

Thermal Analysis

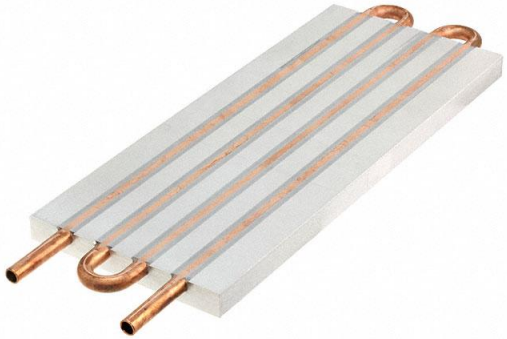
XMUT303 Analogue Electronics

Topics in Thermal Analysis

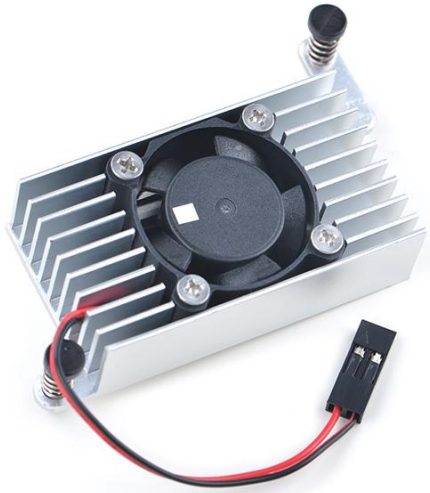
- Heat in electronic devices and circuits.
- Thermal analysis of semiconductor materials.
- Thermal analysis of semiconductor device case.
- Heat sink in thermal management.
- Thermal analysis (requirements) of heat sinks.

Thermal Analysis

- Graphic cards (Radeon HD 4870 Sonic Dual) for PC:
  - Air cooled heat-sinks
  - Liquid cooled heat-sinks







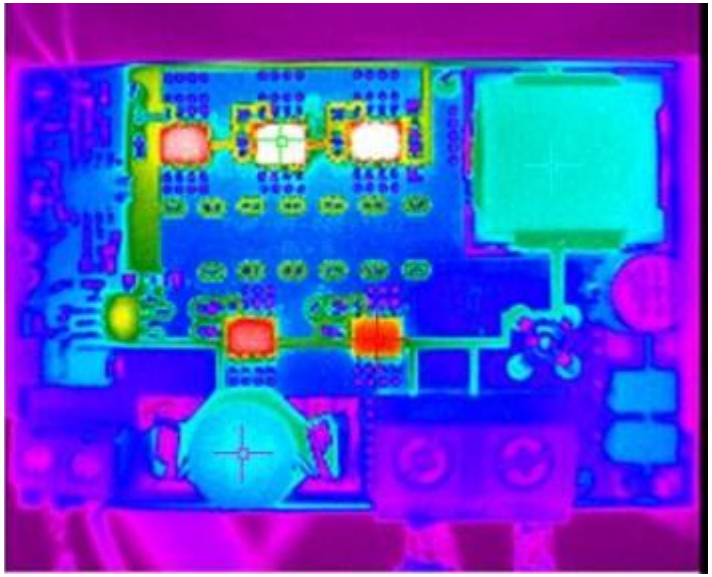


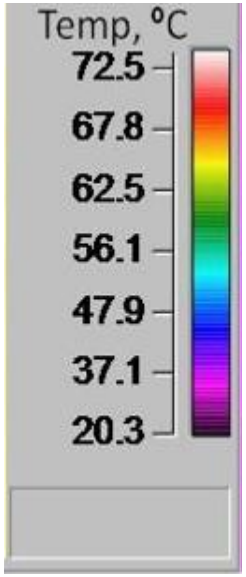


Thermal in Electronic Devices and Circuits

- Hot spots in electronic devices:
  - Heat sinks.
  - Voltage regulator.
  - Active component (e.g. transistors, diode, ICs).
- Hot spots in electronic circuits:
  - Power supply.
  - Power converter.
  - Power amplifier.

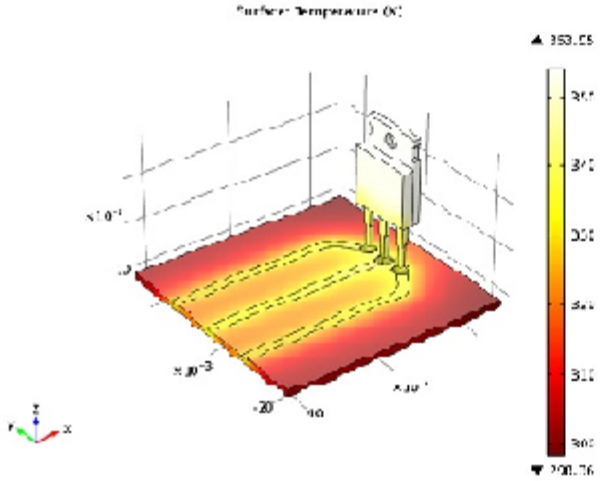


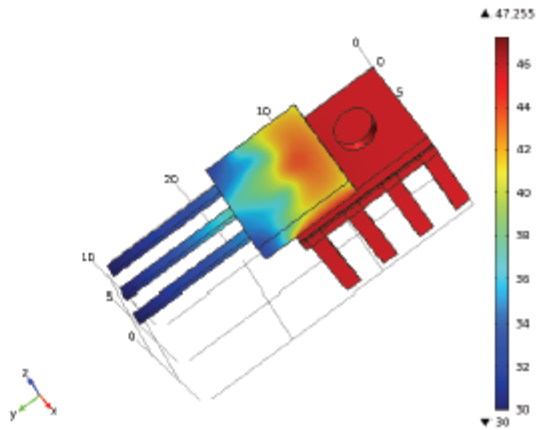




Transistors and Heat

- When power loss occurs, it is turned into heat and the junction temperature increases.
- Increase in junction temperature:
  - Degrades the device characteristics.
  - Leads to device failure (thermal cycling).
- Hence, heat sinks are very important to lower the junction temperature by transferring heat from the junction to ambient.



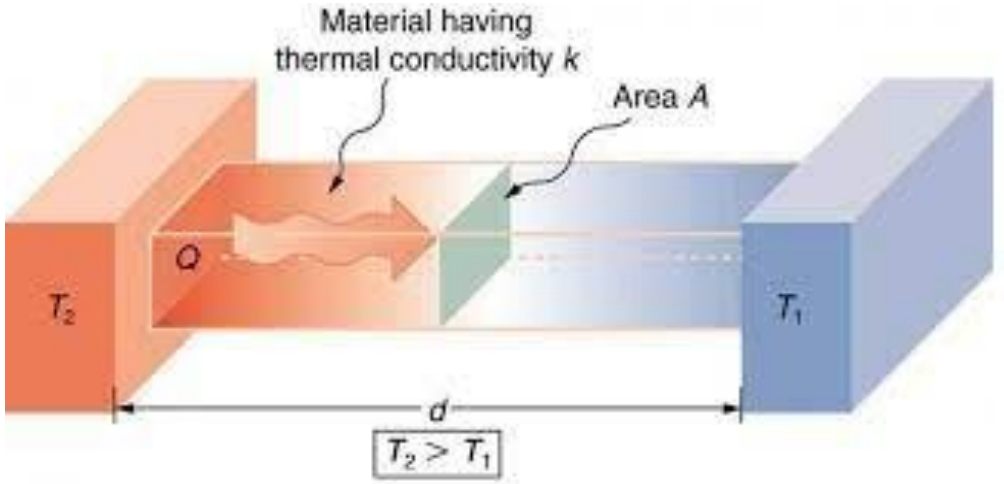


Basic Heat Transfer and Thermal Conduction

- For a material with area and thickness are equal to A and d and thermal conductivity of k, the rate of the heat that is conducted through the material is:

$$P = \frac{dQ}{dT} = \frac{kA(T_2 - T_1)}{d}$$

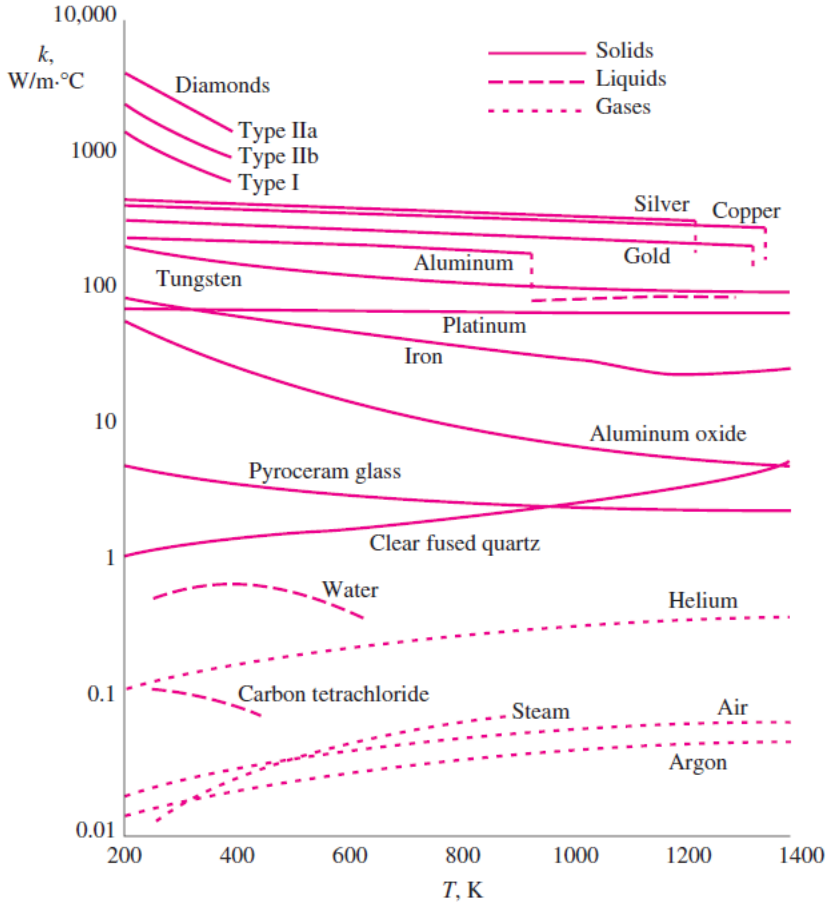
- It is the Fourier law of heat conduction.



Thermal Conductivity

- The following table outlines some of the material's thermal conductivity (k).

No	Material	Conductivity (W/m.°C)
1	Diamond	1,600
2	Silver	420
3	Copper	386
4	Brass	110
5	Lead	35
6	Steel	14
7	Glass	0.8
8	Water	0.6
9	Body fat	0.2
10	Wood	0.15
11	Wool	0.04
12	Air	0.0256
13	Styrofoam	0.01



Thermal Resistance

- For a given material or layer, its thermal resistance can be also calculated from its physical dimensions and material type:

$$R_{\theta jc} = \theta_{jc} = \frac{l}{kA} \quad (°\mathrm{C/W})$$

Where:

- R_θ or θ is thermal resistance of the material.
- k is the thermal conductivity of the material.
- l is length or thickness of the material.
- A is cross sectional area of the material.

Thermal Resistivity

- For several materials, their thermal resistivities (ρ) are listed in the following table.
- Notice that good conductors like metals such as copper, aluminium, etc., they have small ρ.
- On the other hand, insulator such as rubber, mica, etc., they have large ρ.

Material	**Thermal resistivity (ρ)***
Copper (pure)	0.10
Aluminium (1100 series)	0.19
Aluminium (5000 series)	0.28
Aluminium (6000 series)	0.17
Beryllium Oxide	0.32
Carbon Steel	0.84
Alumina	1.15
Anodized Finish	5.60
Silicon Rubber	81.00
Mica	66.00
Mylar	236.00
Silicone Grease	204.00
Dead Air	1200.00

Note: * unit is °C/W-inch

Other Heat and Thermal Parameters

- There are also two other essential characteristics of heat transfer and thermal conduction e.g. strength of heat conduction and effective thermal conductivity.
- Strength of heat conduction (*f*) in a given material e.g. material 1 relative to other material e.g. material 2 is:

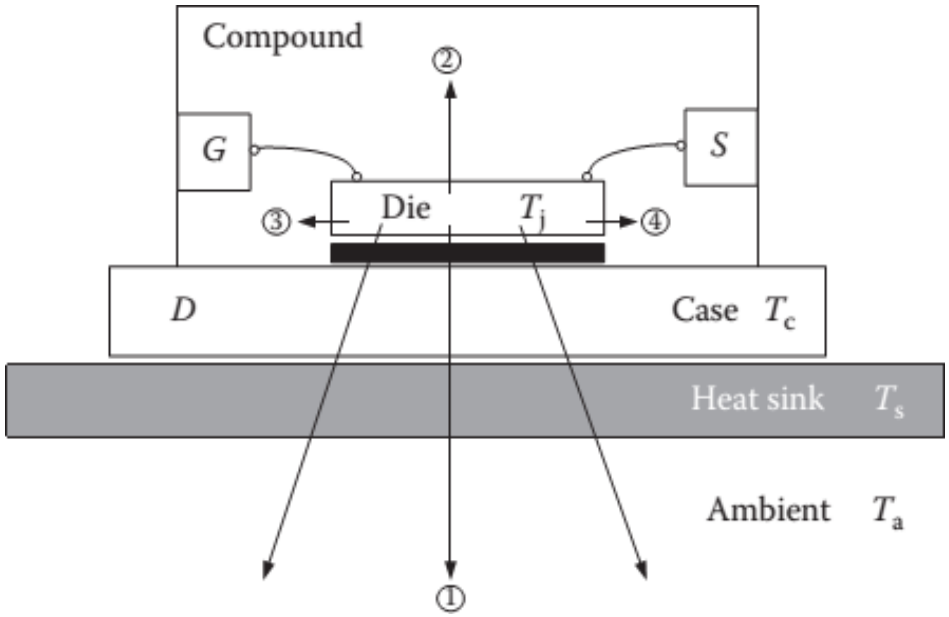
$$f = \frac{(kt)_1}{(kt)_2}$$

- If the heat is conducting through two different materials or more e.g. materials 1, 2, 3, etc., the effective thermal conductivity of the heat through the compound material is:

$$k_{\text{eff}} = \frac{kt_1 + kt_2 + \cdots + kt_{nth}}{t_1 + t_2 + \cdots + t_{nth}}$$

Thermal Path of Transistor

- Heat produced at the die junction due to power dissipations of the component.
- It flows to the compound, case, and heatsink before it is dissipated in the ambient.
- 80 % radiates in the direction of 1.
- 20 % in direction of 2, 3, and 4.



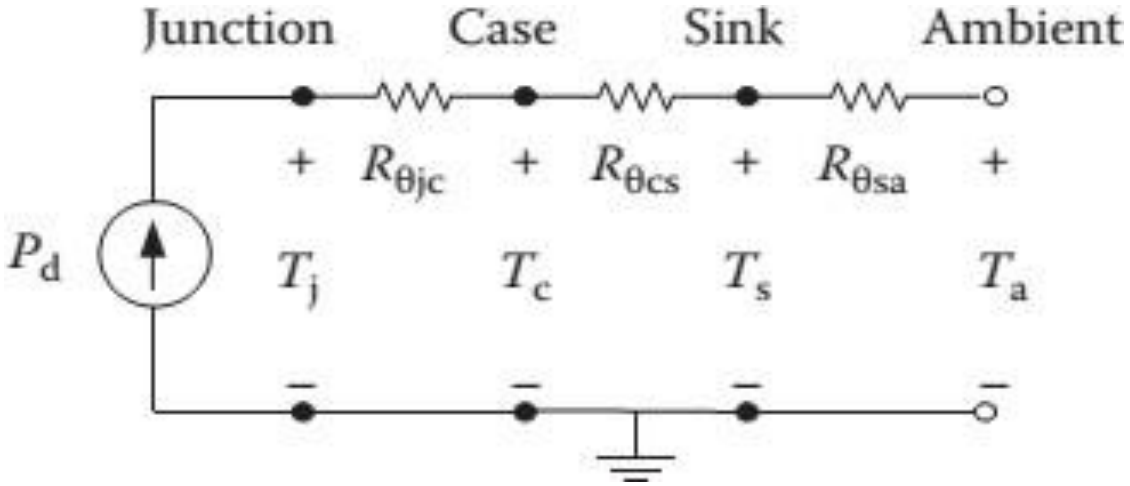
Equivalent Thermal Circuit

The equivalent thermal circuit of the thermal path of the transistor is:

$$R_{\theta ja} = R_{\theta jc} + R_{\theta cs} + R_{\theta sa}$$

Note: Thermal resistance is R_θ or θ.

- j is Junction
- c is Case
- s is (heat) Sink
- a is Ambient



Equivalent Thermal Circuit

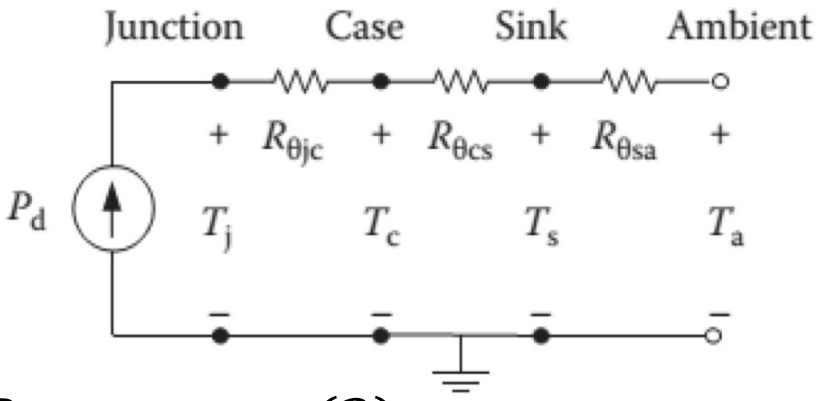
- For a given thermal circuit, thermal resistance of the junction-to-case of the component ($R_{\theta jc}$) is:

$$R_{\theta jc} = \theta_{jc} = \frac{T_j - T_c}{P_d} [\text{°C/W}]$$

- Note: T_j is junction temperature, T_c is case temperature, and P_d is power dissipated.
- You could derive the other thermal resistances in the circuit based on their temperature differences and how much heats to be dissipated.
- Notice that in datasheets and technical reports $R_{\theta jc} = \theta_{jc}$.

Ohms Law of Thermal Analysis

Equations used for determining thermal analysis:



$$T_j = P_d * \theta_{ja} + T_a \qquad (1)$$

$$\theta_{ja(max)} = \left(T_{j(max)} - T_{a(max)}\right)/P_{d(max)} \qquad (2)$$

$$P_{d(max)} = \left(T_{j(max)} - T_{a(max)}\right)/\theta_{ja} \qquad (3)$$

$$T_{a(max)} = T_{j(max)} - \left(P_{d(max)} * \theta_{ja}\right) \qquad (4)$$

Note:

- Equation 1 is used for analysing the existing system.
- Equation 2 is used for designing the heat sink.
- Equations 3 and 4 are used for establishing the design limits.

Thermal Resistivities in the Equivalent Circuit

- Case-to-sink thermal resistivity:

$$\theta_{cs} = \frac{\rho \times t}{A}$$

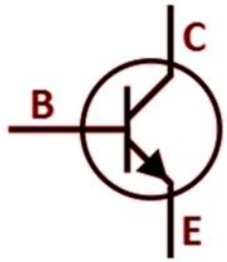
  Where: t in inches, A in inches

- Notice that θ_{cs} is normally less than 1° C/W.
- The higher the value, the higher the resistance to dissipate heat.
- Contact resistance is not included.
- We could derive the other layer-to-layer thermal resistivities of the other materials that exist in the equivalent thermal circuit.

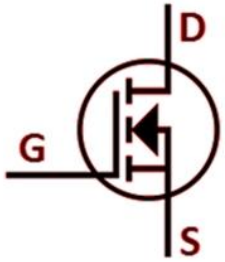
Transistor Thermal Junction

- For typical BJT power transistor, most of the heats are dissipated in term of power losses across the Collector-Emitter junction (and the Drain-Source junction in FET).

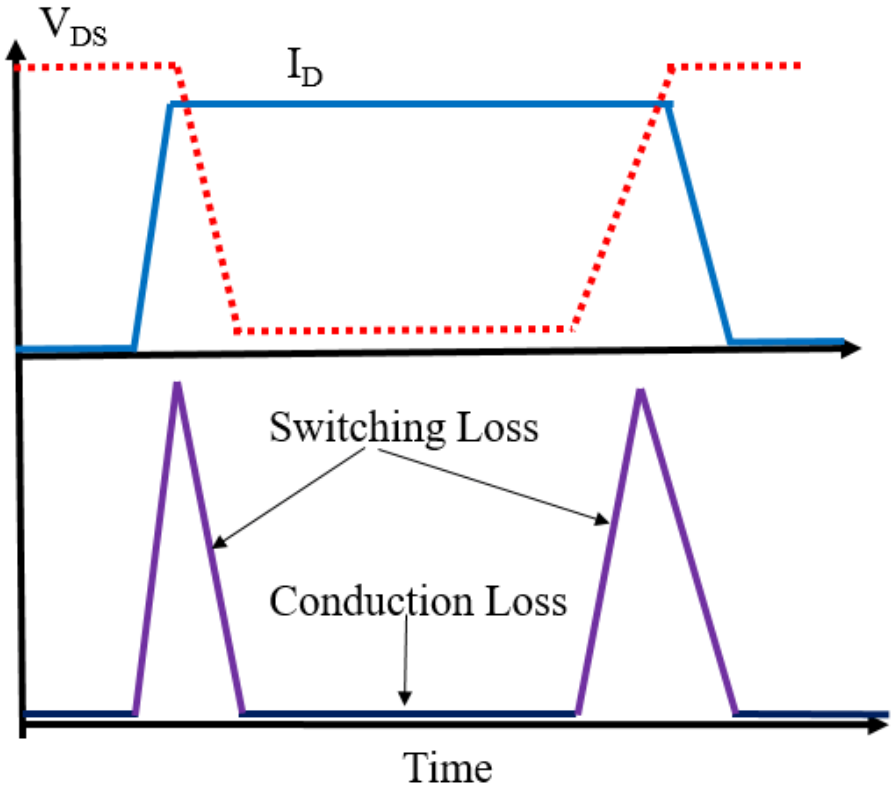
$$P_{\text{loss}} = P_{\text{conduction loss}} + P_{\text{switching loss}}$$



BJT



FET

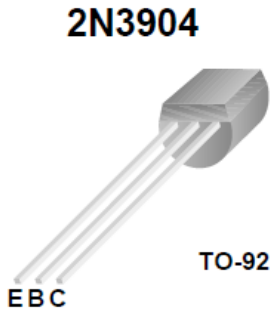


Transistor Thermal Junction

- Power loss in the Collector-Emitter junction places a limit on allowable power dissipation (and the Drain-Source junction in FET).
- Data sheets commonly specifies the maximum junction temperature at 125 °C, 150 °C, or 200 °C:
  - $T_{j(\max)}$ of 2N39XX is 150°C.
  - $T_{j(\max)}$ of 2N37XX is 200°C.
- Maximum dissipating power, $P_{d(\max)}$ is specified typically at an ambient temperature of 25°C:
  - 2N19XX e.g. general-purpose transistor is 4-10 W.
  - KSD19XX e.g. small-power transistor is 30-100 W.

Transistor Thermal Junction

- Thermal specifications of BJT NPN general purpose transistor 2N3904: $T_j = 150°\text{C}$, $P_D = 5\ \text{mW}/°\text{C}$, $R_{\theta jc} = 83.3°\text{C/W}$, and $R_{\theta ja} = 200°\text{C/W}$



Absolute Maximum Ratings* T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
V_{CBO}	Collector-Base Voltage	60	V
V_{EBO}	Emitter-Base Voltage	6.0	V
I_C	Collector Current - Continuous	200	mA
T_J, T_{stg}	Operating and Storage Junction Temperature Range	-55 to +150	°C

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

NOTES:

1) These ratings are based on a maximum junction temperature of 150 degrees C.

2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Thermal Characteristics T_a = 25°C unless otherwise noted

Symbol	Parameter	Max.			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

* Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06".

** Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

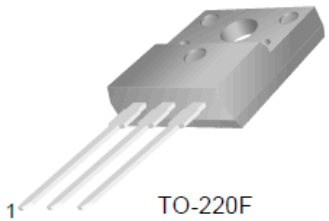
Transistor Thermal Junction

- Thermal specifications of BJT NPN small power transistor KSD1944.

$$T_j = 150°\text{C}$$

Absolute Maximum Ratings T_C=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector-Base Voltage	80	V
V_{CEO}	Collector-Emitter Voltage	60	V
V_{EBO}	Emitter-Base Voltage	8	V
I_C	Collector Current	3	A
P_C	Collector Current (T_C=25°C)	30	W
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	- 55 ~ 150	°C



TO-220F

1.Base 2.Collector 3.Emitter

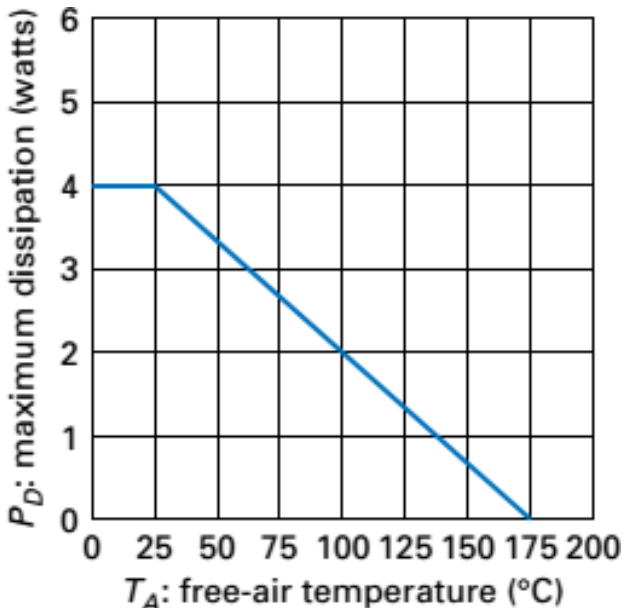
Derating: Temperature Over 25°C

- For condition over room temperature (e.g. > 25° C), we need to derate the power rating of the components.

- Some datasheets list a derating factor D.
- Derating factor of 2N1936 is 26.7 mW/°C.

$$\Delta P = D(T_A - 25°C)$$

ΔP is decrease in power rating

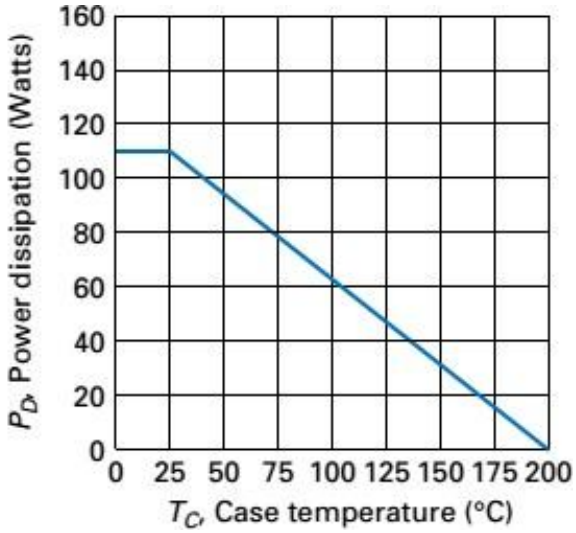


- Considering the safe operating condition of the components, operational temperature range must be specified.

Derating and Case Temperature

- Order of temperature in semiconductor device packaging or casing: Case Temp > Sink Temp > Ambient Temp.
- Data sheets of large transistors give derating curves for case temperature than ambient temperature.
- Figure below is for 2N3055 from Onsemi Semiconductor ≈ 115 Watts.





Case Thermal Condition and Datasheets

- Case thermal condition is typically referred to in the manufacturer datasheet of the device or heatsink.
- Various thermal variables can be derived from these that later will lead to the actual thermal analysis.
- From the semiconductor device datasheet, we could obtain the junction-to-case thermal resistance or other variables:

$$R_{\theta jc} = \theta_{jc} = \frac{T_j - T_c}{P_d} \quad [°\mathrm{C/W}]$$

- From the heatsink manufacturer datasheet, we can derive the case-to-heatsink thermal resistance or other variables:

$$\theta_{cs} = \frac{\rho \times t}{A}$$

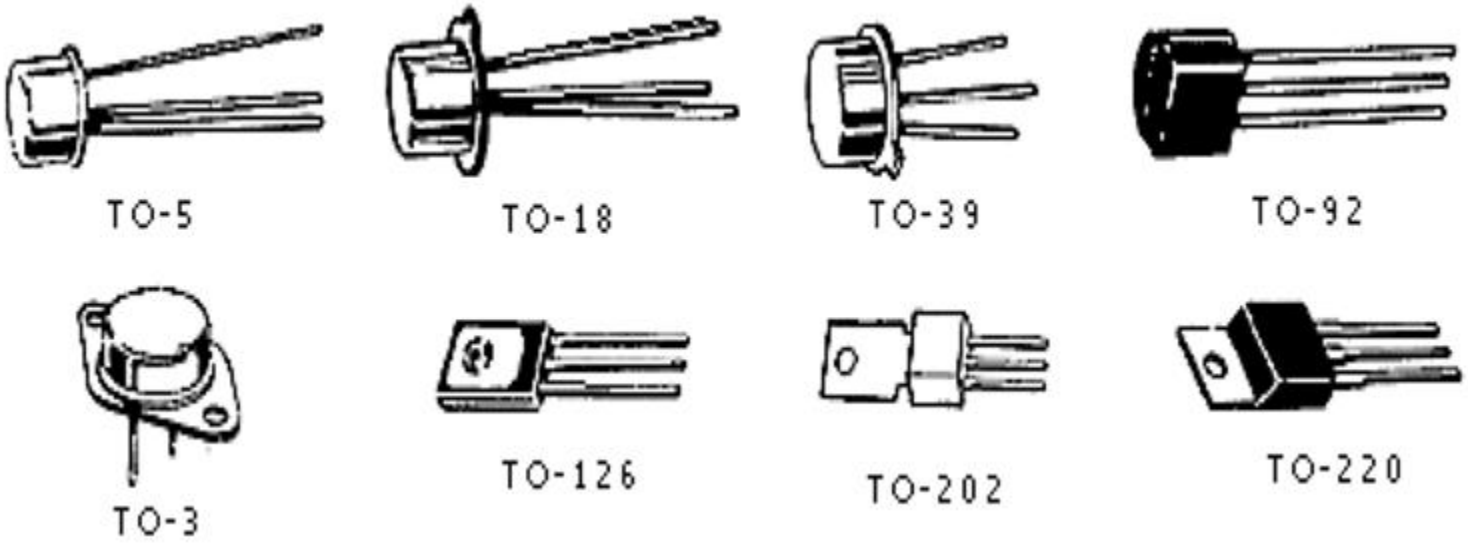
Common Transistor / Diode Cases

- Case for signal applications:

  TO18, TO92, TO5, and TO39.

- Case for power applications:

  Transistor (TO3, TO202, TO126, TO220) and diode (TO126, TO202, TO220).



Common Transistor / Diode Cases

- Maximum possible power dissipation in Watts (e.g. θ in degree Celsius/Watt).

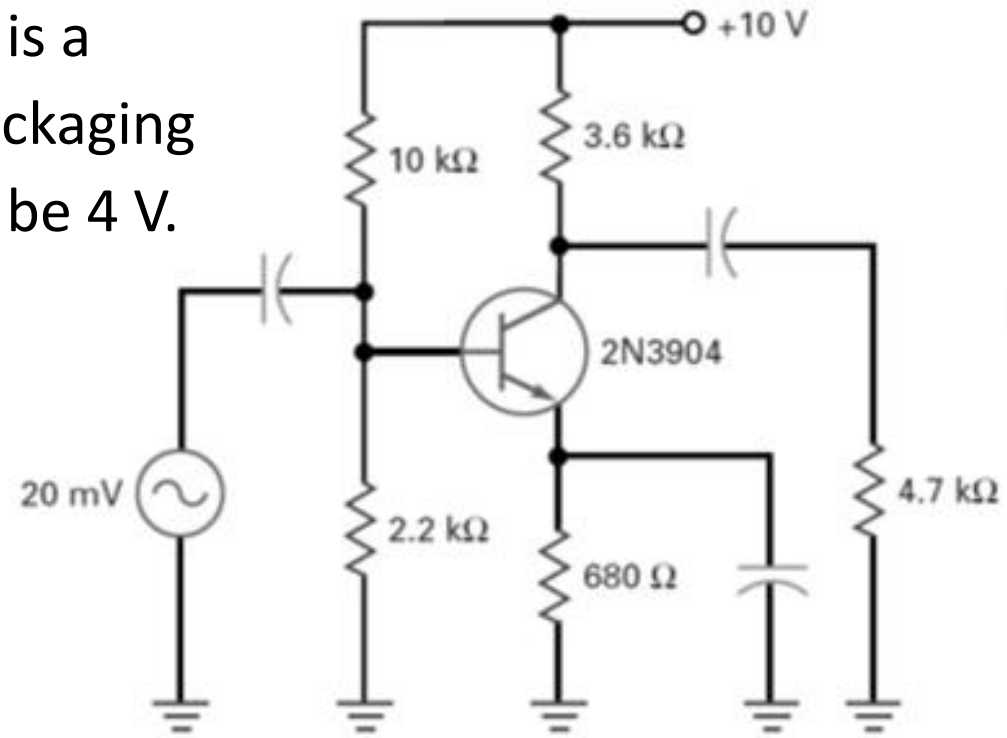
Case	P_d (Infinite Heatsink)	P_d (Good Heatsink)	P_d (No Heatsink)	θ_{jc}	θ_{ca}	θ_{cs}	θ_{sa}
TO-3	100	60	5	0.5	18	0.5	0.5
TO-220	25	15	2	3	45	1	2
T0-5	4	2.5	1	20	75	5	15
TO-18	2	1.2	0.5	40	160	20	30
TO-92	1	0.6	0.33	60	240	40	60

- Part with higher power rating does not mean good power dissipation (P_d).
- Failing to remove heat effectively will affect performance.
- The above numbers can vary a lot depending on parts internal construction.

Example of Case Temperature Analysis

- Determine the maximum junction and case temperatures and maximum power rating and current of the transistor at ambient temperature of 50°C in the amplifier circuit given in the figure below.
- Notice that the transistor is a 2N3904 BJT with TO92 packaging and its V_{CE} is designed to be 4 V.





Example of Case Temperature Analysis

- Expected to be operating at ambient temperature of 50°C.
- From manufacturer datasheet of transistor 2N3904:

$P_d = 625$ mW at 25°C and $D = 5$ mW/°C.

Absolute Maximum Ratings* T_a = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CEO}	Collector-Emitter Voltage	40	V
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* Device mounted on FR-4 PCB 1.6" X 1.6" X 0.06".

** Device mounted on FR-4 PCB 36 mm X 18 mm X 1.5 mm; mounting pad for the collector lead min. 6 cm^2.

Example of Case Temperature Analysis

- The maximum junction temperature of the device is:

$$T_j(\max) = T_a + R_{\theta ja}P_d$$
$$= 25°\text{C} + (200)(625 \times 10^{-3})$$
$$= 150°\text{C}$$

- Notice that this maximum junction temperature is equal to the maximum junction temperature of the transistor as stated in the datasheet.
- The maximum case temperature of the device is:

$$T_c(\max) = T_j(\max) - R_{\theta jc}P_d$$
$$= 150°\text{C} - (83.3)(625 \times 10^{-3})$$
$$= 97.94°\text{C}$$ (i.e. need a heatsink)

Example of Case Temperature Analysis

- Derating factor is $D = 5\ \text{mW/°C}$, so using the equation:

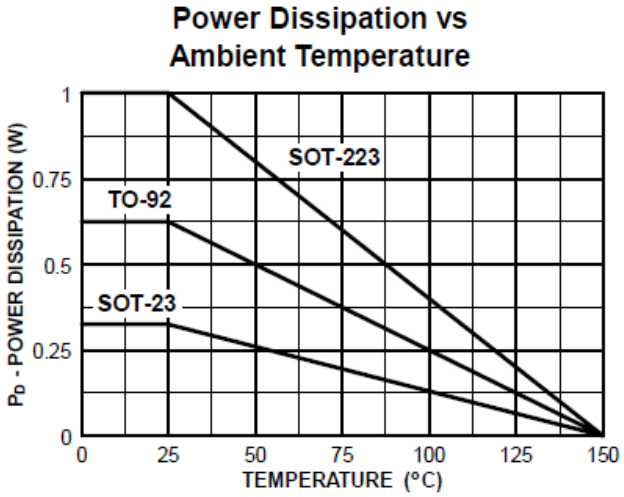
$$\Delta P = D(T_C - 25\text{°C})$$

- Entering values into the equation:

$$\Delta P = (5\ \text{mW})(50 - 25) = 125\ \text{mW}$$

- So, maximum power rating at 50°C:

$$P_{d(max)} = 625\ \text{mW} - 125\ \text{mW} = 500\ \text{mW}$$



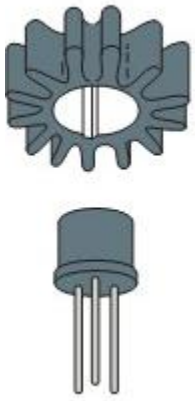
Example of Case Temperature Analysis

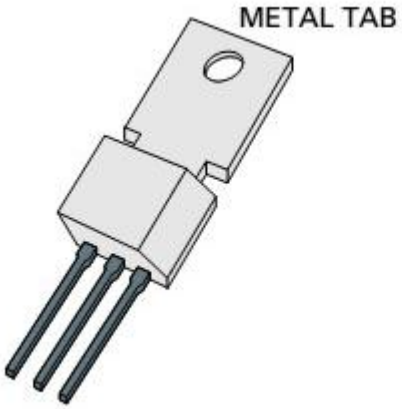
- If the V_{CE} is 4 V, the maximum current that flows in the circuit (e.g. current that flows in the collector-to-emitter junction) at 50°C is:

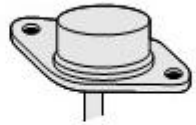
$$I_{\max} = \frac{P_d}{V_{CE}} = \frac{500 \times 10^{-3}}{4} = 125 \text{ mA}$$

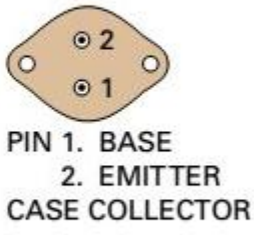
Heat Sinks

- Goal of heat sink: to increase the surface area of the semiconductor device to allow the heat to escape.
- Types of heat sinks, depends on:
  - Cooling approaches.
  - Type of materials used.
  - Geometric designs.
  - Layout and arrangement in the circuit and enclosure.



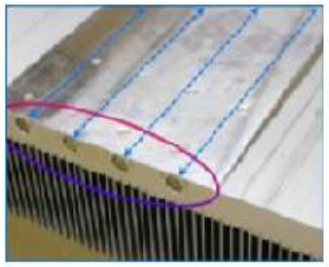






Types of Heat Sinks

- Passive heat sinks: uses natural convection, load limit to 50 W, & cost range is $ 0.50 to $ 10.
- Semi active: uses existing fans in the system, load up to 25 W, & cost up to $ 10.
- Active: uses designated fans, load limit of 160 W, & cost between $ 10-20.
- Liquid cooled: tubes in block design, load is limitless, & cost can be in $ 100s.
- Phase change recirculating system: flow of coolant, expensive.

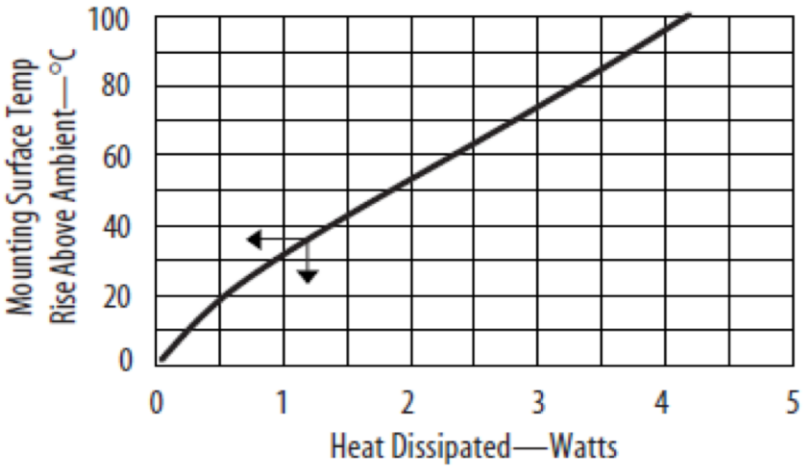


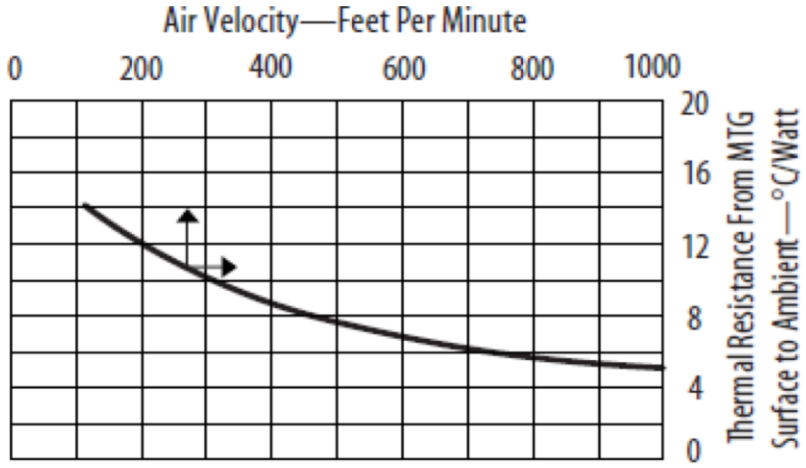




Heat Dissipation

- Determination of heat dissipation:
  - Geometry - Thermal resistance graph (left) is determined by dividing temperature rise by the power input.
  - Flow - Volumetric flow rate (right) is about heat velocity divided by the cross-sectional area.

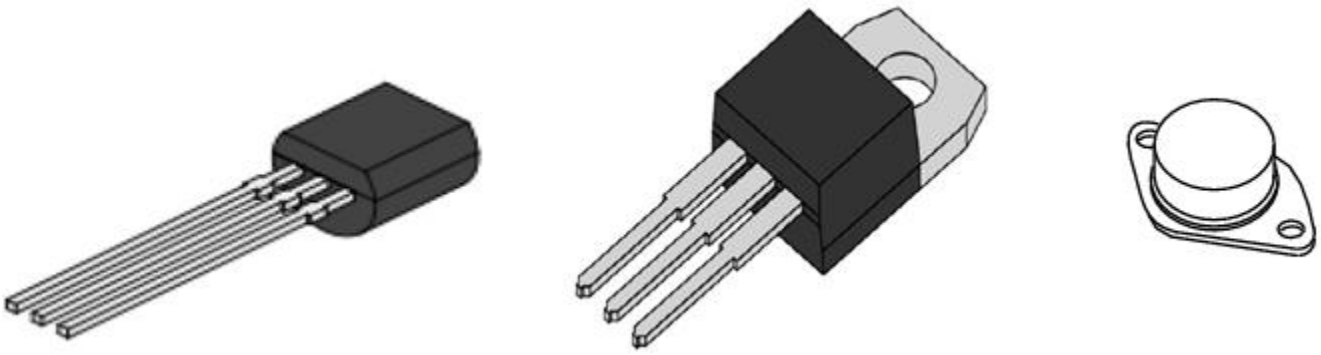




Note: Air flow is linear feet per minute (e.g. still in imperial unit).

Power Dissipation / Heat Sinking

- We need to keep the PN junctions of semiconductors at $T_j \leq 200°\text{C}$, ideally $T_j \leq 150°\text{C}$.
- Typically these thermal design limit parameters are:
  - $\theta_{jc} \approx$ 1.5 - 3°K/W for TO-3 or TO-220 cases (160°K/W for TO-92 cases).
  - $\theta_w \approx$ 0.3°K/W. This includes the washer and thermal paste.
- The actual values can be obtained from the data sheets.



Power Dissipation / Heat Sinking

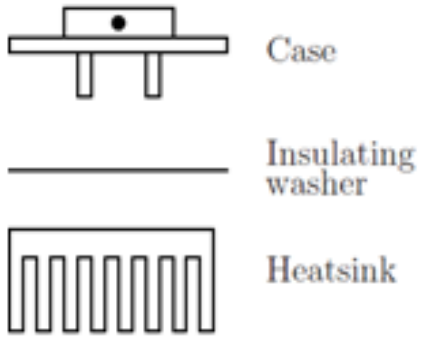
- So, for example, if P_d = 10 W, $T_j \leq 150°\text{C}$, and $T_a \approx 50°\text{C}$ (inside a box), then we require heat sink that has thermal resistance:

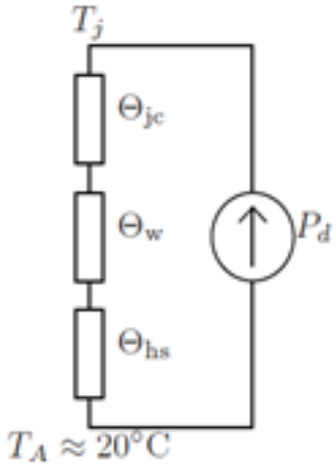
$$\theta_{hs} \leq \frac{(T_j - T_a)}{P_d} - \theta_{jc} - \theta_w$$

- Or

$$\theta_{hs} \leq \frac{150 - 50}{10} - 1.5 - 0.3 \leq 8.2°\text{K/W}$$

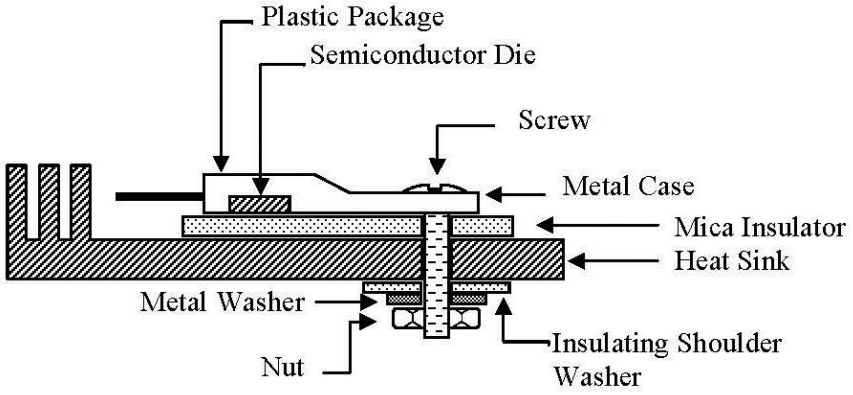
- To obtain a thermal resistance this low, actually we need quite a large heat sink.
- Clip on heat sinks are typically 20-70°K/W.

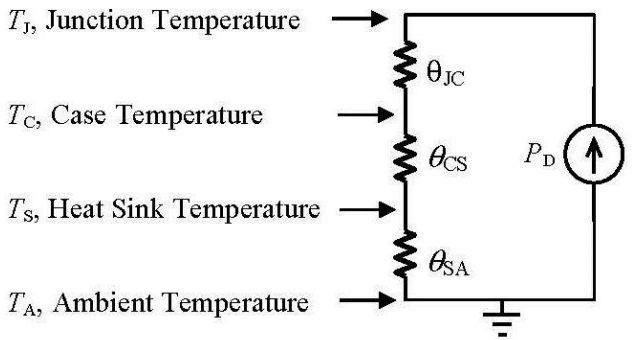




Other Heat Sink Components

- Heat sinks are selected based on the thermal resistance between sink and ambient temperatures.
- Notably other heatsink components are: washer (fastening), insulations (electrical insulation) and grease compound (for smooth heat transfer between materials).
- Case, washer, insulations and heat sink can be considered as components that permit/resist the flow of the heat from devices to the enclosure/ambient.





Selecting Matching Heat Sink

Heuristics for selecting correct heat sink requirements:

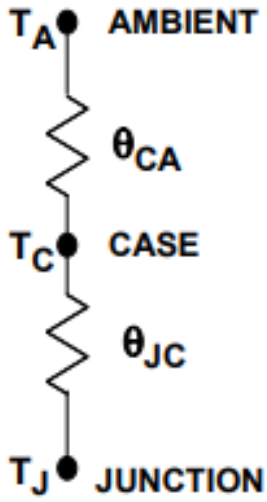
a. Amount of power to dissipate.

b. Maximum allowable junction temperature.

c. Ambient temperature.

d. Junction-Case thermal resistance.

e. Case-Sink thermal resistance.



f. Thermal resistivity, thickness, and contact area.

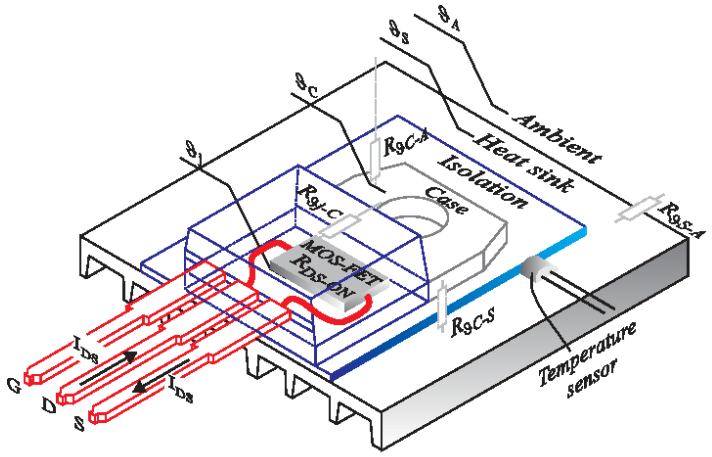
g. Additional components e.g. washer, insulation materials/ paste, protective film, etc.

h. Natural or forced convection cooling.

Heat Sink Determination Example

Determine heatsink requirements for a small power transistor as shown below:

- TO-220 package.
- It is dissipating 7 Watts.
- Maximum junction temperature is 125° C.
- Maximum ambient temperature is 65° C.



Heat Sink Determination Example

- Junction-to-case thermal resistance for the silicon-based semiconductor is considered to be 2.5° C/W.
- Case-to-heatsink thermal resistance is dependent on the thermal material used e.g. insulating contact, silicon grease, fastening clip, etc.

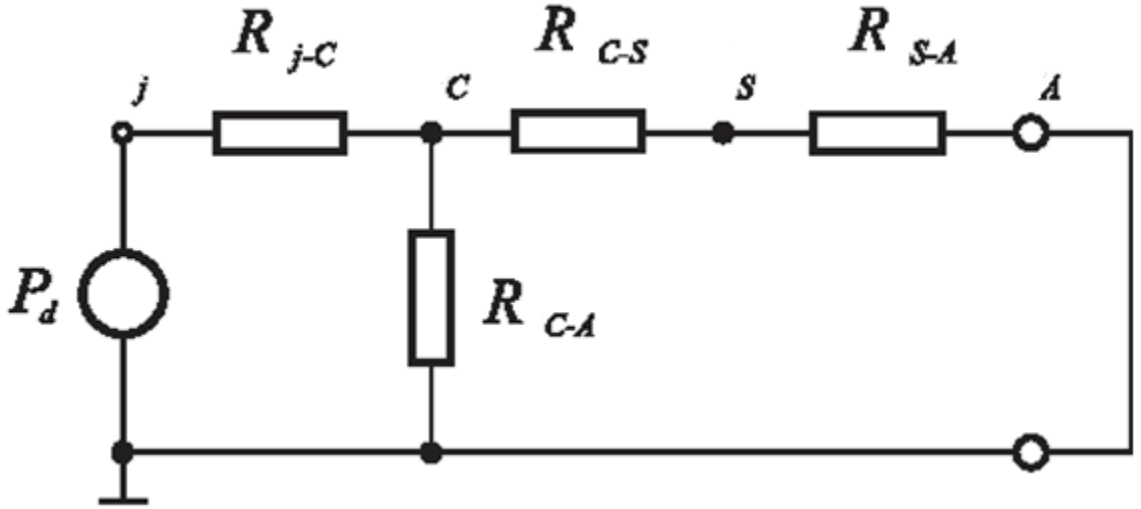
$$\theta_{cs} = \frac{\rho \times t}{A}$$

Where:

- ρ = thermal resistance constant.
- t = thickness (in inch).
- A = surface area (in inch square).

Heat Sink Determination Solution

- The equivalent thermal circuit is shown in the figure below:



Note:

- j = Junction of the device.
- c = Case of the device.
- s = Heatsink of the device.
- a = Ambient temperature of the enclosure/ surrounding air.

Heat Sink Determination Solution

- Referring to the given equivalent thermal circuit, the equation for the equivalent thermal circuit is:

$$\frac{T_j - T_a}{P_d} = \theta_{jc} + \left[\frac{\theta_{ca}(\theta_{cs} + \theta_{sa})}{\theta_{ca} + \theta_{cs} + \theta_{sa}}\right]$$

- As typically $\theta_{ca} \gg \theta_{cs} + \theta_{sa}$, so the thermal circuit equation is:

$$\frac{T_j - T_a}{P_d} = \theta_{jc} + \theta_{cs} + \theta_{sa}$$

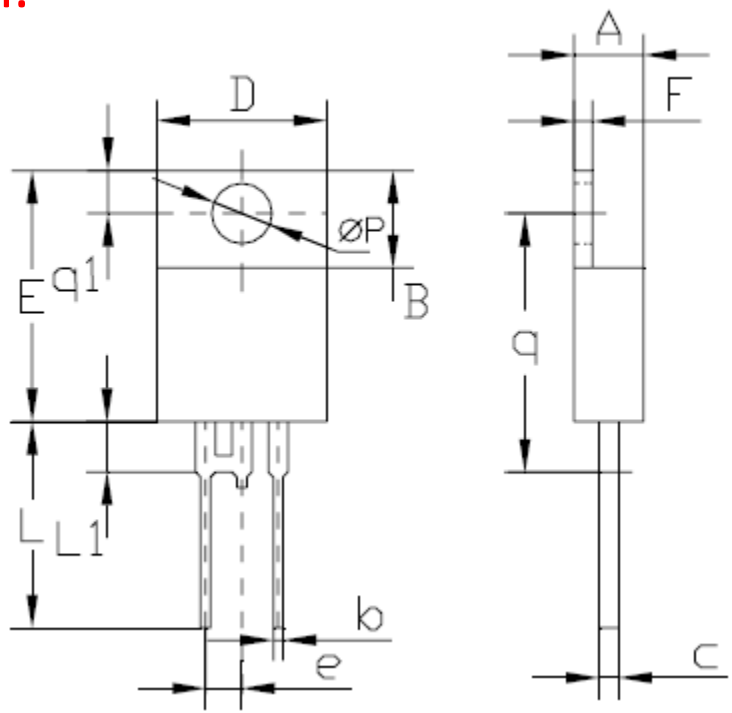
- Heatsink requirements:

$$\theta_{sa} = \frac{T_j - T_a}{P_d} - (\theta_{jc} + \theta_{cs})$$

Heat Sink Determination Solution

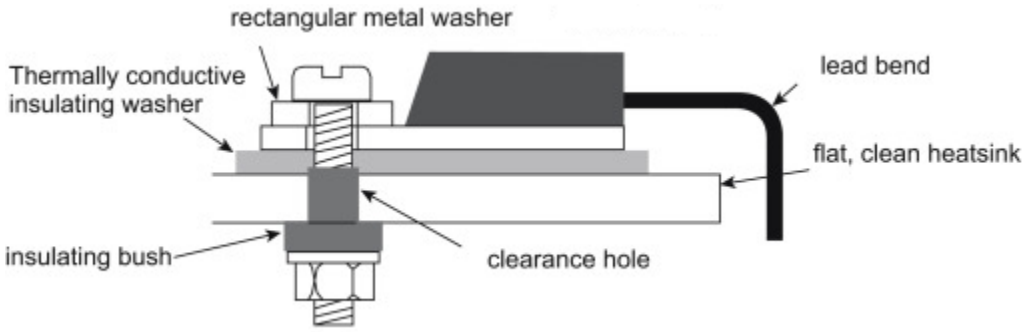
- From its datasheet, the case packaging of transistor is TO220 with its thickness of 0.002 inch and effective area of 0.36 inch square.
- If the case is made from an alloyed aluminium material, its thermal resistivity is 56°C/W-inch.

- Thus, the physical dimension of the transistor's case is:
  - ρ = 56°C/W-inch
  - t = 0.002 inch
  - A = 0.36 inch square



Heat Sink Determination Solution

- Insulating contact is needed to prevent direct electrical connection and washer is required for fastening the device to the heatsink.

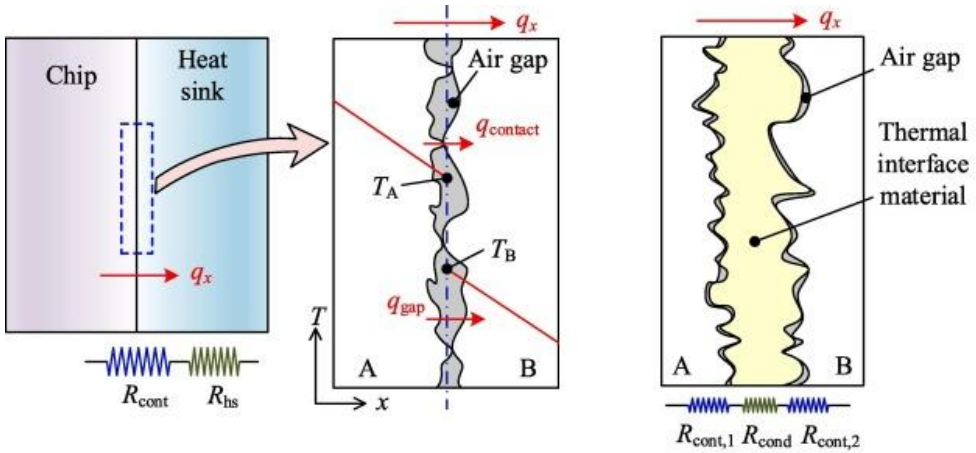


- Grease determination is based on Wakefield 120 series heat sink compound.
- This fills the air gap between mating surfaces with a grease-like material containing zinc oxide in a silicone oil carrier.

Heat Sink Determination Solution

Heat sink compound (grease).

- Emulsion gel like substance.
- Used to increase efficiency of heat transfer between different materials.



(a) thermal contact resistance without TIM

(b) thermal contact resistance with TIM



120 SERIES - THERMAL JOINT COMPOUND

Characteristic	Description
Volume Resistivity	5 x 10 ohm/cm
Dielectric Strength	225 volts/mil
Specific Gravity	2.1 min.
Thermal Conductivity	0.735 W/(m) (K)
	5:1 (Btu) (in.)/(hr)(ft)
Thermal Resistivity (P)	56 (degrees C) (in.)/watt
Bleed, % after 24 hrs at 200 degrees C	0.5
Evaporation, % alter 24 hrs at 200 degrees C	0.5
Color	opaque while
Shell life	5 years
Operating Temperature Range (degrees C)	-40/+200

Heat Sink Determination Solution

- Determine the thermal resistances of the junctions in the thermal circuit. Grease thermal resistance is 56°C-inch/W.
- Grease compound (Case-to-Heatsink) thermal resistance:

$$\theta_{cs} \text{ or } R_{cs} = \frac{\rho \times t}{A} = \frac{56 \times 0.002}{0.36} = 0.311°\text{C/W}$$

- Heatsink-to-Ambient thermal resistance:

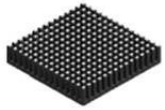
$$\theta_{sa} = \frac{(T_j - T_a)}{P_d} - (\theta_{jc} + \theta_{cs})$$

$$= \frac{(125°\text{C} - 65°\text{C})}{7\ \text{W}} - (2.5°\text{C/W} + 0.311°\text{C/W})$$

$$= 5.76°\text{C/W}$$

- Need a heat sink with thermal resistance of 5.76° C/W or less.

Heat Sink Determination Solution

Specification	Type A	Type B	Type C	Type D
Model	Stamping	Cross-cut	Bonded fin	Active fan
Length (mm)	12.5	20.2	38.8	Diameter = 8
Width (mm)	4.8	20.2	25.6	
Thermal resistance (°C/W)	23.4	15.3	5.2	1.2
Heatsink material	Aluminium	Aluminium	Aluminium	Copper alloy
Form				
Attachment	Screw	Adhesive	Screw	Clip
Price (dollars)	1.5	3.2	8.24	24.5

- Thus, comparing the specifications (e.g. dimension, thermal resistance, material, form, price, etc.) of several heatsinks from the manufacturers in table above, the heat sink that meets the requirement is Type C heat sink.