

Thermal Resistance and its Applications

For integrated circuits (ICs) to operate, the user must provide electrical power in the form of a power supply voltage and current that flows from the power supply into the electronic device. This current is conducted through the pins of the device to the package of the device and finally to the semiconductor die.

The consumption of power results in heat generation, consequently increasing the silicon junction temperature. The junction temperature is transferred to the surface of the integrated circuit's package through thermal conduction. This process involves the movement of heat from the junction, where it is generated, through the various materials that make up the IC package, and finally to the external environment.

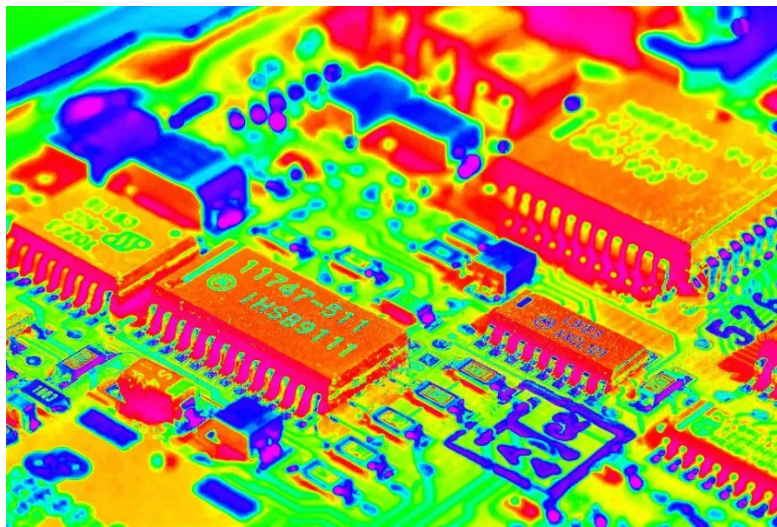
Thermal management is a significant challenge in electronics because semiconductors are highly sensitive to temperature fluctuations. Many reliability issues can be traced back to extreme temperature conditions. Electrical Engineers are constantly battling temperature, often declaring heat as their arch-nemesis.

According to Watt's Law, the generated power is equal to the product of the applied voltage and the device current:

$$P = V \cdot I$$

This relationship is crucial for understanding how power consumption translates into heat generation within the device.

Below is a heat map of a PCB, illustrating the temperature distribution. The hottest regions, displayed in pink and red, are the silicon dies inside the package. The orange and yellow areas represent medium temperatures, while green and blue indicate relatively cooler regions of the PCB.



1. Picture is from [End users, gainers of thermal management - Power Electronics News](#)

Heat emanates from the silicon die of the electronic device and propagates through the solid plastic mold. As the heat spreads over an increasingly larger volume, the temperature decreases as it approaches the surface of the case. However, not all heat can be transferred from the junction to the surface of the case. The plastic mold of the device package resists heat transfer. This resistance is referred to as Thermal Resistance (denoted by the Greek letter θ and pronounced 'theta')

Thermal resistance measures a material's ability to resist the flow of heat, much like electrical resistance measures a material's ability to resist the flow of electric current. For calculations and practical purposes, this phenomenon is modeled similarly to an electrical circuit and resembles Ohm's Law.

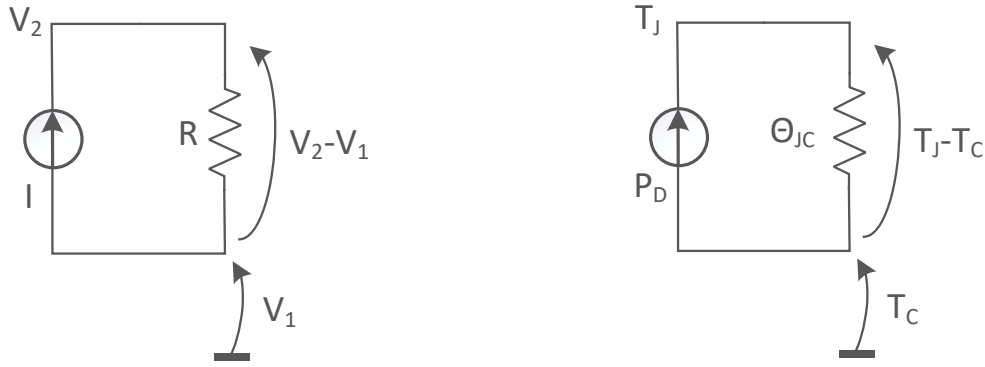


Figure 1. Voltage Drop Across a Resistor (Ohm's Law) | Figure 2. Equivalent Thermal Resistance Model

Ohm's Law states that the voltage drop across a resistor is equal to the product of the electrical resistance of the resistor and the current flowing through it (Figure 1):

$$\Delta V = V_2 - V_1 = R \cdot I$$

Similarly, the equivalent Thermal Resistance Model (Figure 2) stipulates that the temperature difference between the junction (T_J) and the case (T_C) is directly proportional to the product of the junction-to-case thermal resistance of the package (θ_{JC}) and the power it dissipates (P_d):

$$\Delta T = T_J - T_C = \theta_{JC} \cdot P_d$$

In this model:

- ΔT represents the difference between the junction (T_J) and the case temperature (T_C).
- T_C is the case temperature of the semiconductor device.
- T_J is the Operating Junction temperature, which is the temperature of the device circuit itself under given operating conditions. T_J must be calculated or inferred from the case and/or ambient temperature.

In practical applications, the maximum T_J temperature (T_{Jmax}) is often used, which represents the highest temperature at which the device can reliably operate. Most modern semiconductor devices are silicon-based, and the industry standard for T_{Jmax} is 125 °C, with some exceptions. Although devices can operate at higher temperatures, doing so may affect their longevity and reliability due to failure mechanisms like electromigration and hot electron effects. Therefore, it is strongly recommended that system designers ensure the actual T_J remains below T_{Jmax} .

There are some exceptions for specific devices, such as high-power transistor amplifiers or similar, where the component manufacturers are pushing the limits by designing their devices purposefully to operate under extremely harsh conditions. To achieve this, they may use different materials, technologies, and processes. In such cases, T_{Jmax} can be as high as 150 °C or, in some cases, even 175 °C.

Understanding and managing thermal resistance is crucial for the design and operation of ICs. It ensures that the devices operate within safe temperature limits, thereby enhancing their reliability and performance. By carefully considering the thermal properties of the materials and the design of the IC package, engineers can effectively manage heat dissipation and maintain the integrity of the device.

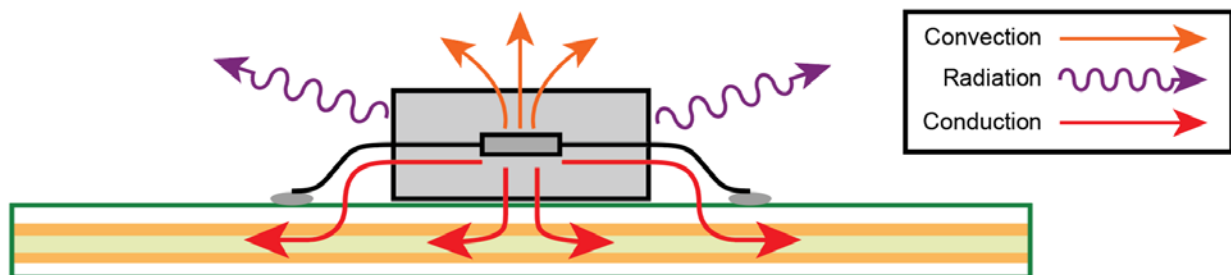
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1. Thermal Resistance

Thermal resistance is the ability of a device to dissipate internally generated heat, expressed in units of °C/W. ICs are typically mounted on a PCB and, except in special circumstances, operate in the Earth's atmosphere, with electronic parts immersed in air. As the heat generated by the device's power consumption gradually reaches the surface of the case, it is:

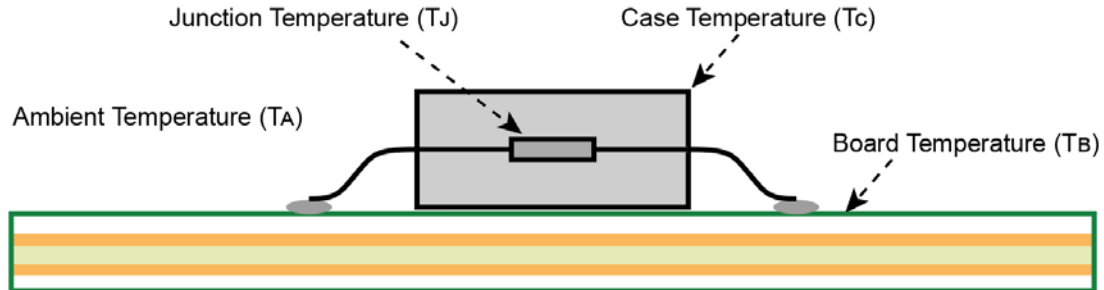
- Partially radiated out into the surrounding area (Radiation)
- Partially transferred to the surrounding air via convection (Convection)
- Partially conducted away from the device to the PCB through its metal pins (Conduction)



There are several types of Thermal Resistance, each of them will be individually discussed in the sections below.

1.1. Junction-to-Case (θ_{JC})

θ_{JC} is the junction-to-case thermal resistance, defined as the temperature difference between the junction (T_J) and a reference point on the package/case (T_C) when the device is dissipating 1 W of power. The diagram below shows where each temperature is measured in relation to the part.



It is expressed in °C/W and calculated as:

$$\theta_{JC} = \frac{(T_J - T_C)}{P_d}$$

In practical applications, θ_{JC} is used for calculating the maximum case temperature or maximum allowable power dissipation, ensuring that the maximum junction temperature (T_{Jmax}) specified by the manufacturer is never exceeded. θ_{JC} primarily depends on the die (junction) size/volume, the thermal properties of the mold compound constituting the package, and the lead frame / substrate design. P_d is the power dissipated by the device. For corner cases, the worst-case scenario is considered, where power dissipation is at maximum, denoted by P_{dmax} .

$$P_{dmax} = V_{max} \cdot I_{max}$$

1.2. Case-to-Ambient (θ_{CA})

θ_{CA} is the case-to-ambient thermal resistance, defined as the temperature difference between the case (T_C) and the ambient air (T_A) when the device is dissipating 1 W of power. It is expressed in °C/W and calculated as:

$$\theta_{CA} = \frac{(T_C - T_A)}{P_d}$$

T_A is the ambient temperature, specifically the temperature of the environment, including still air. θ_{CA} mainly depends on the surface area of the package and the ambient conditions (primarily temperature), among other factors. The cooler the ambient temperature relative to the case, the more effective the cooling will be. In practice, this is controlled by:

- Using heat sinks (which increase surface area that is in contact with the surrounding air)
- Implementing better thermal conduction paths
- Utilizing air or liquid cooling.

1.3. Junction-to-Ambient (θ_{JA})

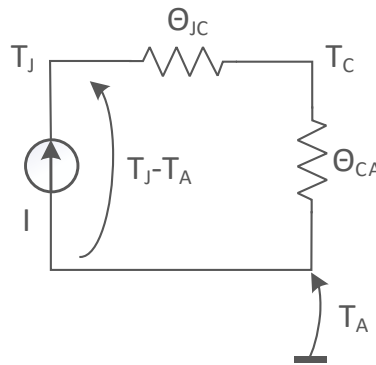
θ_{JA} (junction-to-ambient thermal resistance) is the most commonly used type in practical applications. It indicates the effectiveness of the temperature transfer from the silicon die (junction) to the surrounding air.

This parameter is especially useful because it avoids indirect calculations involving case temperature (T_C), junction-to-case (θ_{JC}), and case-to-ambient (θ_{CA}) parameters.

The junction-to-ambient thermal resistance is the sum of the junction-to-case and case-to-ambient thermal resistances. In other words, the relationship between the thermal parameters can be expressed as:

$$\theta_{JA} = \theta_{JC} + \theta_{CA}$$

The equivalent electrical schematic for this case is:



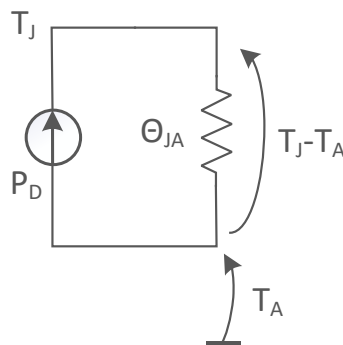
Substituting for the definitions of each of the thermal resistances,

$$\theta_{JA} = \frac{(T_J - T_C)}{P_d} + \frac{(T_C - T_A)}{P_d}$$

we obtain the final formula:

$$\theta_{JA} = \frac{(T_J - T_A)}{P_d}$$

Below is the equivalent electrical model:



When θ_{JA} is provided in the manufacturer's datasheet, we can directly calculate:

- the maximum allowable power consumption of the device under specific ambient temperature, or
- the maximum ambient temperature for specific power consumption.

Additionally, θ_{JA} varies with airflow rate. Typically, θ_{JA} values are provided for airflows ranging from 0 m/s to 5 m/s, and the thermal resistance decreases with increasing airflow.

1.4. Junction-to-Board (θ_{JB})

If we are interested in how much heat gets transferred into the PCB from the junction, we can use θ_{JB} . It is used less commonly in practice.

It is calculated as:

$$\theta_{JB} = \frac{(T_J - T_B)}{P_d}$$

where T_B is the temperature of the PCB measured at a predefined location near the device on the PCB.

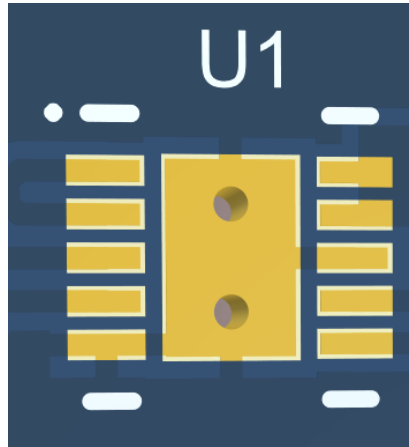
2. Mitigation Techniques

A specific set of design choices can mitigate the maximum power dissipation and maximum ambient air temperature. To improve the extraction of heat from the device, we aim for minimizing thermal resistance. The lower the thermal resistance, the higher the power dissipation and/or ambient temperature can be.

Essentially, there are four paths for heat to transfer out of the chip into the PCB:

1. A relatively small amount of heat transfers from the case to the ambient through the air around the device. This path can be improved through attaching a heat sink or a fan for critical components.
2. Heat transfers into the PCB through the top layer via the device's metal pins and copper traces on the PCB, to which the pins are soldered.
3. Heat transfer to the internal dielectric material and copper layers through a via array.
4. Heat that travels through the via array to other internal solid copper layers provides a very efficient way of extracting heat from the PCB area near the device.

If the package has a heat slug (thermal pad), it should be connected to a copper ground patch underneath the package and use a via (or a multitude of vias) to connect to a large, solid copper plane in the PCB. That will enable the heat to be conducted away from the case.



Vias provide a very effective thermal conduction path. The more vias under the chip, the lower the thermal resistance. Consequently, the junction temperature of the chip will be reduced. Optimized conduction paths from vias to copper layers and dielectric material through accurate design of the via array provide the most efficient paths in the design for removing heat from the chip.

If required, the thickness of the copper traces and solid copper planes can be increased to increase the volume of heat-conducting material that will extract heat from the case. For instance, we can use 1 oz instead of a 0.5 oz copper plane.

The metal (copper traces) on PC boards conduct heat away from the package and dissipate heat to the ambient, thus the larger the trace area, the lower the thermal resistance.

The dielectric material used in the PCB with higher thermal conductivity can also help to get lower thermal resistances. Empirically, it was shown that the thermal resistance from junction to board (θ_{JB}) is somewhat lower in the case of ceramic-filled PTFE composite RT/duroid 6035HTC (Rogers) than standard board material FR-4.

If that is still not sufficient, we should consider adding a heatsink to our device. This will increase the surface area of the device that is in contact with the surrounding air and will improve thermal convection, hence reduce thermal resistance.

If further cooling is required, due to very high-power consumption (such as performance CPUs) and/or allowing the device to operate at very high ambient temperatures, we can introduce forced air cooling. This is accomplished by using fans that increase airflow over the surface of the device, improving thermal convection.

3. Practical Case Studies

In practical applications, we are interested in establishing boundary conditions under which the die (junction) temperature will remain at or below the maximum junction temperature (T_{Jmax}). Let's explore two case studies to illustrate this.

3.1 Case Study 1

We want to determine the maximum average current for the device at a maximum ambient air temperature of 85 °C, ensuring that the junction temperature remains below its maximum value of 125 °C, as specified by the manufacturer. The maximum power supply voltage (V_{CCmax}) is 3.6 V. The datasheet specifies $\theta_{JA} = 96.7$ °C/W

First, let's calculate the power dissipation (P_d):

$$P_d = \frac{(T_J - T_A)}{\theta_{JA}} = \frac{(125^\circ\text{C} - 85^\circ\text{C})}{96.7^\circ\text{C/W}} = 0.414\text{W}$$

Knowing P_d we can calculate I_{max} :

$$I_{max} = \frac{P_d}{V_{CCmax}} = \frac{0.414\text{W}}{3.6\text{V}} = 0.115\text{A}$$

The maximum average current must be less than 115 mA.

3.2 Case Study 2

Calculate the maximum allowable ambient air temperature, if we know that the maximum voltage (V_{CCmax}) is 5 V, the maximum average current (I_{max}) is 88 mA and T_{Jmax} is 125 °C.

The datasheet specifies $\theta_{JA} = 124.2$ °C/W

First, calculate the power dissipation:

$$P_d = V_{CCmax} \cdot I_{max} = 5\text{V} \cdot 0.088\text{A} = 0.44\text{W}$$

Next, calculate the maximum ambient temperature (T_A):

$$T_A = T_J - \theta_{JA} \cdot P_d = 125^\circ\text{C} - 124^\circ\text{C/W} \cdot 0.44\text{W} = 70.44^\circ\text{C}$$

Therefore, the maximum ambient temperature cannot exceed 70.44 °C to ensure that the maximum junction temperature does not exceed 125 °C.

4. Summary

The amount of heat transferred from the IC's semiconductor junction to the surrounding air depends on several factors:

- IC packaging material (mold compound)
- IC packaging technique (e.g., flip chip vs. wire bond)
- Number of leads on the IC package and the size of the copper traces on the PCB
- Package/heatsink surface area
- Airflow (forced or static)
- Printed circuit board (PCB) materials
- Number of vias connecting to solid copper planes on the PCB
- Thickness of the solid copper layer
- Ambient temperature
- Heat originating from neighboring components

In practice, a Thermal Resistance model was developed to help designers calculate either:

- The maximum power dissipation the device can handle (P_{dmax}) under specific ambient conditions (ambient temperature T_A), or
- The maximum ambient temperature (T_A) at a specified power dissipation level (P_d), to ensure that the junction temperature does not exceed its specified maximum value (T_{Jmax}).

The model utilizes various parameters called Thermal Resistance. There are several types of thermal resistances: θ_{JC} , θ_{CA} , θ_{JA} , θ_{JB} . These parameters are established either empirically or through thermal simulations and are typically published in the datasheet of the IC device. If not found in the datasheet, they can be obtained upon request from the IC manufacturer.

5. Definitions

The following are some important definitions pertaining to the operating conditions of the devices:

- T_A = Ambient temperature: This is the temperature of the environment, typically still air.
- T_C = Case temperature: This is the temperature of the semiconductor device's case.
- T_J = Operating Junction temperature: This is the temperature of the device circuit itself under given operating conditions. T_J must be calculated or inferred from the case and/or ambient temperature.
- T_{Jmax} = Maximum Junction temperature: This is the maximum temperature that the device tolerates to guarantee reliable operation. Most of today's semiconductor devices are silicon-based, and the typical T_{Jmax} for those devices is 125 °C, with some exceptions. Devices can likely operate at higher temperatures, but it may affect their longevity and reliability. Therefore, it is strongly recommended that the system designer ensures that T_J does not exceed T_{Jmax} . There are some exceptions for specific devices, such as high-power transistor amplifiers, where T_{Jmax} can be as high as 150 °C or, in rare cases, even 175 °C.
- P_d = Power Dissipation: This is the power consumed while the device is in operation, creating heat. It is expressed in Watts.

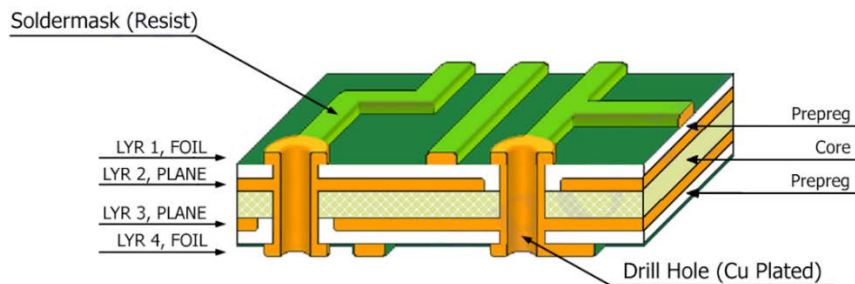
When parameters are established by simulations, the conditions must also be specified. For example, we may have to specify the parameters of the PCB on which the device was mounted:

- **PCB: 114.3 x 76.2 x 1.6 mm³ 4L JEDEC Board, 70 μm external (5.5% Cu) & 35 μm internal (100% Cu) layer thickness, no vias PCB.**

This line can be deciphered as follows:

- 114.3 x 76.2 x 1.6 mm³: PCB dimensions (Width x Depth x Height)
- 4L JEDEC Board: Four-layer PCB with the following stack-up: signal/GND/PWR/signal, in literature often referred to as s2p2 (two signal and two power plane layers).
- 70 μm external (5.5% Cu): Top and bottom layers are 70 μm thick, with only 5.5% of the surface area being copper, corresponding to 2 oz of copper thickness.
- 35 μm internal (100% Cu): The two internal layers are 35 μm thick, with 100% of the surface area being copper (solid copper), corresponding to 1 oz copper thickness.
- No vias: Indicates there are no vias on power and signal traces that would provide heat conductivity to the internal solid copper and dielectric layers.

An example of a 4-layer PCB is shown in the picture below:



6. Revision History

Revision	Date	Description
A0	09 / 2025	Initial release.

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