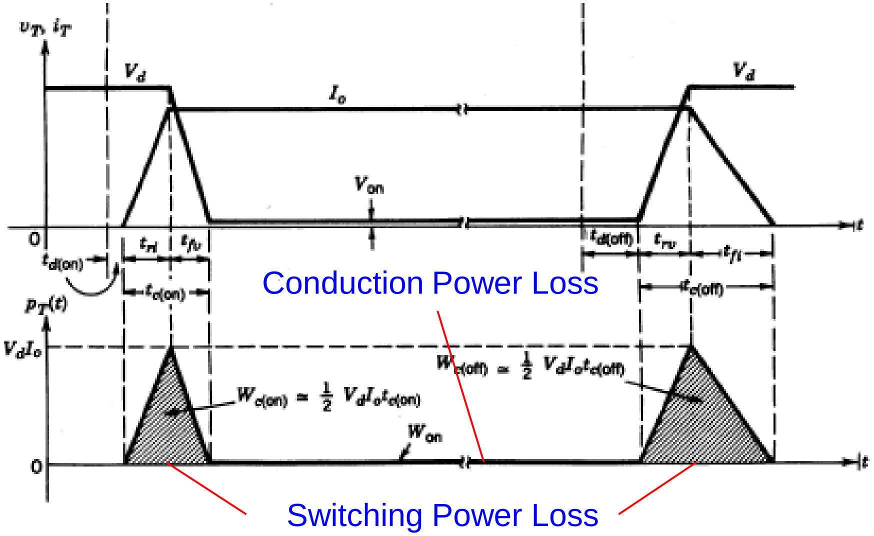
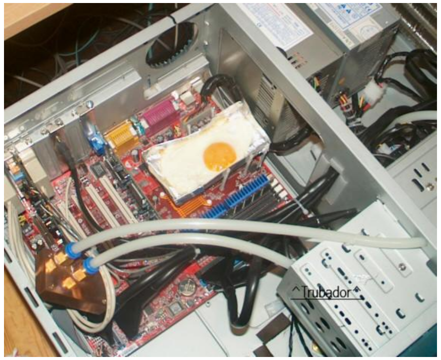
University of Glasgow

ENG2045

Power Electronics

Thermal Management





fry eggs on it !!!

Thermal Management.

No electronic device is 100% efficient and therefore every device must loose some energy in the form of heat. For power electronic devices this energy loss can be considerable. Most semiconductors have a maximum operating temperature of 125°C and to prevent this temperature being exceeded, some form of *heatsink* is needed.

•Another reason to keep electronic components cool is to do with their reliability, The failure rate for semiconductor devices doubles for approximately every 10°C temperature rise.

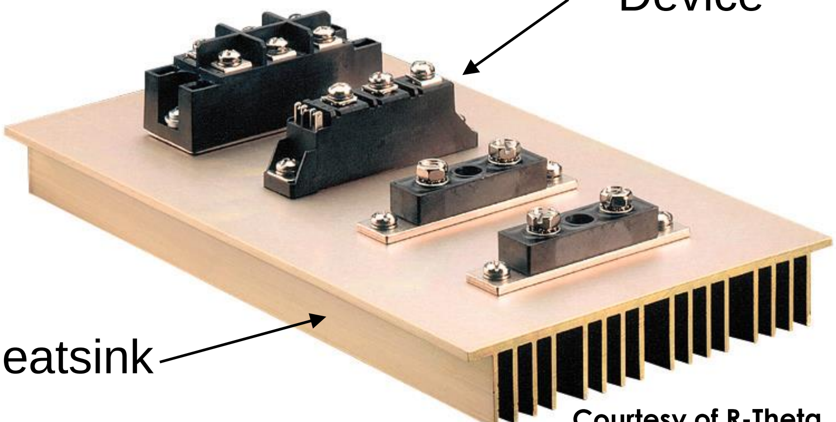
•In addition to the maximum temperature, semiconductors also have an absolute maximum power rating that cannot be exceeded without damaging the device, regardless of its temperature.

A heatsink(散热器）is usually made of a **good thermal conductor** such as copper (expensive) or aluminium (not so expensive). The device to be cooled is mechanically attached to the heatsink.

Example Heatsinks

Natural Air Cooled

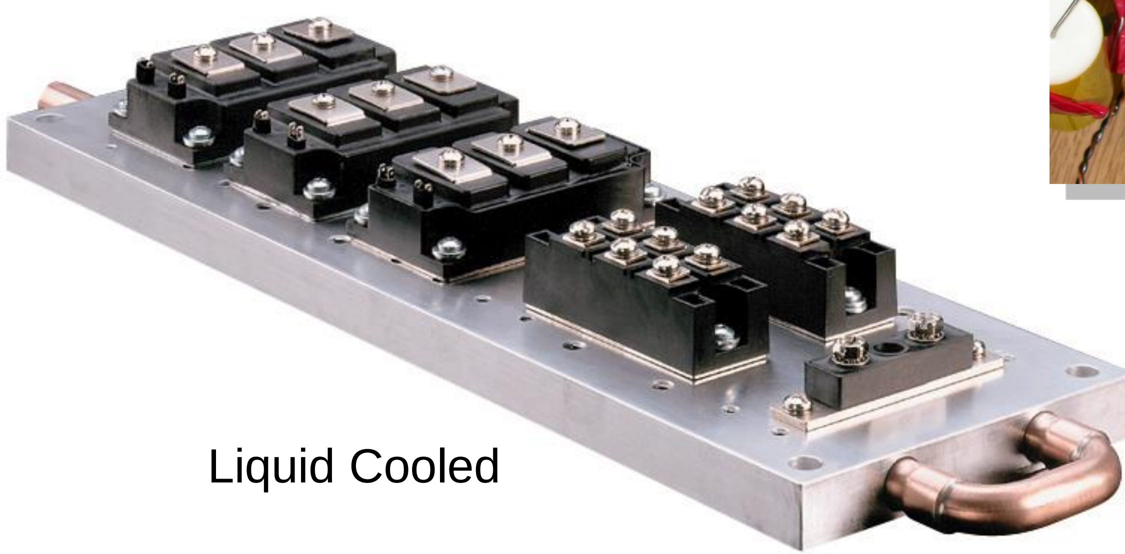
Device



Heatsink

Courtesy of R-Theta, Inc.

Forced Air Cooled



Liquid Cooled

Liquid

There are three heat transfer mechanisms: conduction, convection and radiation.

Conduction: The primary mode of heat transfer for solids in contact with one another.

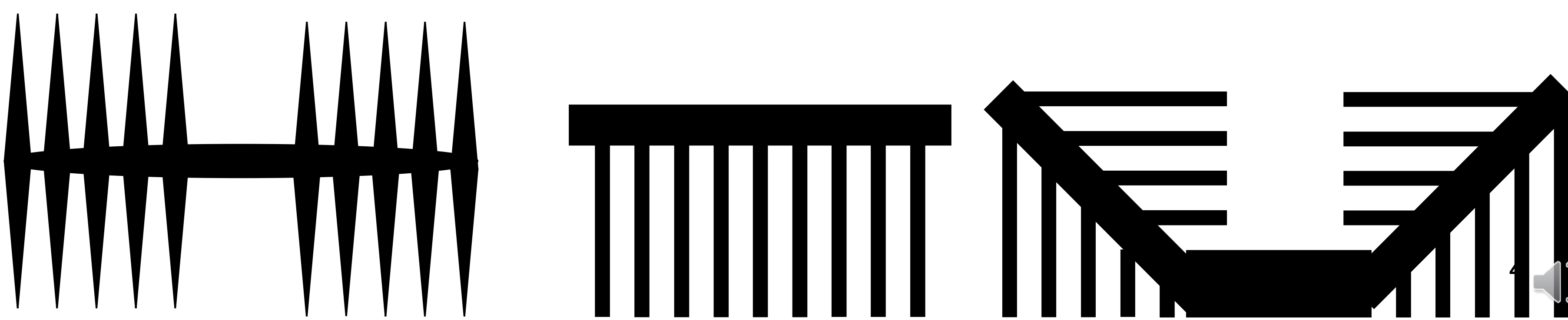
Convection: Heat energy is transferred between a solid and a fluid (air or water).

Radiation: Energy transfer is by electromagnetic radiation.

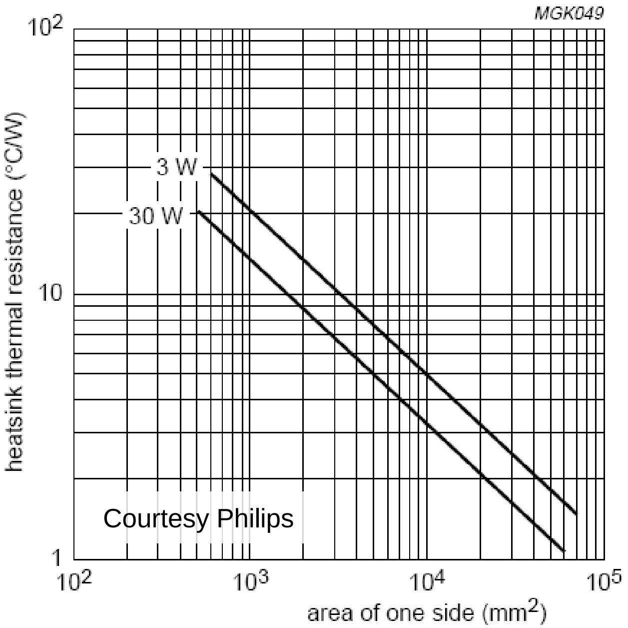
Two air convection mechanisms are commonly used:

Natural convection: Warm air around the heatsink rises and this natural convection current carries the energy away. Heatsink performance is usually quoted as “fins vertical in free air” – the orientation of the heatsink is optimal for natural air flow to occur and there are no obstacles in the air’s path.

Forced convection: A fan is used to blow air over the heatsink surfaces, thereby removing more energy. Turbulent flow(湍流) is more effective than laminar flow(层流) and hence it is usual to blow air at a heatsink rather than pull air over it.



The ability of a heatsink to dissipate energy, i.e., the rate of flow of power, is called the heatsink's thermal resistance, measured in °C/W. The Greek letter theta (θ_{XX}) with two suffixes is used to denote the thermal resistance between two points in the thermal circuit. For example, θ_{JA} denotes the thermal resistance between the semiconductor junction and the ambient surroundings.



For power device heatsinks, **typical thermal resistances are:**

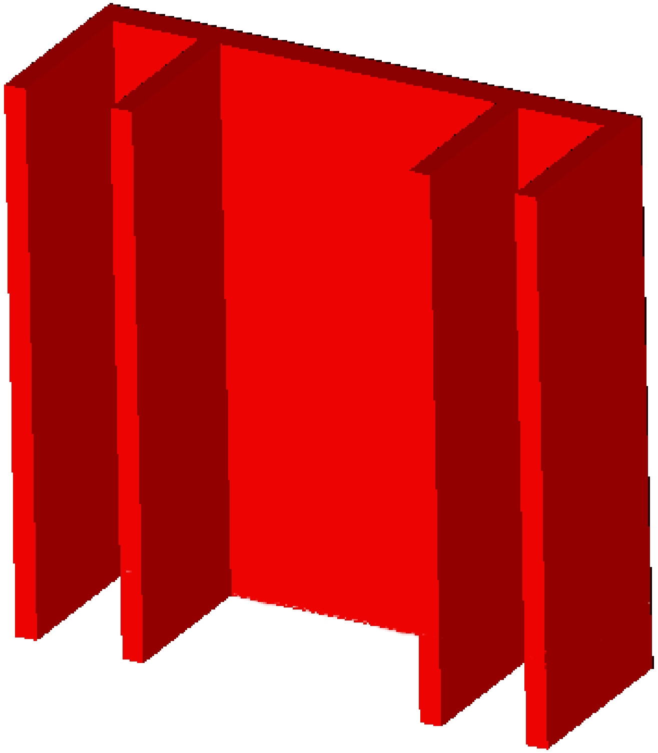
Natural convection	$1°C/W \rightarrow 0.1°C/W$
Forced Air	$0.1°C/W \rightarrow 0.01°C/W$
Water cooled	$0.01°C/W \rightarrow 0.001°C/W$

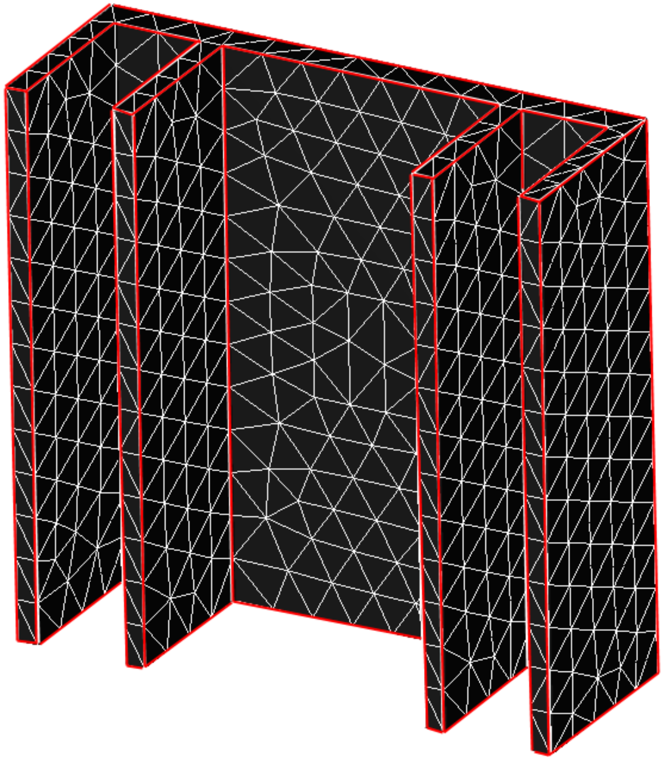
[A 300mm x 300mm x 3mm black aluminium plate ≈ 1°C/W]

Heatsinks are often formed from aluminium extrusions, with the flow of air in the extrusion direction. The extrusions do not have to be very thick because, for natural convection, power loss is relatively low and hence the metal thermal conductivity dominates. Black coating the heatsink improves the radiation characteristics when $\Delta T > 50°C$ and reduces the free air thermal resistance by about 15%. The most effective way to decrease the thermal resistance is by maximising the surface area since the predominant heat loss mechanism is by convection.

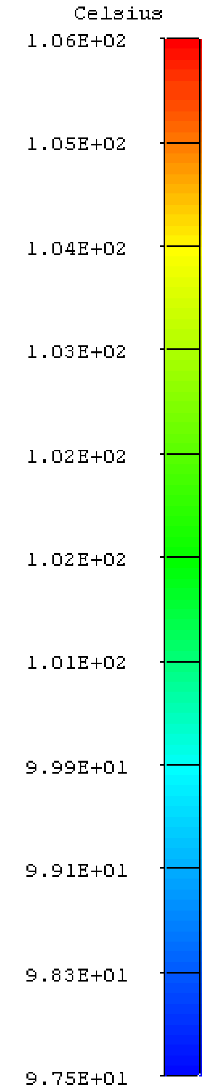
Use of computer simulations for heatsink design.

We can use numerical (e.g. Finite Element) analysis to examine the performance of different heatsink shapes. For example, 4 fins（鳍） added to a flat plate: how does it perform? The first step is to create the solid model of the part and then represent it by a mesh of elements (tetrahedra（四面体）).

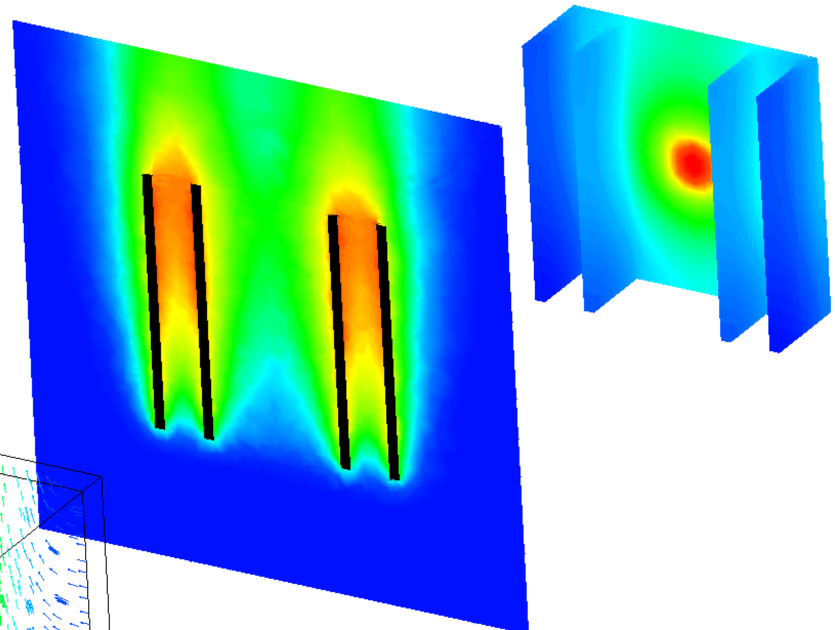


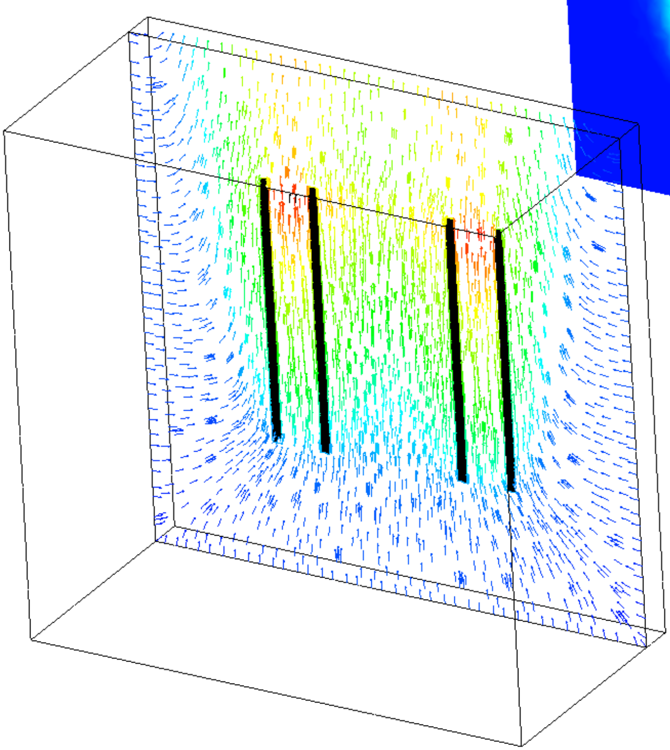


The computer will solve the differential equations governing the flow of energy through the material and take into account the energy lost through conduction etc. to the surrounding air (or water). The induced air flow is also calculated and velocity (for example) can be plotted around the solid. This is an example of the application of computational fluid dynamics (CFD).



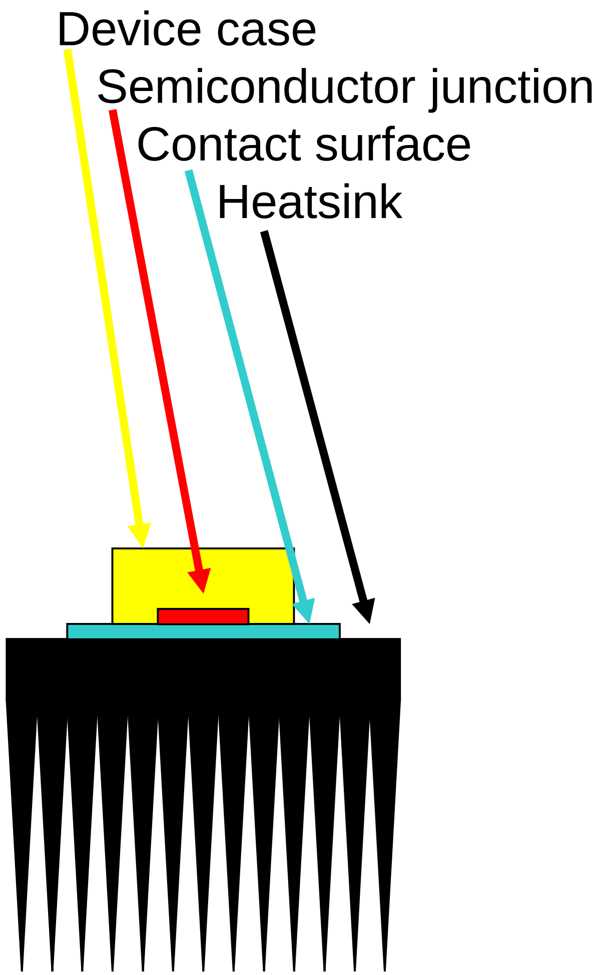
50mm x 50mm x 20mm
heatsink with P=15W



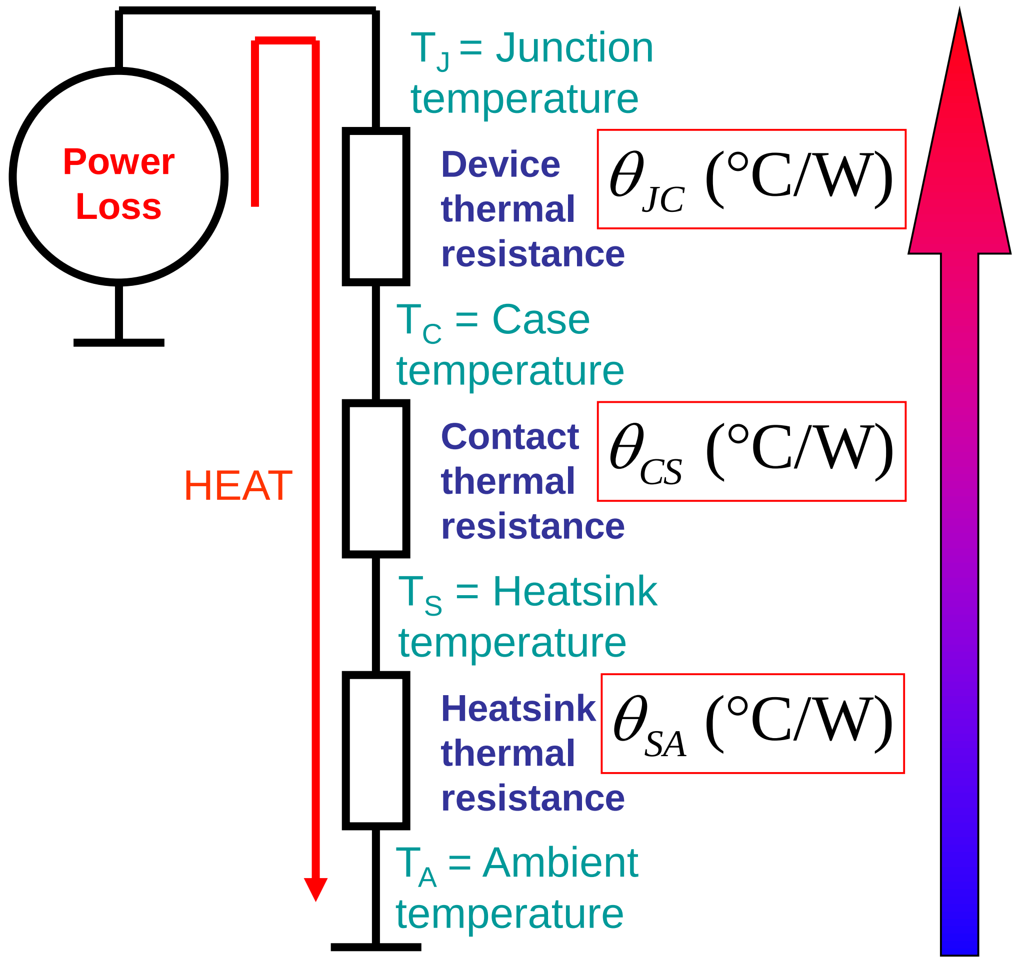


This type of analysis is particularly good at allowing the designer to visualise the way in which his/her designs are performing compared to expectations. Obviously the actual thermal performance can also be evaluated.

Equivalent Thermal Model



Ambient (“Free air”)



$$\boxed{\Delta\ \text{Temp}\ (^\circ\text{C}) = \text{Power}\ (\text{W}) \times \sum \theta_{XX}}$$

The heatsink needs to have low thermal resistance to the surrounding cooler air.

Steady-state thermal analysis.

From the previous figure, consider a power diode attached to a heatsink. There are three thermal resistances between the power source (the semiconductor junction) and the ambient surroundings:

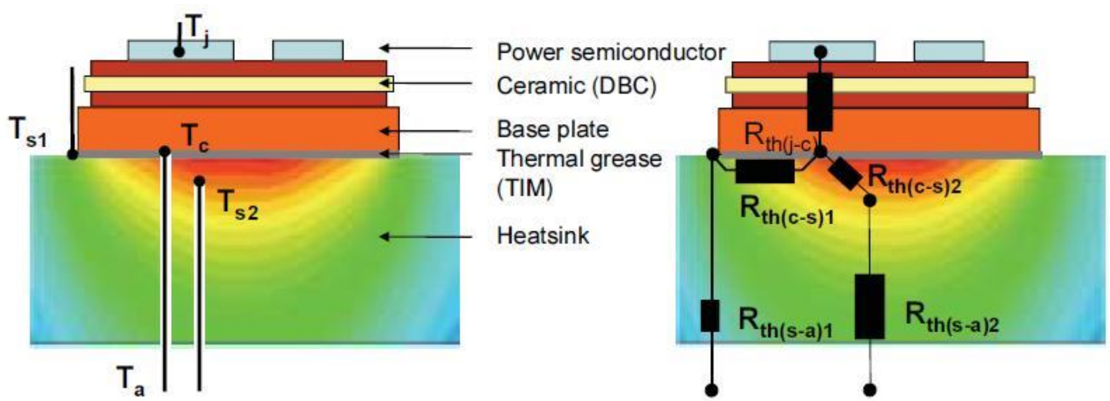
θ_{JC} = The thermal resistance between the junction and the case

θ_{CS} = The thermal resistance between the case and the heatsink

θ_{SA} = The thermal resistance between the heatsink and the surrounding air.

This can be modelled as a set of resistors in series, with the temperature drop across each being dependent on the power flowing through it.

The **temperature drop** is given by ΔT (°C) = Power (W) x θ_{XX} (°C/W)



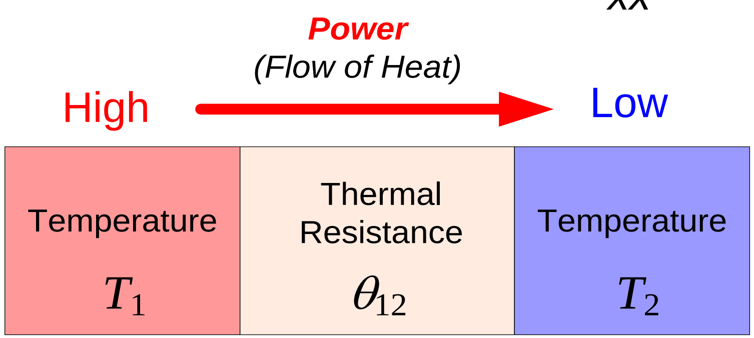
thermal interface material (**TIM**)

Direct bonded copper (DBC) substrates are commonly used in power modules, because of their very good thermal conductivity

The DBC substrates also have excellent electrical insulation and good heat spreading characteristics

Thermal Circuit Analysis

Thermal Resistance θ_{xx}



Thermal **"Ohm's Law"**

$$i = \frac{v}{R}$$

thermal "current"

thermal "voltage"

$$P = \frac{\Delta T}{\theta_{12}} = \frac{T_1 - T_2}{\theta_{12}} \quad {}^\circ C / W$$

thermal resistance

It can be used to model the steady-state heat **conduction** (solids) and **convection** (liquids and gases)

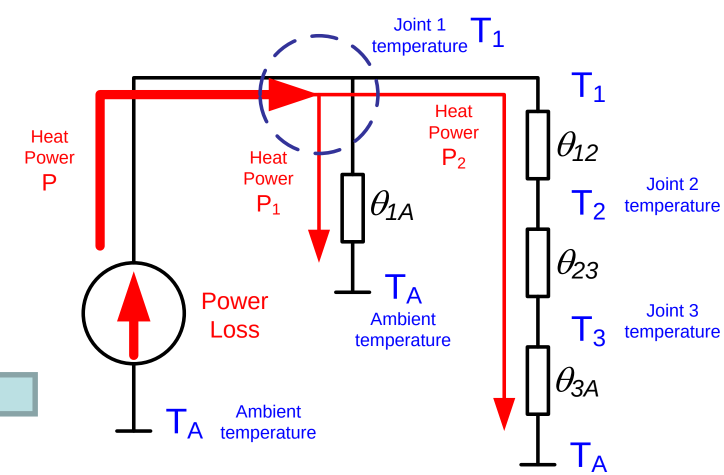
Thermal **"Kirchhoff's Law"**

$$\text{"KVL"}: \quad \sum_{xx} \Delta T_{xx} = 0, \quad \textit{for any loop}$$

$$\text{"KCL"}: \quad \sum_{k} P_k = 0, \quad \textit{for any node}$$

Example:

$$\left.\begin{aligned} P &= P_1 + P_2 \\ \Delta T_{1A} &= \Delta T_{12} + \Delta T_{23} + \Delta T_{3A} \end{aligned}\right\}$$



Thermal Circuit

Example.

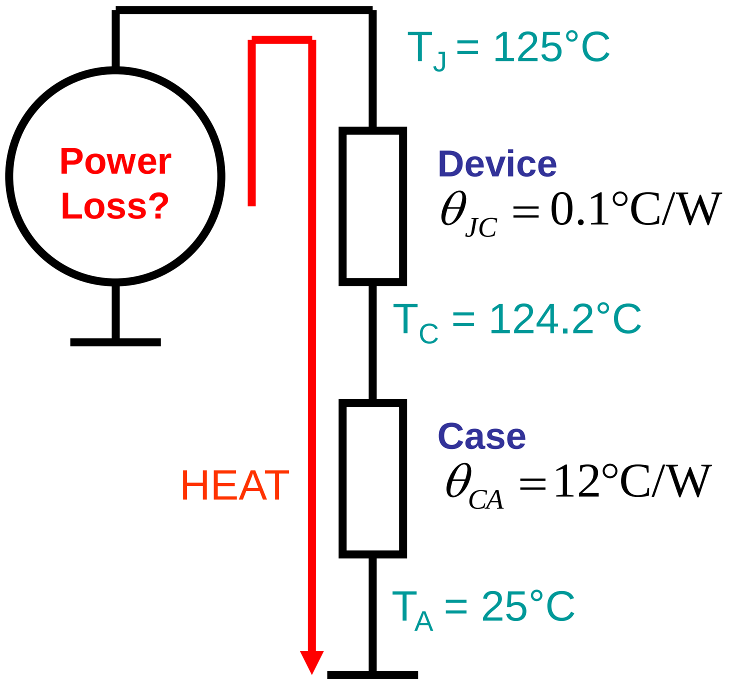
A power diode has thermal resistances θ_{JC} of 0.1°C/W and θ_{CA} of 12°C/W. If the diode is operated in free air with an ambient temperature of 25°C, how much power can it dissipate without the junction temperature exceeding 125°C?

The thermal equivalent circuit looks like:

$$\Delta T = \text{Power} \times \Sigma\theta$$

$$\Rightarrow \text{Power} = \frac{\Delta T}{\Sigma\theta} = \frac{100°\text{C}}{12.1°\text{C/W}} = 8.26\text{W}$$

$$T_C = T_A + \text{Power} \times \theta_{CA} = 25 + 8.3 \times 12 = 124.2°\text{C}$$



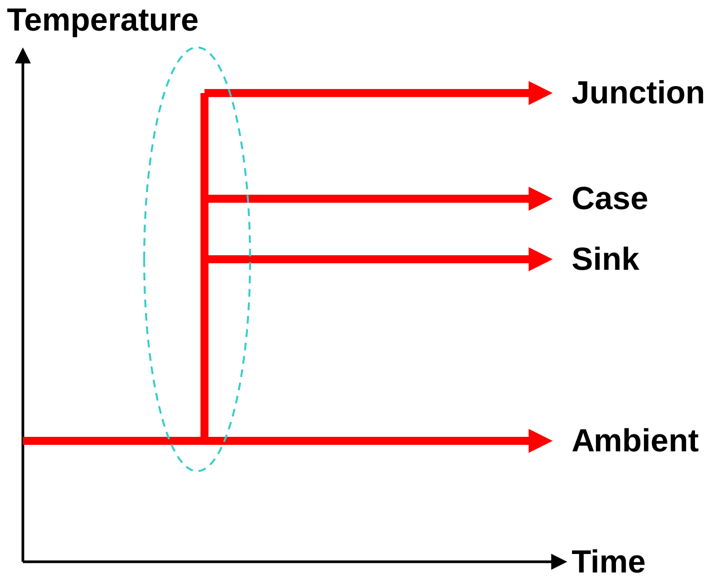
Example (contd).

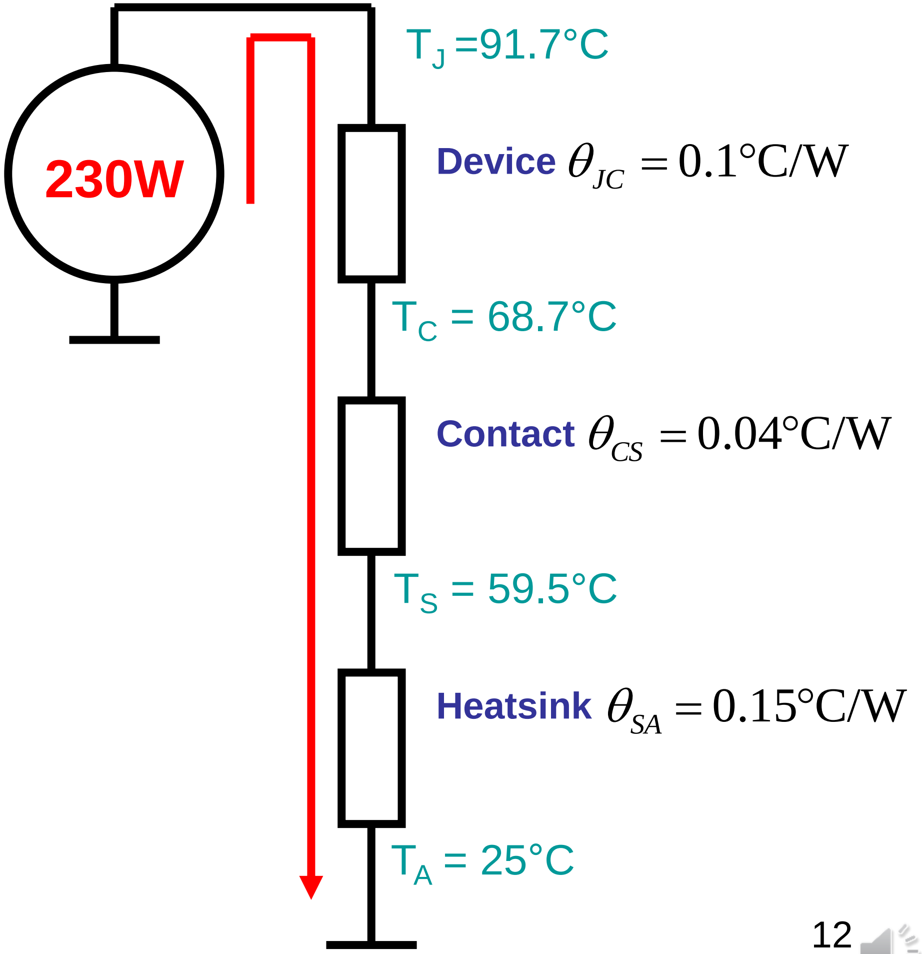
The diode is bolted to a heatsink of thermal resistance 0.15°C/W. The thermal resistance of the contact is 0.04°C/W. What is the heatsink temperature and junction temperature when the diode is dissipating 230W?

$$T_S = T_A + P \times \theta_{SA}$$
$$= 25 + 230 \times 0.15 = 59.5°C$$

$$T_C = T_A + P \times (\theta_{SA} + \theta_{CS})$$
$$= 25 + 230 \times 0.19 = 68.7°C$$

$$T_J = T_A + P \times (\theta_{SA} + \theta_{CS} + \theta_{JC})$$
$$= 25 + 230 \times 0.29 = 91.7°C$$





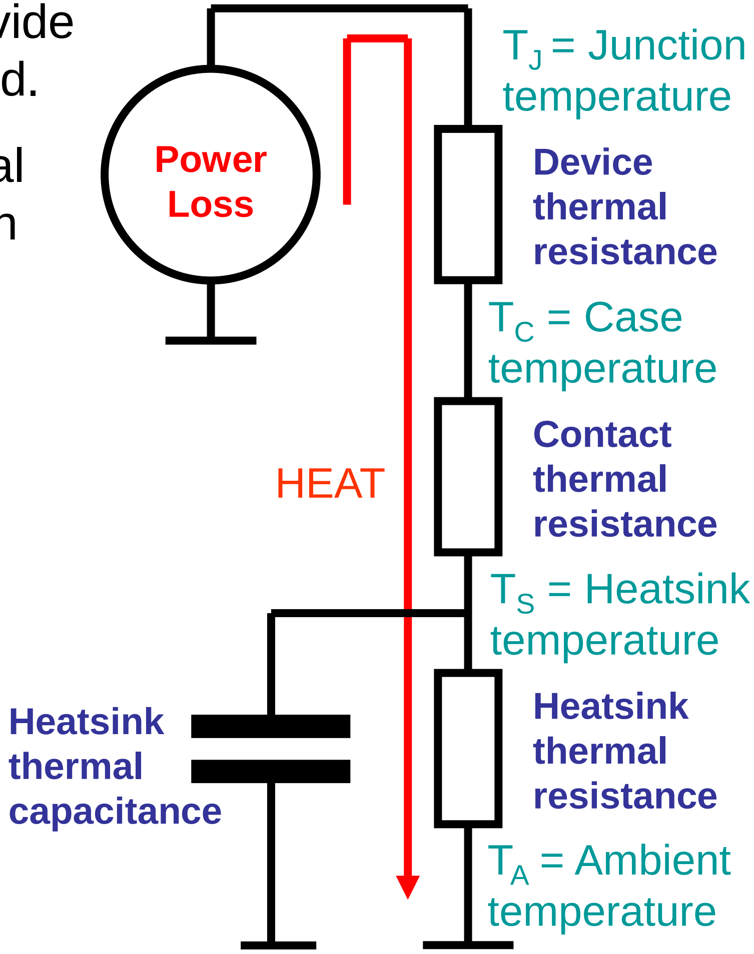
Transient Thermal Circuit Analysis.

Large heatsinks are generally fairly massive aluminium blocks. As such, they cannot change their temperature instantaneously and this thermal inertia can be exploited to limit the temperature rise for short periods. This can provide a more economical design or provide a safety margin in the event of a short overload.

The thermal mass can be added to our thermal equivalent model as a capacitor in parallel with the heatsink thermal resistance.

Other elements also have a thermal capacitance, but it is so small it can be usually ignored.

We want to be able to determine the rate at which the heatsink temperature rises as a function of its mass and the power being added to it.



T_{SS} is the steady-state temperature of the heatsink. The *thermal time constant* τ is simply the product of the thermal resistance and the thermal capacitance.

$$\boxed{\tau = RC = \theta_{SA} \times C_{SA}}$$

The actual temperature T at any given time t is given by: $T_{Actual} = T_{Final}\left(1 - e^{\frac{-t}{RC}}\right)$

If we plug some numbers into this equation, we see:

$t = 0.5\tau = 39\%$

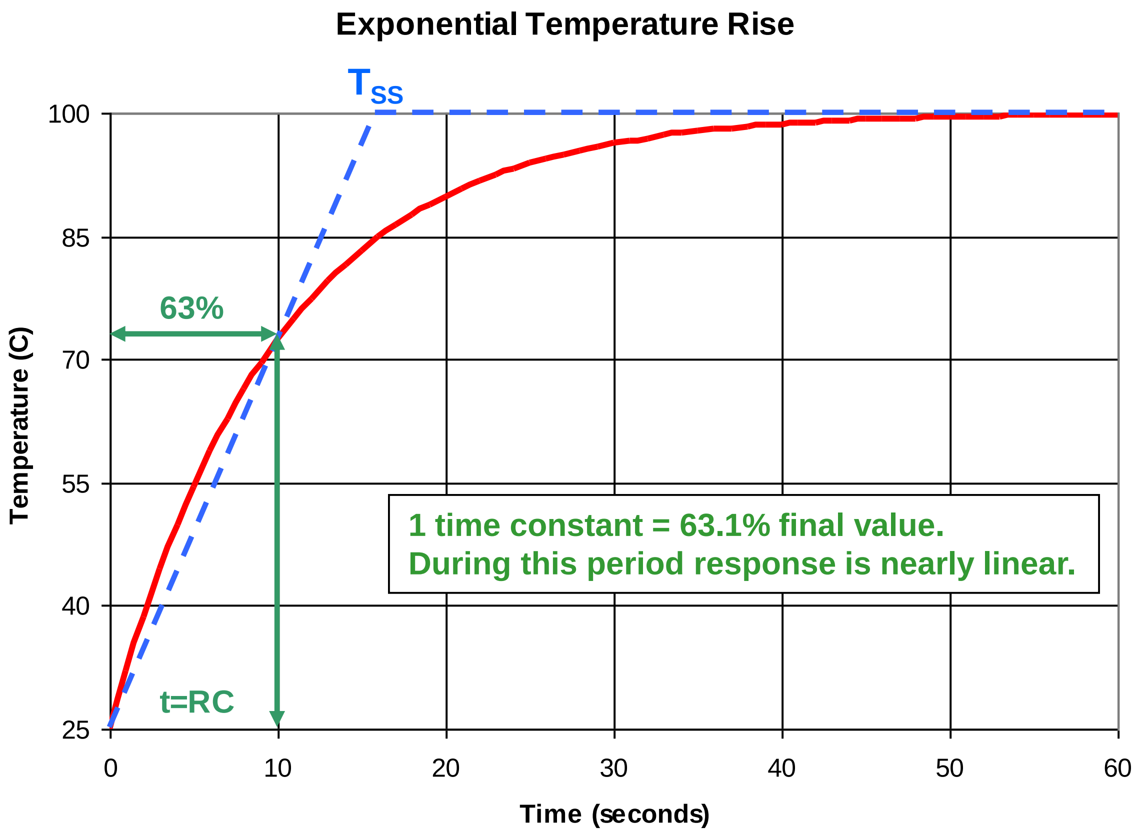
$t = \tau = 63\%$

$t = 2\tau = 86\%$

$t = 3\tau = 95\%$

$t = 4\tau = 98\%$

$t = 5\tau = 99\%$



The thermal capacitance is the product of the heat capacity of the material multiplied by the mass of the material. (Aluminium = 913J/kg per °C)

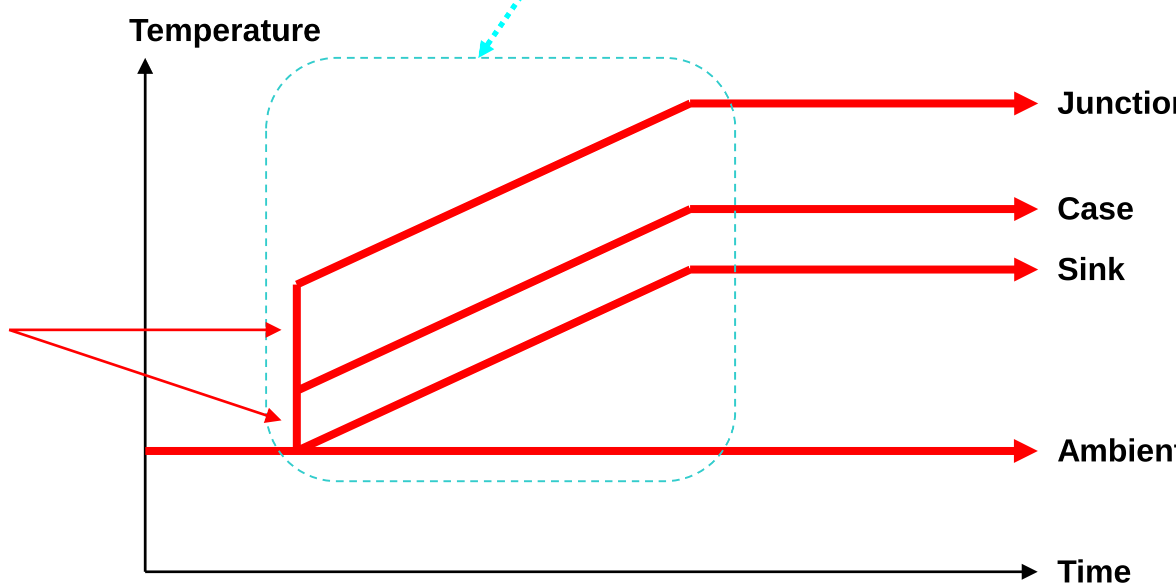
$$\boxed{C_{SA}(\text{Joules per °C}) = \text{Heat Capacity}(\text{J per kg °C}) \times \text{Mass}(\text{kg})}$$

If we approximate the temperature rise to be linear during the first part of the curve and assume no heat is dissipated during the period of temperature rise:

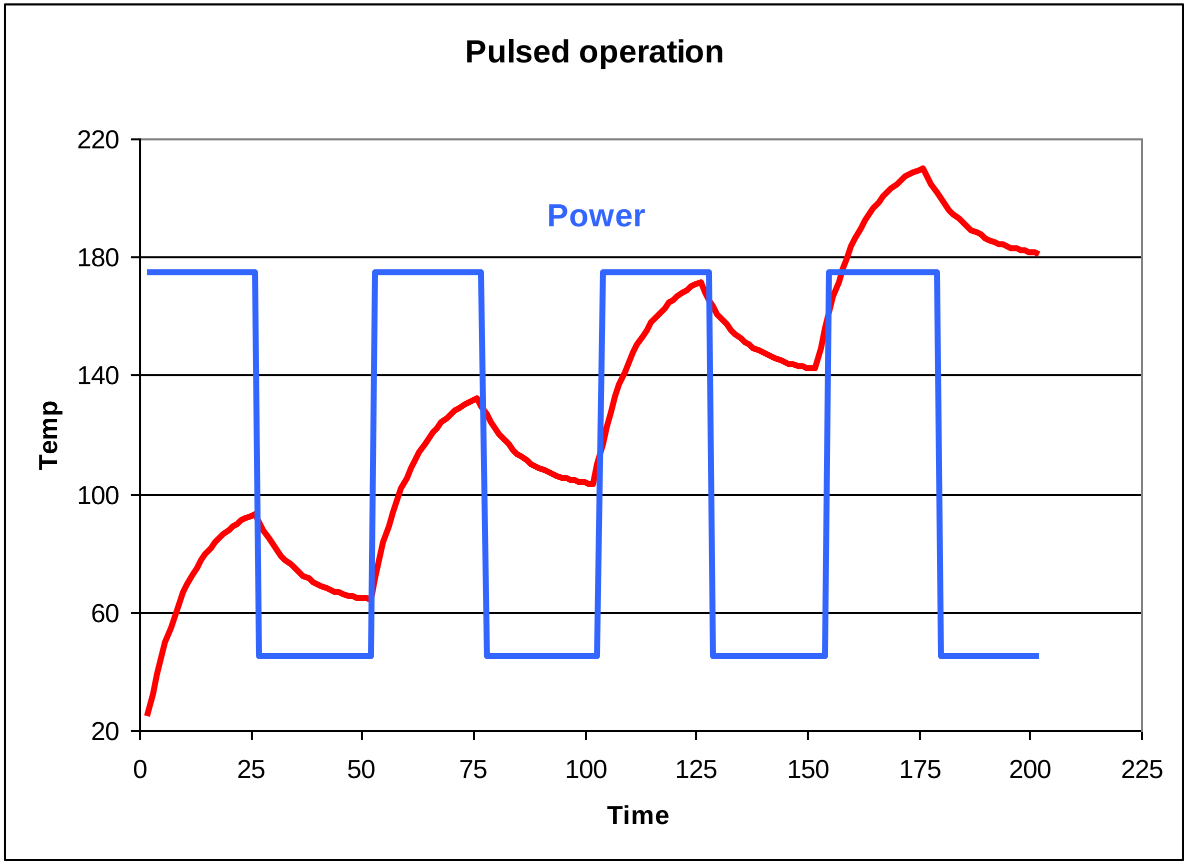
$$\boxed{\Delta T = \frac{\text{Power} \times \text{Time}}{\text{Thermal Capacitance}}}$$

During this period the rate of change of temperature is limited by heatsink's mass. For $t < \tau$ we can assume a linear slope.

Thermal inertia of case and junction are tiny.



Transient operation of the heatsink needs to be handled carefully. The cool-down period of the heatsink will be much longer than the time to warm up when high power is being dissipated. It is also important to ensure the junction temperature is not exceeded.

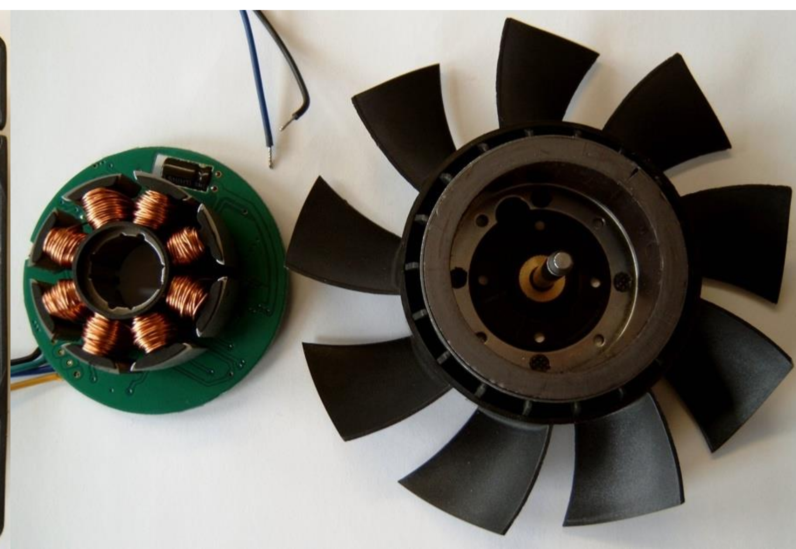


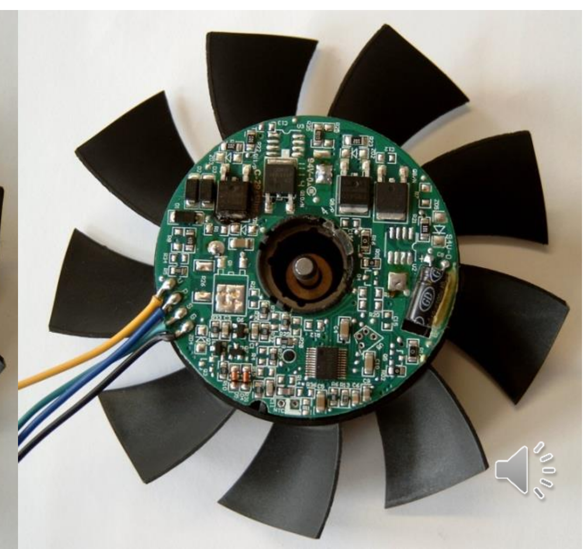
In pulsed operation the device may be OK initially, but the slow cool-down of the heatsink means the maximum junction temperature can quickly be exceeded.

Smart Cooling fans.

As electronic devices have become more embedded in domestic life, noise levels have become a big issue. In the “old days” (2005), the noise a computer made didn’t really matter since they were usually in an office environment (noisy). Fans had only 2 wires (‘+’ and ‘–’). High end PCs and servers used a 3 wire fan: the third wire was a tacho output which gave 2 pulses (usually) per revolution. In this way the computer could monitor the fan’s speed and create an alert if a fan was stalled (and hence system cooling was compromised). Modern fans use 4 wires: the fourth wire is a Pulse Width Modulated (PWM) input. The duty cycle %age controls the fan’s speed [and the tacho is there to provide feedback]. 0% = “off” and 100% = “full speed”, with a usually linear variation in fan RPM between these limits.

Apart from the noise, the power drawn by the fan varies as the cube of the speed of rotation and so halving the fan’s RPM drops the power drawn by a factor of 8. Thus the computer (for example) can measure its internal temperature and need only provide sufficient cooling to keep itself within the temperature specification.





Example 1.

Two diodes and a transistor share a single heatsink. The thermal resistances are given in the table below. What is the junction temperature for each device if the ambient temperature is 45°C and the heatsink thermal resistance is 0.75°C/W?

Each Diode	Transistor
θ_{JC}=0.33°C/W	θ_{JC}=0.2°C/W
θ_{CS}=0.15°C/W	θ_{CS}=0.1°C/W
Power = 10W	Power = 50W

First, calculate the heatsink temperature:

$T_{sink} = T_{amb} + P_{total} \times \theta_{SA} = 45 + 70W \times 0.75 = 97.5°C$

Now calculate the diode junction temperatures:

$T_{Diode} = T_{sink} + P_{diode} \times (\theta_{JC} + \theta_{CS})$

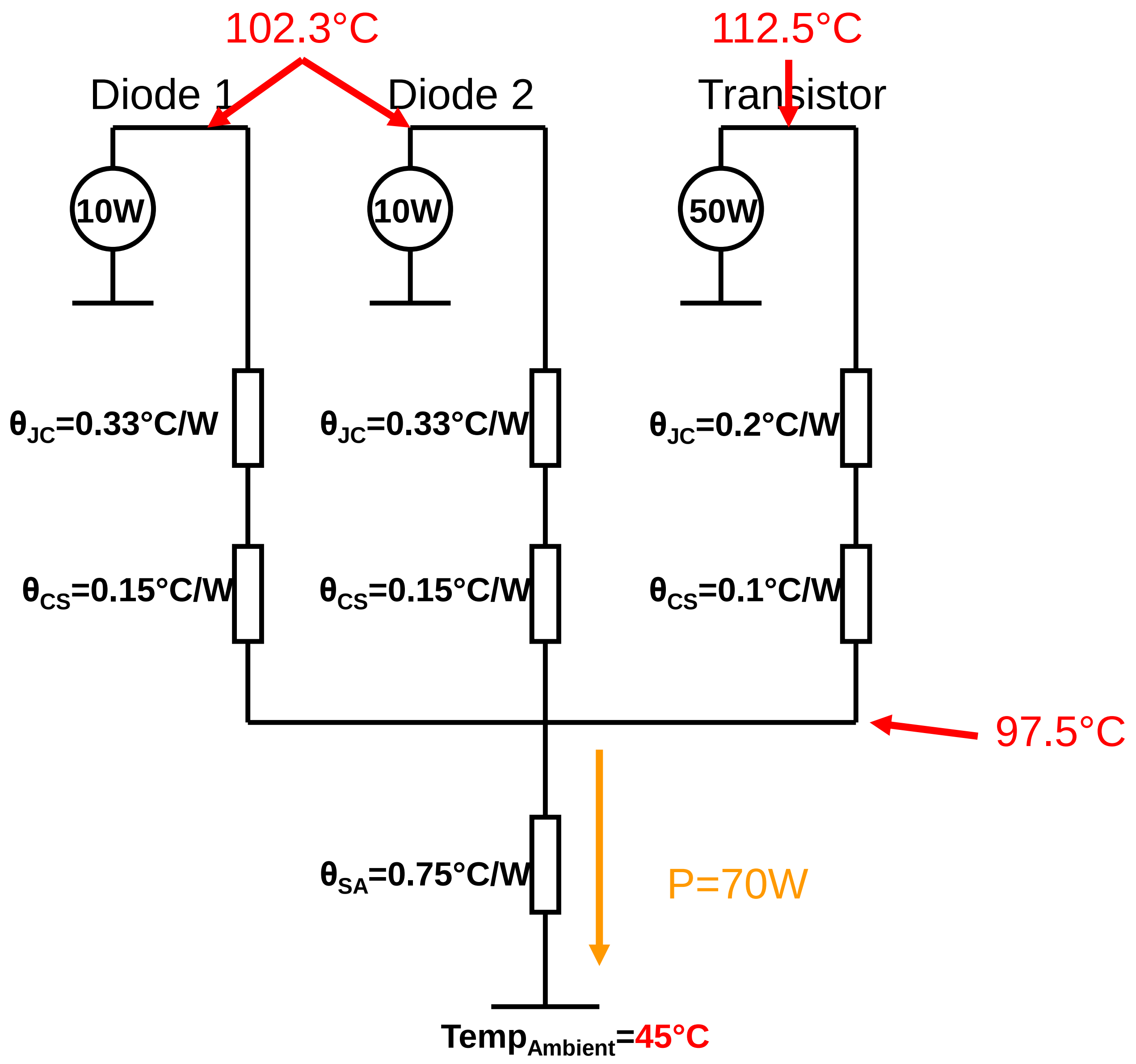
$= 97.5°C + 10 \times 0.48 = 102.3°C$

Finally, calculate the transistor junction temperature:

$T_{trans} = T_{sink} + P_{trans} \times (\theta_{JC} + \theta_{CS})$

$= 97.5°C + 50 \times 0.3 = 112.5°C$

Thermal circuit diagram for example 1.



Example 2.

With the values shown, how long does it take for the junction temperature to reach 125°C? Assume the heat capacity of aluminium is 913J/kg °C.

First, find T_{sink} for $T_{junction}$ = 125°C:

θ_{JS}=0.2°C/W, P = 250W => ΔT_{JS} = 50°C.

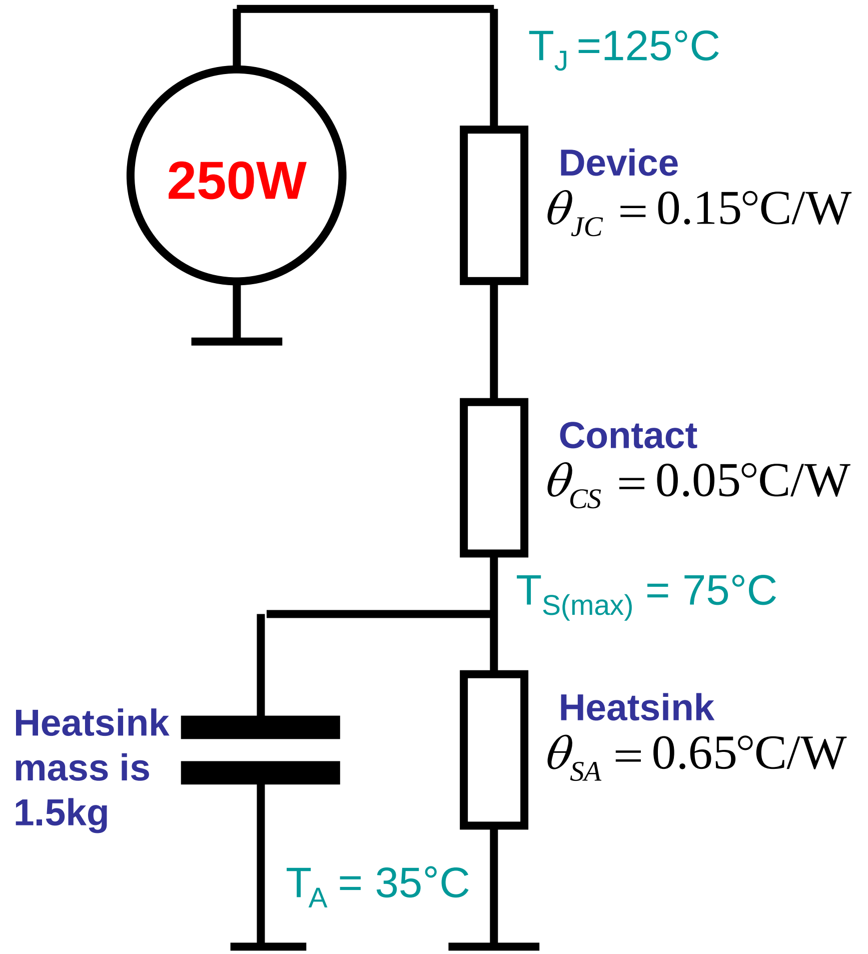
Hence $T_{sink\ (max)}$ for T_j = 125°C is 75°C.

The maximum change in temperature of the heatsink is the maximum temp allowed than the ambient:

$\Delta T_{sink} = T_{max} - T_{amb}$ = 75°C – 35°C = 40°C

$$\boxed{\Delta T = \frac{\text{Power} \times \text{Time}}{\text{Thermal Capacitance}} \Rightarrow \text{Time} = \frac{C \times \Delta T}{P}}$$

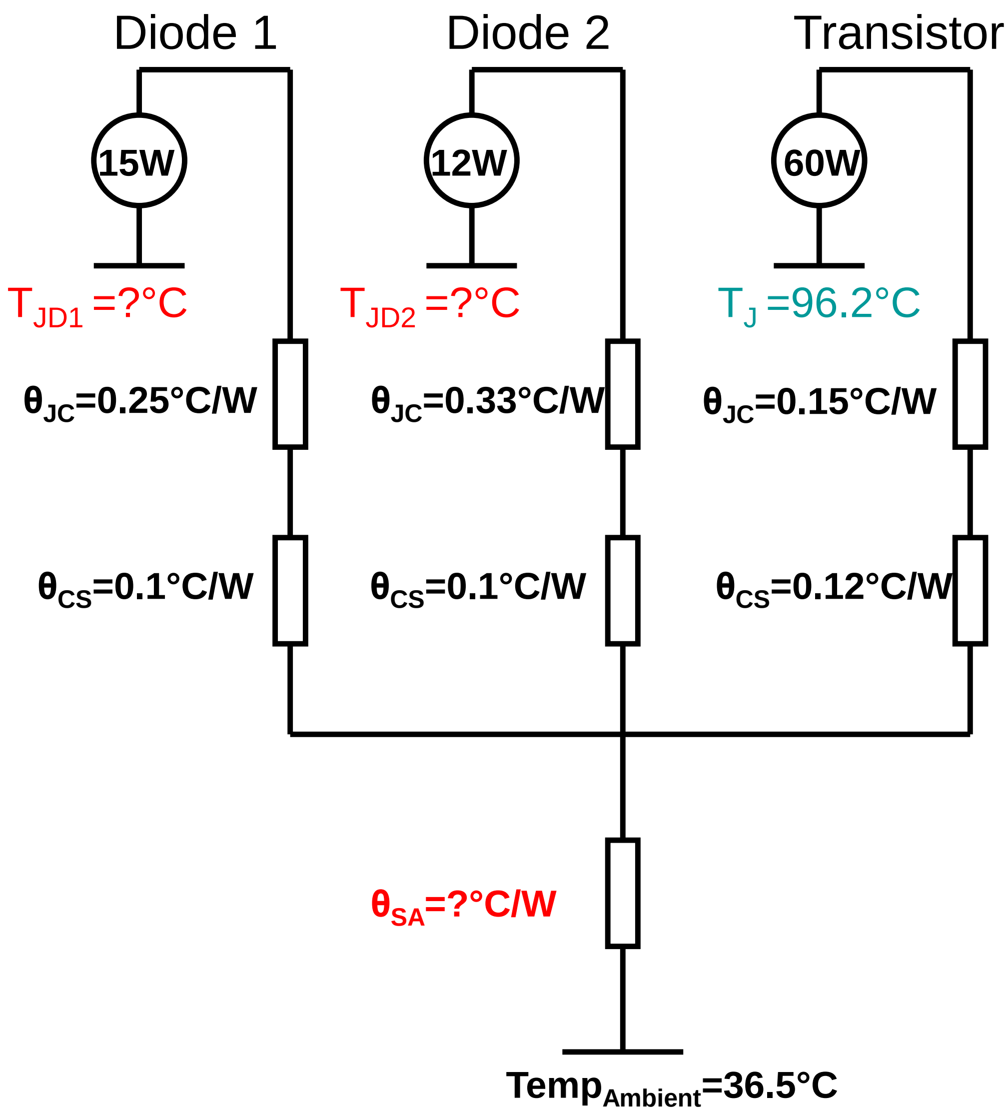
Time = (40 x 1.5 x 913) / 250
= 219 seconds.



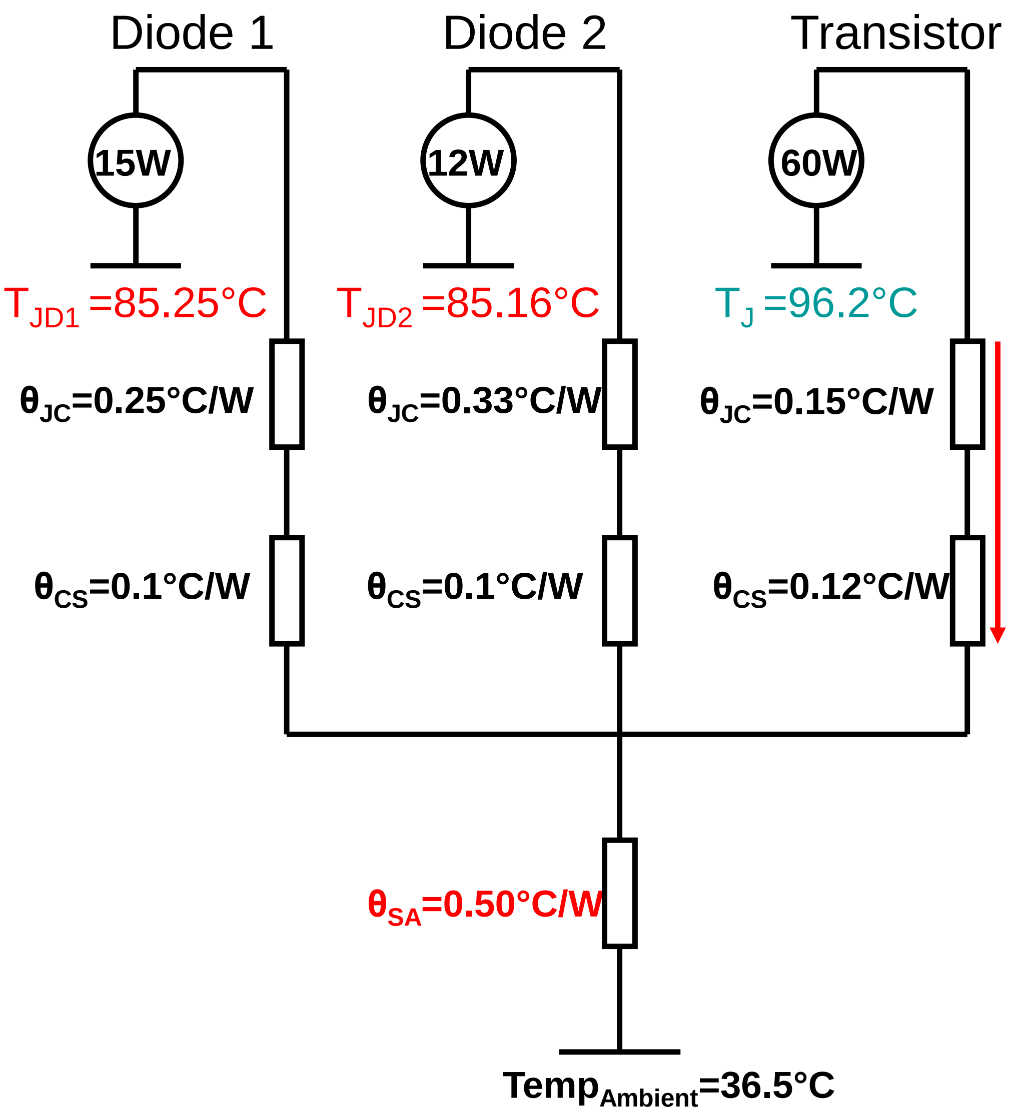
(T_{SS} if allowed = 247.5°C)

$$\boxed{\text{Check}: \tau = RC = \theta_{SA} \times C_{SA} = 0.65 \times 1369.5 = 890 \text{ seconds, so } t < \tau \text{, so OK.}}$$

Question: What is θ_{SA}, T_{JD1} and T_{JD2} for the values shown?



Answer. Use the transistor to determine the heatsink temperature. Then, divide the heatsink ΔT by the total power to get its thermal resistance. The diode junction temperatures are offset from the calculated sink temperature accordingly.



P = 60W.

=> ΔT = 0.27°C/W x 60W = 16.2°C

=> T_{Sink} = 96.2°C – 16.2°C = 80°C.

P_{Sink} = 60+12+15=87 W and ΔT= (80-36.5) =43.5°C

=> θ_{Sink} = ΔT / P_{Sink} = 0.5°C/W