XMUT303 Analogue Electronics

Note 14: Thermal Analysis

Topic

- 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.

14.1. Introduction to Thermal Analysis

Thermal analysis is required in electronic circuit analysis and design for stable operation of the circuit.

14.1.1. Why We Need Thermal Analysis?

The following diagrams illustrate a graphic card (Radeon HD 4870 Sonic Dual) for PC. There are two versions of this graphic card: air cooled heat-sinks and liquid cooled heat-sinks. Nowadays, graphic cards in PCs are some very popular examples of electronic component and circuit that require thermal management for their use and applications.

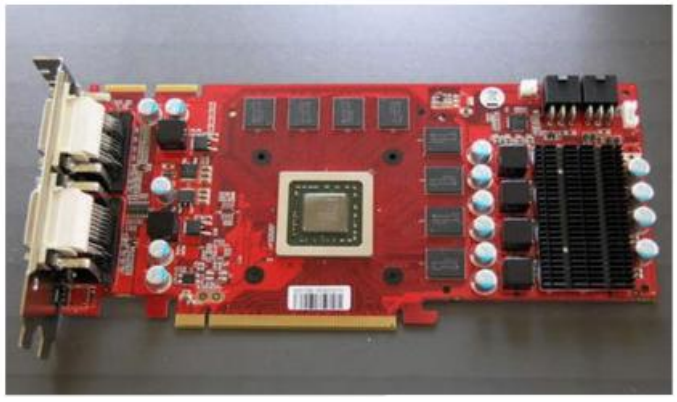


Figure 14.1: Air-cooled heatsinks of Radeon HD 4870 Sonic graphic cards



Figure 14.2: Liquid-cooled heatsinks of Radeon HD 4870 Sonic graphic cards

Thermal management of electronic component and circuit utilise devices such as cooling system, heatsink and cooling fan to dissipate heat built up in them.



Figure 14.3: Thermal and cooling mechanisms e.g. liquid (left), air (middle) and fan (right)

14.1.2. Thermal in Electronic Devices and Circuits

For given electronic devices and circuits as shown in the figures below, you could identify the hot spots.

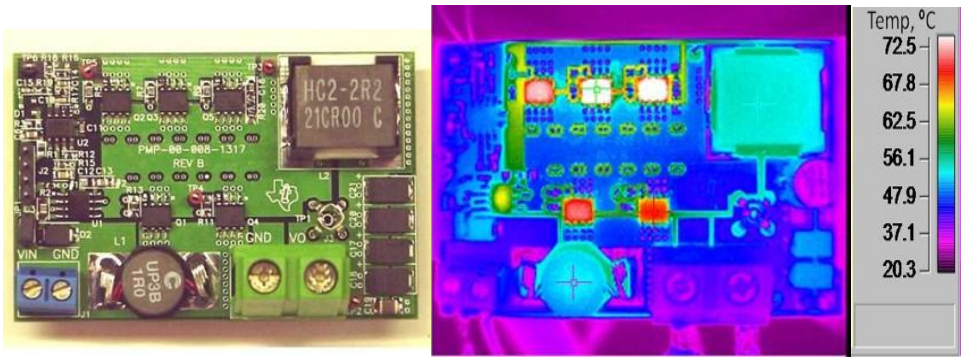


Figure 14.4: Thermal visualisation of hotspots in the electronic circuit

As shown in the figure above, hot spots commonly found in electronic devices are heat sinks, voltage regulator, active components (e.g. transistors, diodes, ICs, etc.). On the other hand, hot spots in electronic circuit are usually power supply, power converter, power amplifier, etc.

14.1.3. 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.

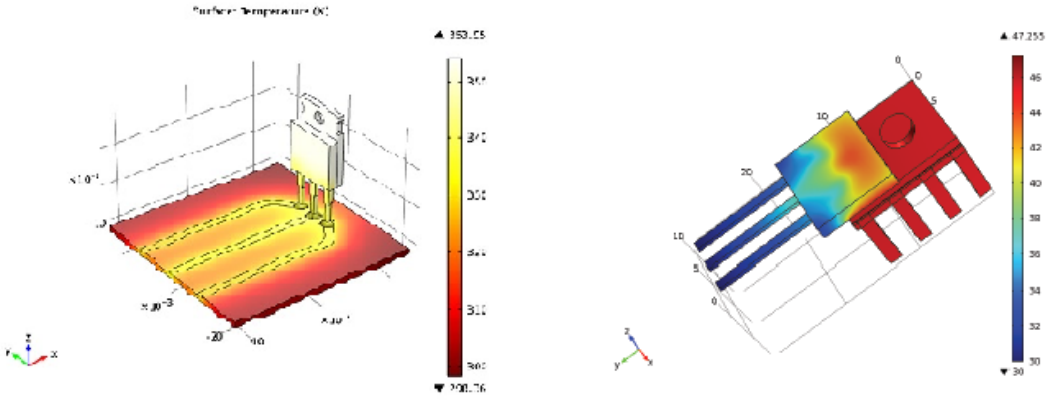


Figure 14.5: Heat spots in a typical transistor on PCB (left) and with its heatsink (right)

14.2. Basic Heat Transfer and Thermal Conduction

For a given material with its area and thickness are equal to A and d and its thermal conductivity of value k, the rate of the heat will be transferred through the material according to the following equation.

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

The above equation is also known as the Fourier law of heat conduction.

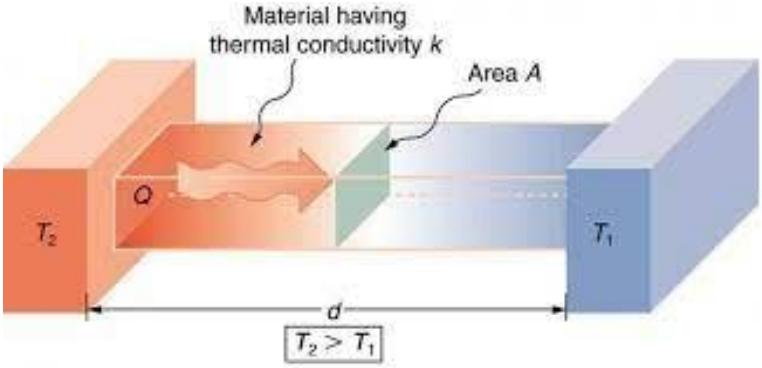


Figure 14.6: Heat conduction along a given material

14.2.1. Thermal Conductivity

The following table outlines some of the material's thermal conductivities at room temperature.

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

Table 14.1: Typical thermal conductivity of several materials

The following graph shows the thermal conductivities of several materials in their various forms and temperature.

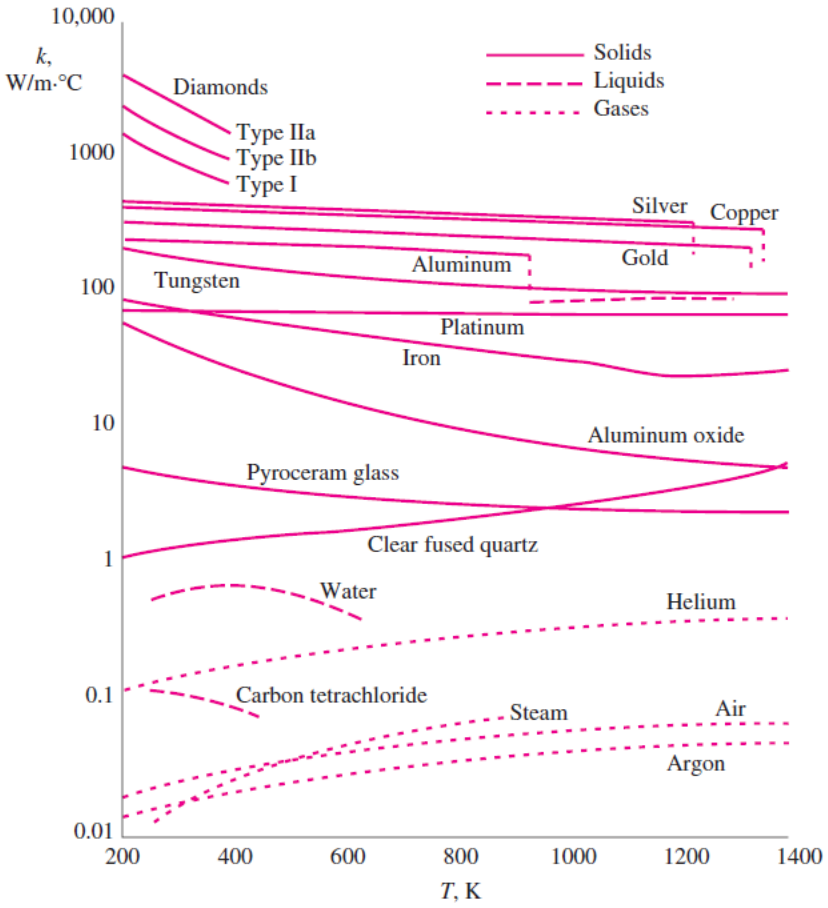


Figure 7: Thermal conductivities of several materials at various forms and temperature

14.2.2. Thermal Resistance

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

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

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.

14.2.3. Thermal Resistivity

For several materials, their thermal resistivities (ρ) are listed in the following table.

Material	**Thermal resistivity, ρ (°C/W-Inch)**
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

Table 14.2: Typical values for thermal resistivity of several materials

14.2.4. Other 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.

We could determine the strength of heat conduction (*f*) in a given material e.g. material 1 relative to other material e.g. material 2 from the ratio of their heat transfer characteristic values:

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

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 determined from:

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

14.3. Thermal Path of Transistor

Heat produced at the die junction is due to power dissipations of the component. Use of high-performance type component and more efficient design of the device and circuit that commonly found in contemporary electronics lead to more power loss and dissipation of heat from the components.

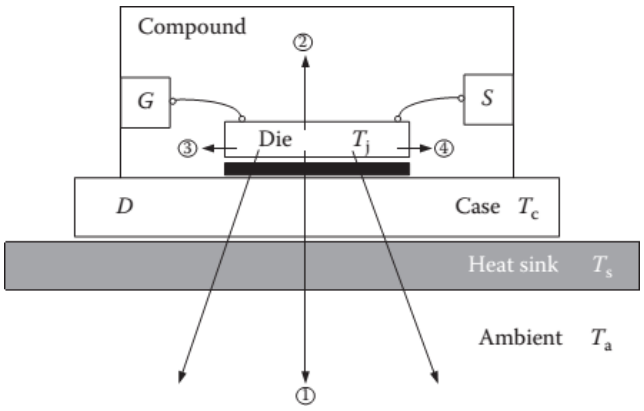


Figure 14.8: Thermal paths in a transistor

The heat flows to the compound, case, heatsink and before dissipated in the ambient. As shown in the figure given above, 80% of the heat loss in the transistor radiates in the direction of 1 and about 20% in direction of 2, 3, and 4. The following diagram shows common equivalent thermal circuit of transistor with heatsink.

14.3.1. Equivalent Thermal Circuit

The following diagram outlines the conversion of thermal path of the transistor to the equivalent thermal circuit.

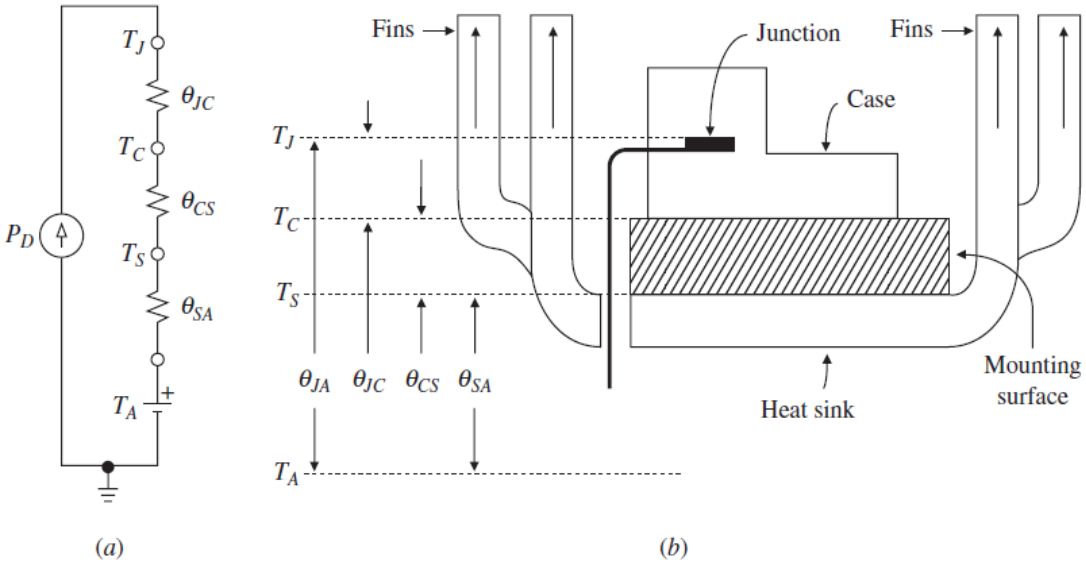


Figure 14.9: Thermal equivalent circuit of a transistor with heatsink

For a given electronic device, the thermal conductivity in a given electronic device could be represented with its equivalent thermal circuit as shown in the figure below.

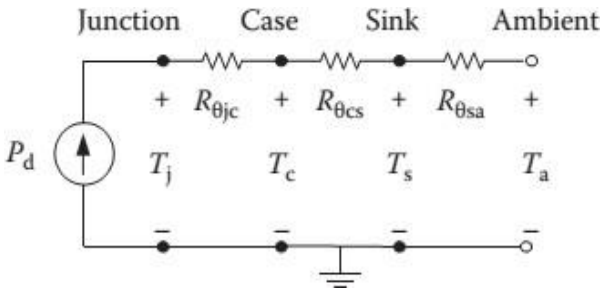


Figure 14.10: Equivalent thermal circuit of an electronic device

14.3.2. Calculation of Thermal Path of Transistor

The equation that represents the thermal circuit given above is:

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

Where:

- Thermal resistance is R_θ or θ
- j is Junction
- c is Case
- s is (heat) Sink

- a is Ambient

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

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

Where: P_d is power dissipated, T_j is junction temperature, and T_c is the case temperature

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 $R_{\theta jc} = \theta_{jc}$.

14.3.3. Ohms Law of Thermal Analysis

We require derivation of equivalent thermal circuit and relevant equations for determining the thermal characteristics of the components and circuit.

There are a number of equations used for determining thermal analysis:

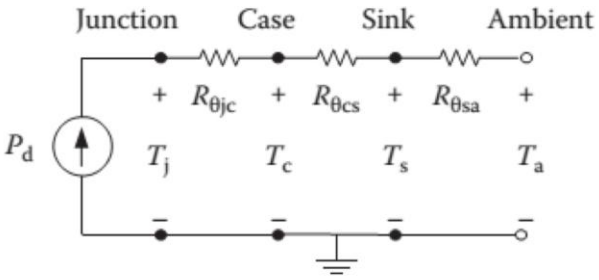


Figure 14.11: Thermal analysis of a transistor

For the given equivalent thermal circuit given above:

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

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

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

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

From all of these equations, equation 1 is typically used for analysing the existing system. Equation 2 is used for designing the heat sink and equations 3 and 4 are commonly used for establishing the design limits.

14.3.4. Thermal Resistivity

The equation used to determine the case-to-sink thermal resistivity is:

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

Where: t in inches, A in inches and θ_{cs} is normally less than 1° C/W.

The higher the value, the higher the resistance to dissipate heat. In this case, 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.

14.4. 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 Drain-Source junction for FET).

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

Furthermore, the transistor's collector-emitter junction places a limit on allowable power dissipation.

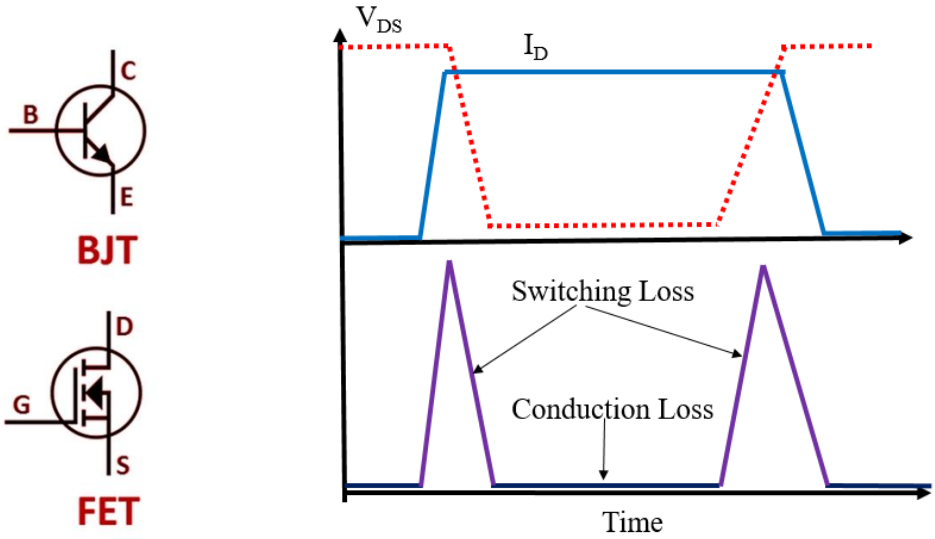


Figure 14.12: Conduction and switching losses in the transistor

Data sheets typically 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.

Then, maximum dissipated power of the component, $P_{d(\max)}$ is typically specified 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.

14.4.1. Thermal Specifications of Transistors

From the datasheet of the components used in the circuit, we might often obtain their thermal specifications.

14.4.1.1. Thermal Specifications of General-Purpose Transistor

The following diagram outlines the thermal specifications of BJT NPN General Purpose Transistor 2N3904. Notice that $T_j = 150°\text{C}$, $P_d = 5\ \text{mW}/°\text{C}$, $R_{\theta jc} = 83.3°\text{C/W}$, and $R_{\theta ja} = 200°\text{C/W}$.

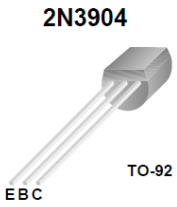


Figure 14.13: 2N3904 transistor

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.

Figure 14.14: Datasheet specification of a 2N3904 transistor

14.4.1.2. Thermal Specifications of Small Power Transistor

The following diagrams show the thermal specifications of BJT NPN small power transistor KSD1944. Notice that $T_j = 150°C$.

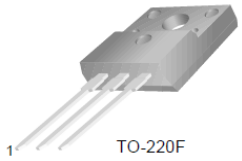


Figure 14.15: KSD1944 transistor

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

Figure 14.16: Datasheet specification of KSD1944 transistor

14.4.2. Thermal Derating

For temperature over 25°C, considering the condition over room temperature (e.g. > 25° C), we need to derate the power rating of the components. Some manufacturer datasheets list a derating factor D. For example, as shown in the graph below, derating factor of 2N1936 is 26.7 mW/°C.

$$\Delta P = D(T_A - 25°C)$$

Where: ΔP is decrease in power rating

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

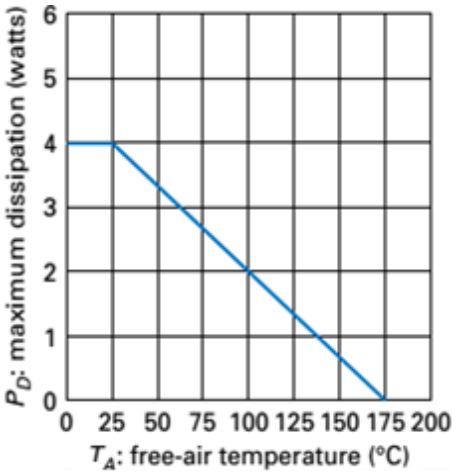


Figure 14.17: Graph of thermal derating of a transistor

Depending on the materials used, order of temperature in semiconductor device packaging or casing: Case Temperature > Sink Temperature > Ambient Temperature.

Data sheets of large transistors give derating curves for case temperature than ambient temperature. Figure given below for 2N3055 transistor from Onsemi Semiconductor ≈ 115 Watts.

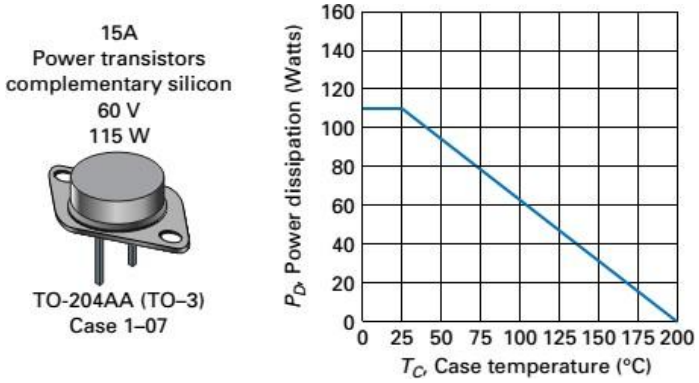


Figure 14.18: 2N3055 transistor and its thermal derating graph

14.5. Cases of Electronic Devices

Different cases of electronic devices result in different thermal characteristics and behaviours.

14.5.1. Case Temperature

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:

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

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

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

14.5.2. Common Transistor 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

Table 14.3: Thermal specification of several common transistor cases

Part with higher power rating does not mean good power dissipation (P_d). Failing to remove heat effectively will affect performance of the components and circuit. The above given thermal specification numbers can vary a lot depending on parts internal construction.

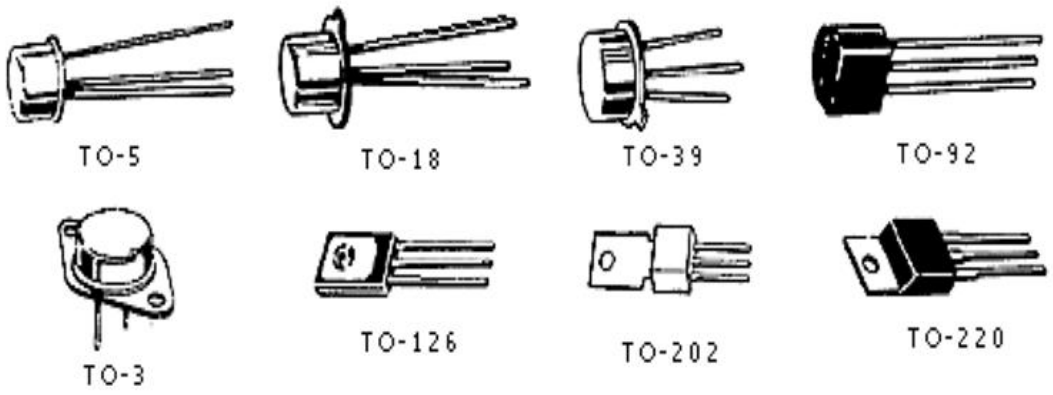
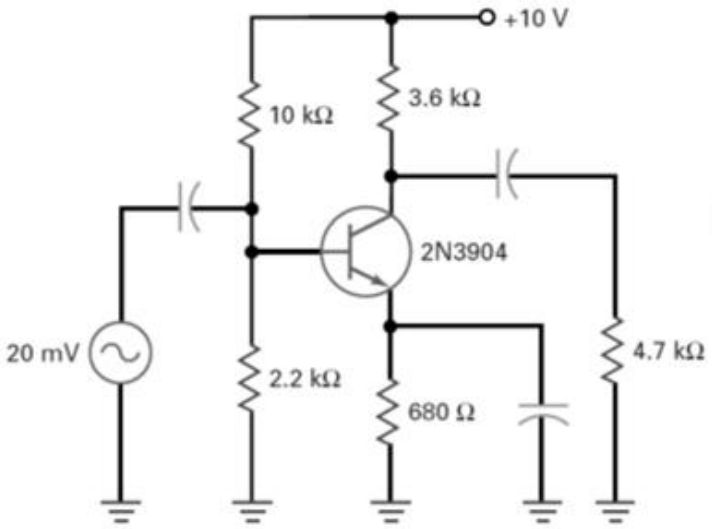


Figure 14.19: Common cases of transistor

For signal application, typically we use TO18, TO92, TO5, and TO39. On the other hand, for power application, transistors are found in TO3, TO202, TO126, TO220 packages and diodes are TO126, TO202, TO220 packages.

Example for Tutorial 1 - 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. [12 marks]



Solution

Expected to be operating at ambient temperature of 50°C. From datasheet of 2N3904, the maximum dissipated power, P_d = 625 mW at 25°C and derating factor, D = 5 mW/°C. The following figure shows the packaging lay out of the 2N3904 transistor.



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:

$$T_{c(\max)} = T_{j(\max)} - R_{\theta jc}P_d = 150°\text{C} - (83.3)(625 \times 10^{-3}) = 97.94°\text{C}$$

It looks like the device needs a heatsink as its case temperature is almost 100°C considering the ambient temperature is 50°C. The following figure shows the datasheet specification of 2N3904 transistor

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.

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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.

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

$$\Delta P = D(T_C - 25°\text{C})$$

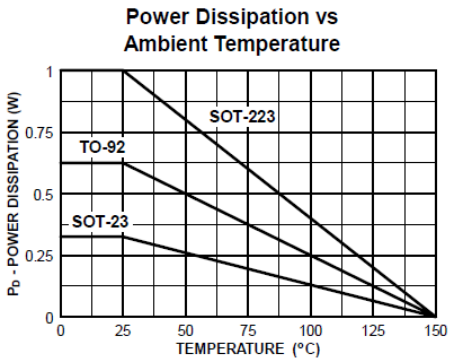
Entering values into the equation:

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

So, maximum power rating at 50°C:

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

The following figure outline a graph of power dissipation vs temperature of several transistor cases



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:

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

14.6. Heat Sinks

To help dissipate heat from the components and/or circuit, heat sinks are employed in the design.

14.6.1. Introduction to Heat Sink

Goal of heat sink: to increase the surface area of the semiconductor device (i.e. transistor) 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.

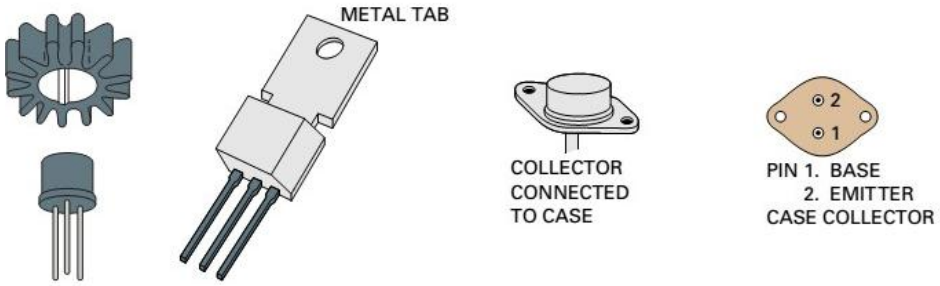


Figure 14.20: Heatsinks of several common transistor cases

Depending on their types, these heatsinks are:

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



Figure 14.21: Heatsink arrangements e.g. air (left), fan (middle), and liquid (right)

14.6.2. Heat Dissipation

The following graphs outline the heat dissipation characteristics and the thermal resistance with the speed of air-cooling system.

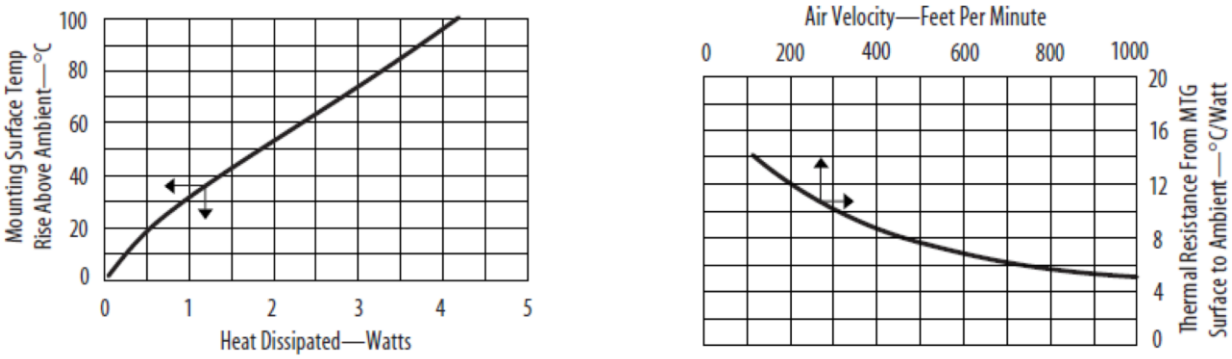


Figure 14.22: Graph of surface temperature vs heat dissipation (left) and graph of air velocity vs. thermal resistance (right)

For determination of heat dissipation, the thermal resistance graph (left) is determined by dividing temperature rise by the power input. On the other hand, volumetric flow rate (right) is about heat velocity divided by the cross-sectional area. It is shown in the graph that cooling helps to dissipate heat from the component and/or circuit.

14.6.3. 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.

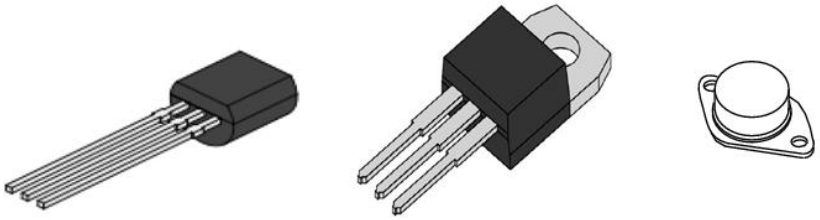


Figure 14.23: Several common cases of transistor (e.g. TO92, TO220, and TO3 packages left-right)

So, for example, if P_d = 10 W, $T_j \leq 150°C$, and $T_A \approx 50°C$ (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 quite a large heat sink. Clip-on heat sinks are typically 20 - 70° K/W.

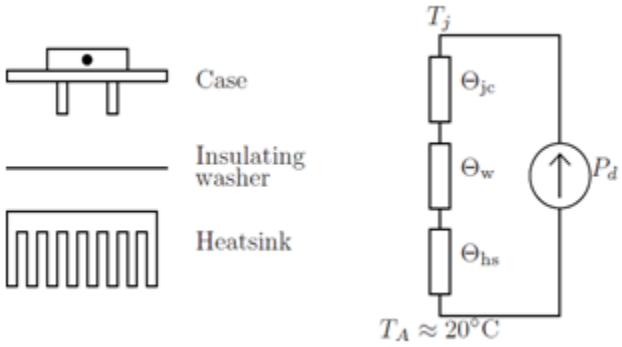


Figure 14.24: Thermal resistance circuit of a transistor (TO3 package)

The above and below diagrams show different packages of transistor for determining the thermal resistances circuit of a transistor with heatsink.

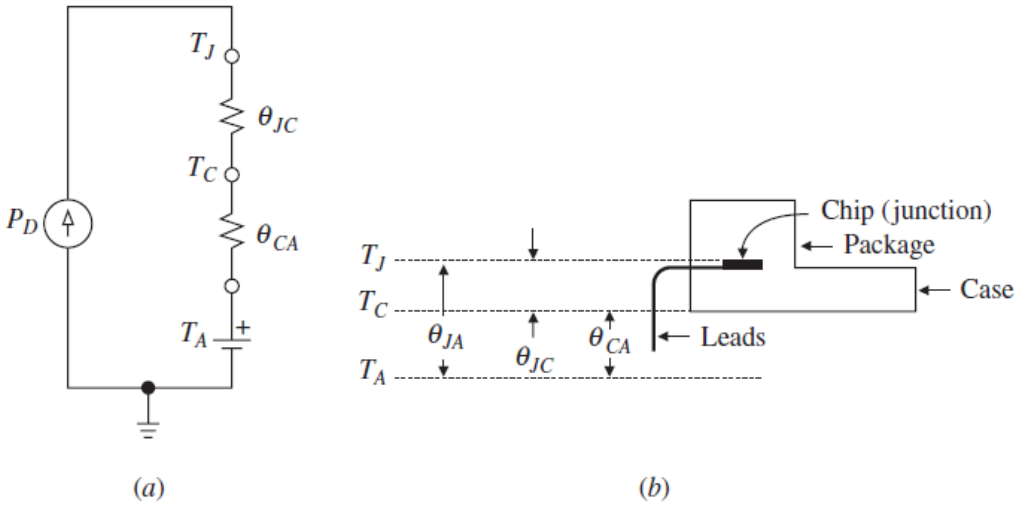


Figure 14.25: Thermal resistance circuit of a transistor (TO220 package)

14.6.4. 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 (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.

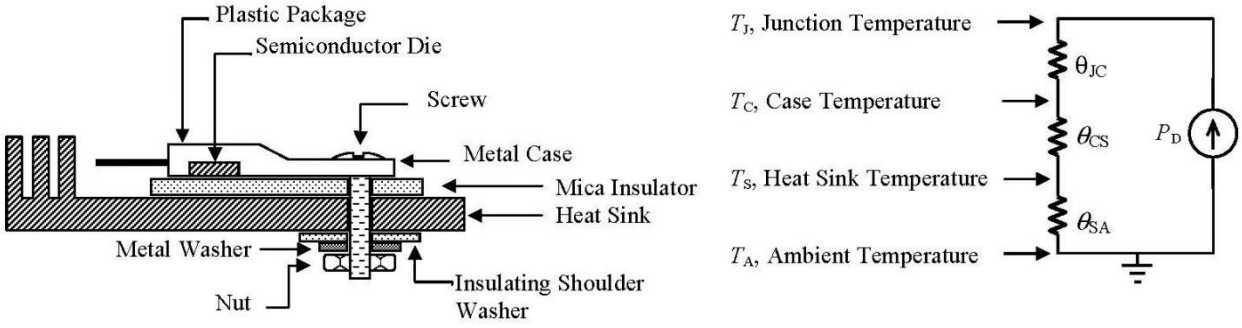


Figure 14.26: Heatsink arrangement of a transistor (left) and its thermal equivalent circuit (right)

14.6.5. 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.

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

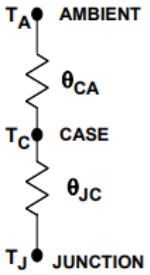


Figure 14.27: Thermal circuit for matching heatsink

14.6.6. Thermal Compound Applications

It is also important to implement some sort of thermal compound between the chip and heatsink to improve the conduction between these two parts.

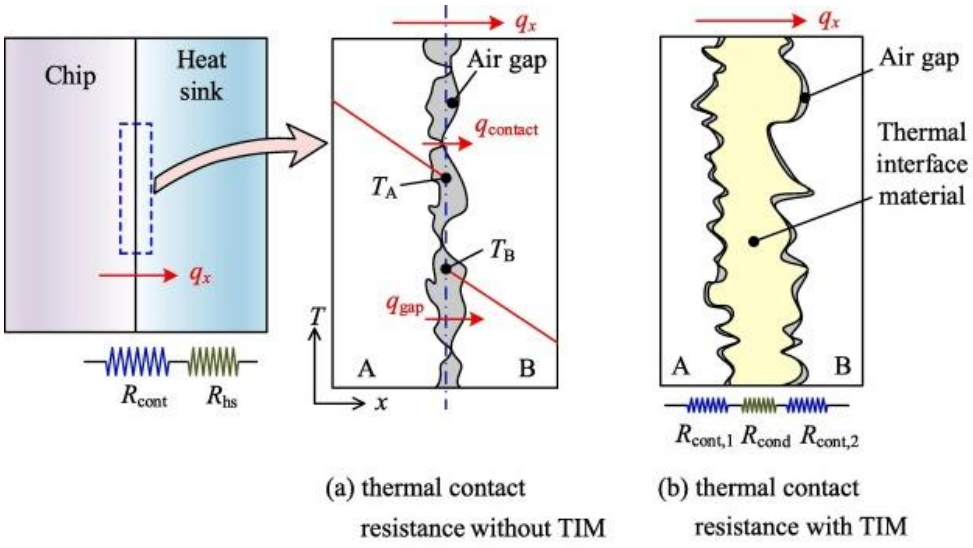


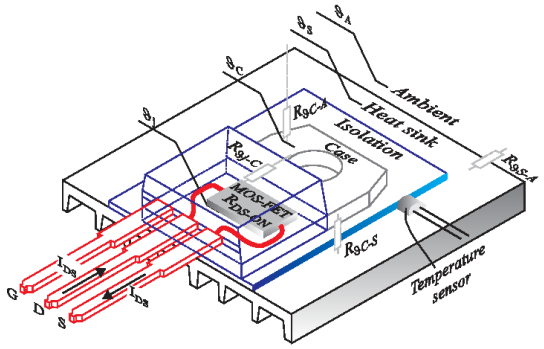
Figure 14.28: Heat profile of cooling system without and with thermal joint compound (grease)

As illustrated in the diagram given above, thermal joint compound (grease) improves the heat transfer from the chip to the heatsink.

Without the thermal joint compound, the heat flows through air gap that has poor conduction property. As a result, heat is not flowing freely from the chip to the heatsink.

Example for Tutorial 2 - Heat Sink Determination

For a given small power transistor arrangement with a heatsink as shown in the following figure, perform the following tasks.



From its datasheet, we know that the transistor has the following specification:

- TO-220 package is dissipating 7 Watts.
- Maximum junction temperature is 125°C.
- Maximum ambient temperature is 65°C.
- Junction-to-case thermal resistance for the silicon-based semiconductor is 2.5°C/W.
- Case-to-heatsink thermal resistance is dependent on the thermal material used e.g. insulating contact, silicon grease, etc.

a. Derive the equation for determining the heatsink requirement for the transistor. [8 marks]

b. Determine the physical dimension of the transistor. [6 marks]

c. Explain why thermal (grease) compound is needed and describe the thermal requirement of the transistor. [6 marks]

d. Determine the thermal resistance of the junctions in the thermal circuit of the transistor. [4 marks]

e. Determine the heatsink requirement for the transistor. [4 marks]

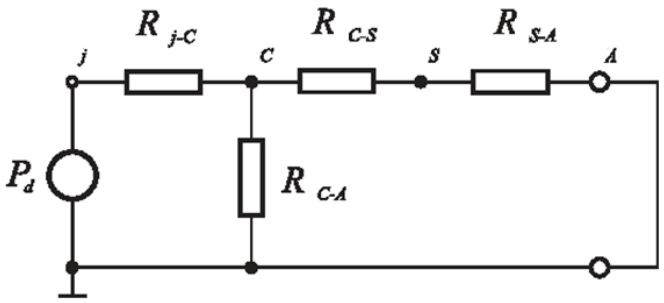
Solution

a. The thermal resistance of case to sink in the transistor is given as:

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

Where:

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



Referring to the equivalent thermal circuit given above, 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 $\theta_{ca} \gg \theta_{cs} + \theta_{sa}$, the equation for determining the thermal equivalent circuit as given above is:

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

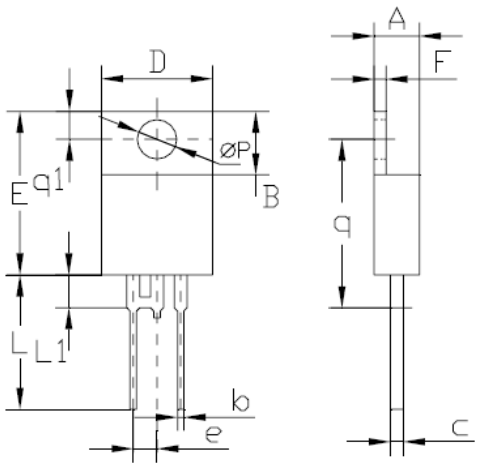
Where:

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

Heatsink requirements:

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

b. From its datasheet, the case packaging of transistor is TO220 with its physical dimensions of transistor's as shown in the figure below has 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, physical dimension of the case of the semiconductor device is:

- ρ = 56°C/W-inch.
- t = 0.002 inch.
- A = 0.36-inch square.

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

For the example thermal design, grease determination is based on Wakefield 120 series heat sink compound (e.g. it fills the air gap between mating surfaces with a grease-like material containing zinc oxide in a silicone oil carrier).

From the datasheet of the grease compound as shown in the figure below, its thermal resistivity is 56°C inch/W.



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

d. Determine the thermal resistances of the junctions in the thermal circuit.

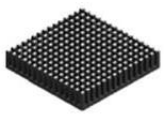
Grease compound (Case-to-Heatsink):

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

Heatsink-to-Ambient:

$$\theta_{sa} = \frac{(T_j - T_a)}{P_d} - (\theta_{jc} + \theta_{cs}) \frac{(125^{\circ}\text{C} - 65^{\circ}\text{C})}{7\ \text{W}} - (2.5^{\circ}\text{C/W} + 0.311^{\circ}\text{C/W}) = 5.76\,^{\circ}\text{C/W}$$

e. Referring to table below that shows design specifications of several heatsink candidates, we require a heat sink with thermal resistance of minimum 5.76°C/W or less.

Specification	Type A	Type B	Type C	Type D
Model	Stamping	Crosscut	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

Finally, comparing the specifications (e.g. dimension, thermal resistance, material, form, price, etc.) of several heat sinks taken from the manufacturer's datasheet in table above, the heat sink that meets the requirement is type C heat sink.