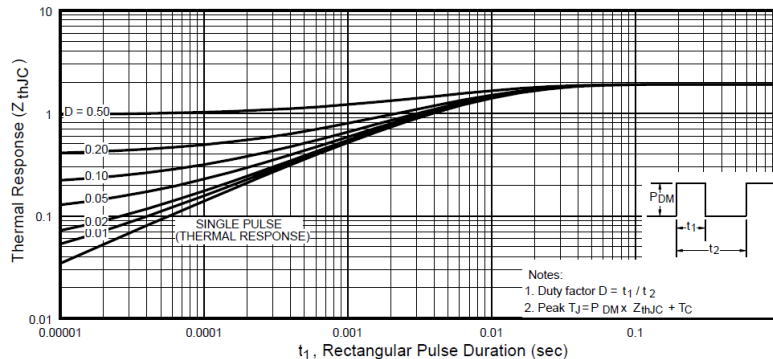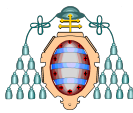
• Concept of transient thermal impedance

• We know that $T_{J\_wide\_pulse} > T_{J\_max} > T_{J\_avg}$.

• We will compute T_{J_max} considering P_{peak} and an impedance lower than R_{thJC}.

• This impedance is called transient thermal impedance, $Z_{thJC}(t)$.

• Its value depends on the duty cycle and on the switching frequency.

• The final equation to compute T_{J_max} is:

$$T_{J\_max} = T_C + P_{peak} \cdot Z_{thJC}(t)$$

$$T_{J\_wide\_pulse} = T_C + P_{peak} \cdot R_{thJC}$$

$$T_{J\_avg} = T_C + P_{avg} \cdot R_{thJC}$$

• **Example of transient thermal impedance (I)**
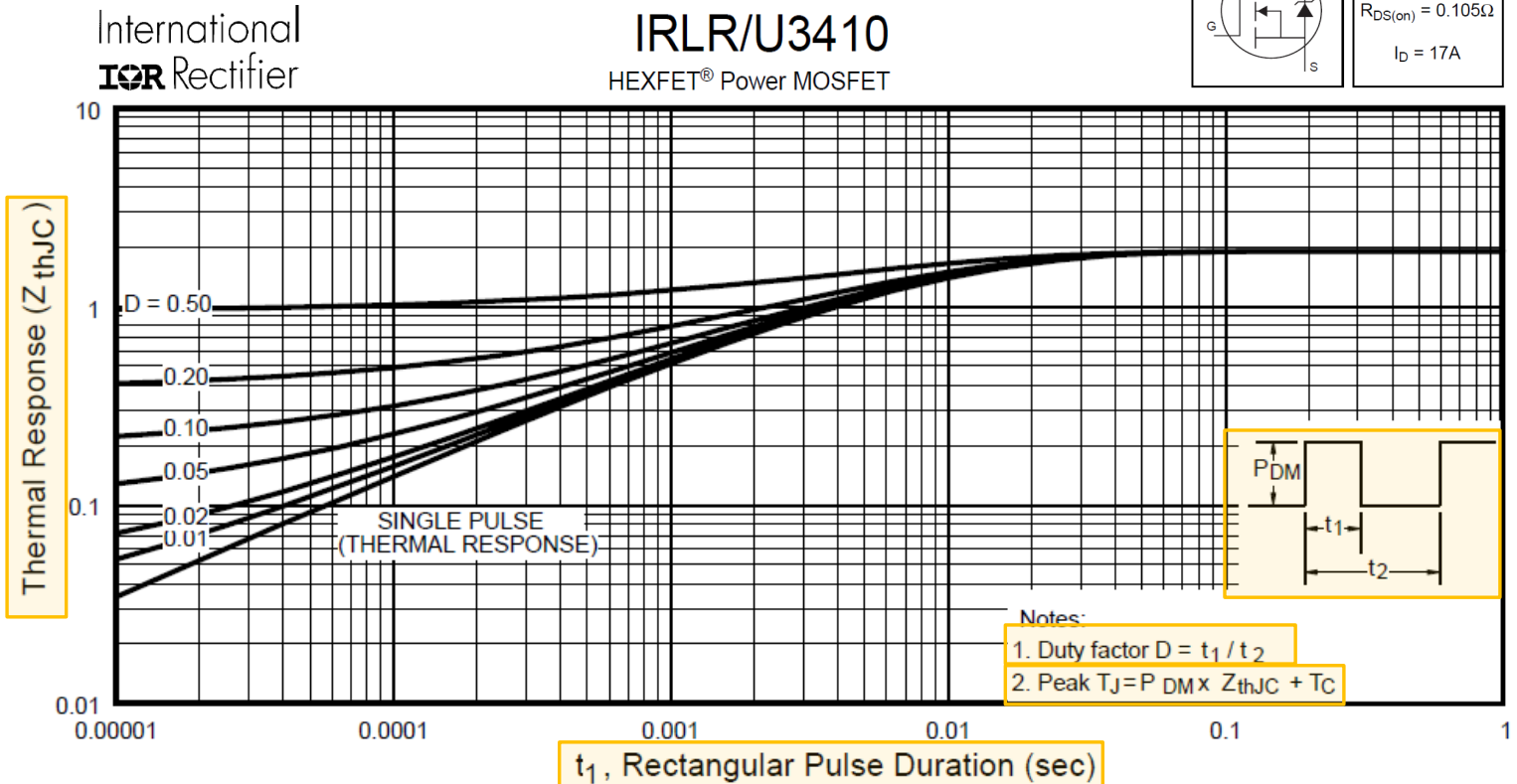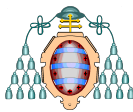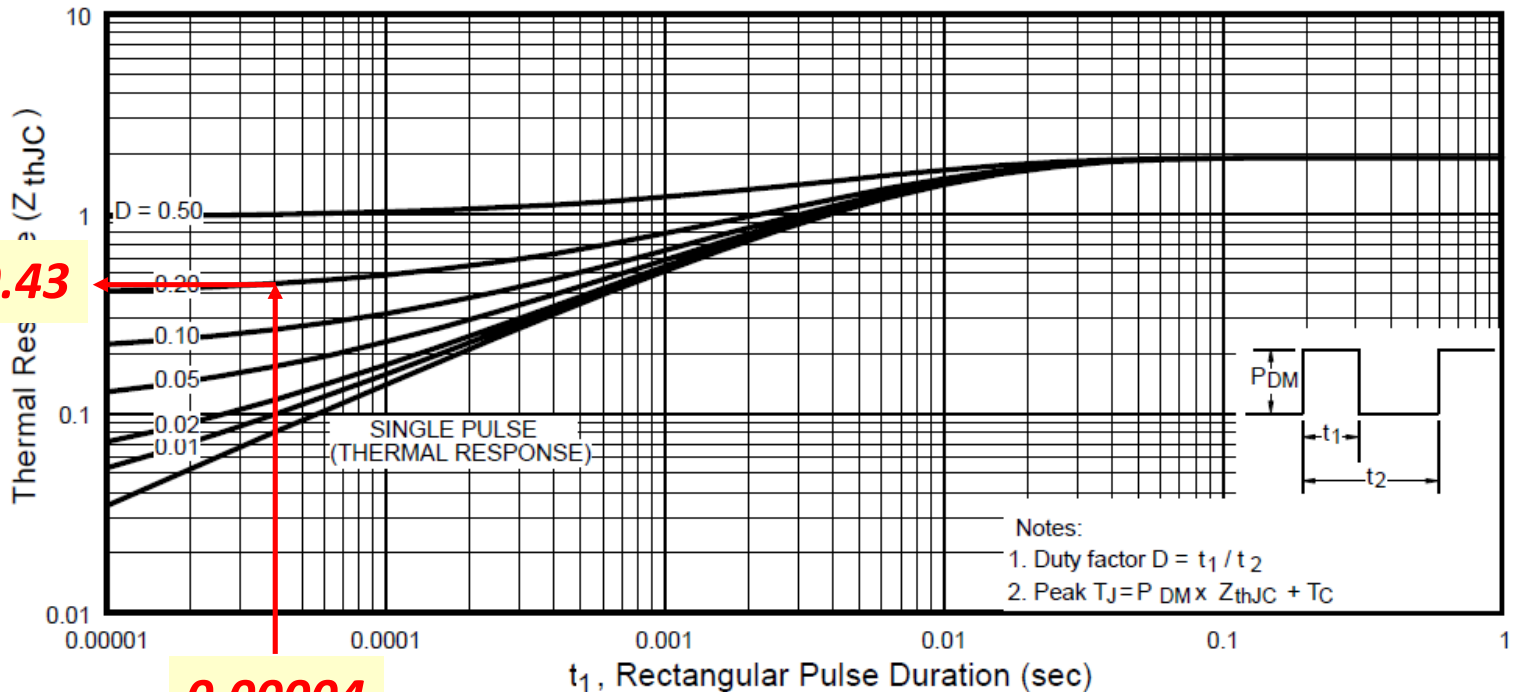
$$T_{J\_max} = T_C + P_{peak} \cdot Z_{thJC}(t)$$

Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

- **Example of transient thermal impedance (II)**

$$t_1 = D \cdot t_2 = D/f_S = 0.2/5 \text{ kHz} = 0.00004 \text{ sec}$$

$f_s = 5 \text{ kHz}$

$D = 0.2$

25 W

$$Z_{thJC} = 0.43 \text{ °C/W}$$

$$T_{J\_max} - T_C = 25 \text{ W} \cdot 0.43 \text{ °C/W} = 10.75 \text{ °C}$$
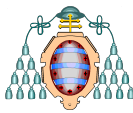
• **Relationship between transient thermal impedance and thermal resistance**

$$Z_{thJC}(\infty) \rightarrow R_{thJC}$$

Notes:
1. Duty factor $D = t_1 / t_2$
2. Peak $T_J = P_{DM} \times Z_{thJC} + T_C$
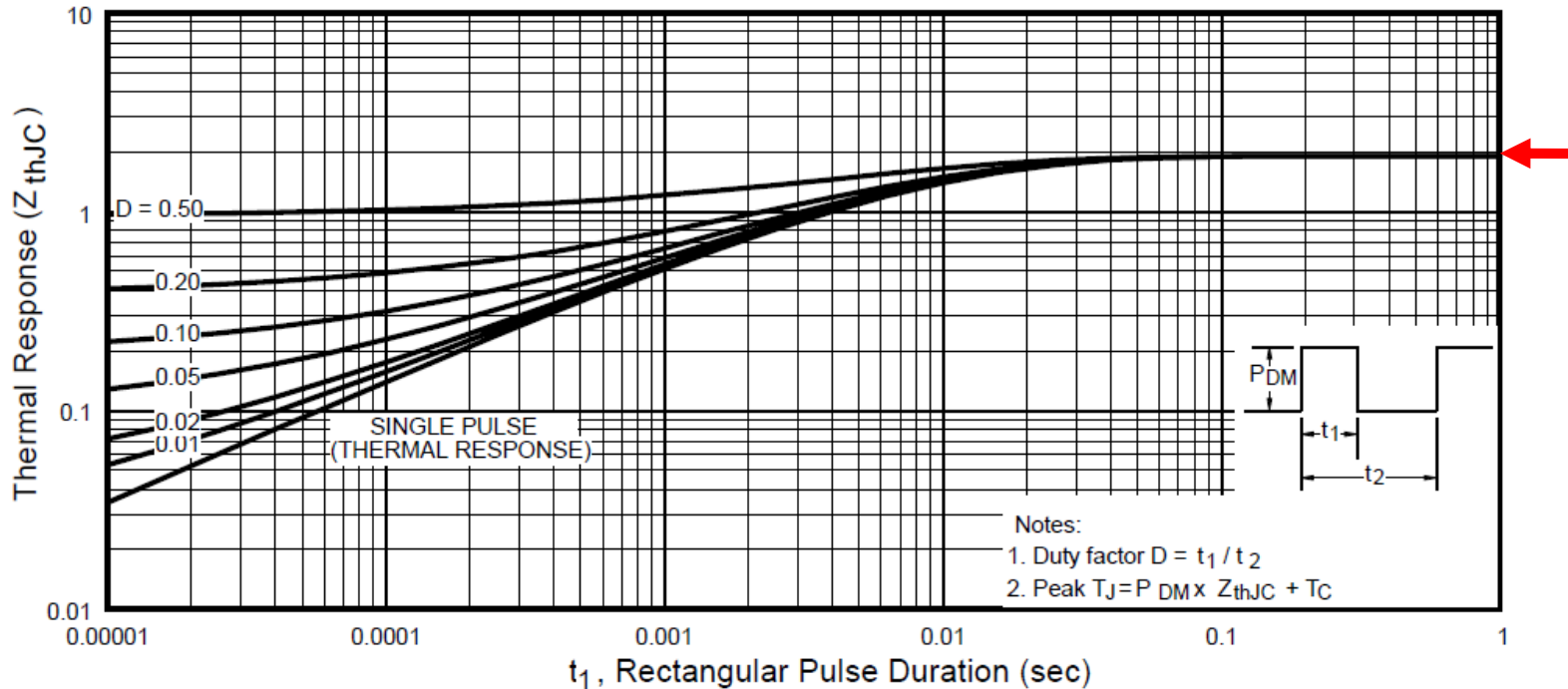
Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	——	1.9	
$R_{\theta JA}$	Junction-to-Ambient (PCB mount) **	——	50	°C/W
$R_{\theta JA}$	Junction-to-Ambient	——	110	