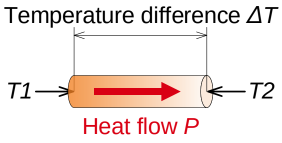
Thermal Design (Basic)

Basics of Thermal Resistance and Heat Dissipation

Challenges in designing electronic equipment include downsizing, improvement in efficiency, support for electromagnetic compatibility (EMC), and countermeasures against heat. Heat has been one of the most important considerations because it affects the performance and reliability of the parts and equipment as well as safety. This application note provides the basics of thermal resistance and heat dissipation considering semiconductor parts such as the ICs and transistors used in electronic equipment.

What is thermal resistance?

Thermal resistance is a quantification of how difficult it is for heat to be conducted. Thermal resistance is represented as the quotient of the temperature difference between two given points by the heat flow between the two points (amount of heat flow per unit time). This means that the higher the thermal resistance, the more difficult it is for heat to be conducted, and vice versa.



$$Thermal\ resistance\ Rth = \frac{T1 - T2}{Heat\ flow\ P}$$

$$= \frac{Temperature\ difference\ \Delta T}{Heat\ flow\ P} \quad [°C/W]$$

R is used as the symbol for the electric resistance, while θ (theta) is used for the thermal resistance. The JEDEC (Joint Electron Device Engineering Council) Solid State Technology Association is a trade organization that standardizes specifications in the field of semiconductor parts. In its integrated circuit thermal measurement method, part of the JESD51 standards, JEDEC has standardized that θ_{XX} or $R_{\theta XX}$ (Theta-XX, if Greek characters are unavailable) should be used. For XX, symbols representing the two given points are entered. For example, θ_{T1T2}, $R_{\theta T1T2}$, or Theta-T1T2 should be used in the case shown in the figure above.

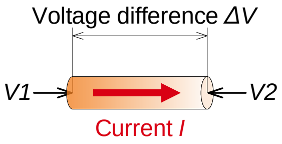
In addition, the IEC (International Electrotechnical Commission), a global organization that specifies and publishes international standards for all electric, electronic, and related technologies, uses Rth in the EN 60747-15 standards for discrete semiconductor devices.

Based on these relationships, in ROHM's data sheets, θ is used for ICs, while Rth is used for discrete devices (with some exceptions).

The unit of thermal resistance is K/W or °C/W (K represents kelvins). Although K and °C are different in their absolute values (0 K = -273.15°C), they can be treated equivalently in terms of relative temperatures (K = °C).

Thermal Ohm's law

The thermal resistance can be considered in the same way as the electric resistance. The basic formulas of thermal calculation can be treated in the same way as Ohm's law. In the figure below, Ohm's law is represented with an illustration and equations. It can be seen that the respective parameters are replaceable by heat and electricity.



$$Electric\ resistance\ R = \frac{V1 - V2}{Current\ I}$$

$$= \frac{Voltage\ difference\ \Delta V}{Current\ I} \quad [V/A]$$

Therefore, as potential difference ΔV is calculated with R × I, temperature difference ΔT can be calculated with Rth × P.

These relations are summarized in the table below.

Electric	Voltage difference ΔV (V)	Electric resistance R (Ω)	Current I (A)
Thermal	Temperature difference ΔT (°C)	Thermal resistance Rth (°C/W)	Heat flow P (W)

Electric	$\Delta V = R \times I$	$R = \frac{\Delta V}{I}$	$I = \frac{\Delta V}{R}$
Thermal	$\Delta T = Rth \times P$	$Rth = \frac{\Delta T}{P}$	$P = \frac{\Delta T}{Rth}$

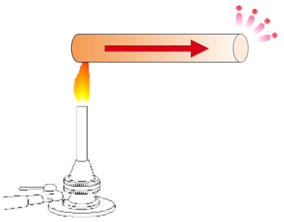
Heat transfer and heat dissipation path

Heat can be transferred through objects and spaces. Transfer of heat means that the thermal energy is transferred from one place to another.

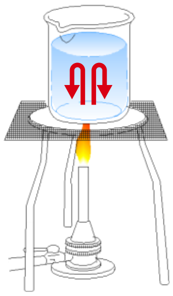
Three forms of heat transfer

The heat transfer occurs in three forms: thermal conduction, convection (heat transmission), and heat radiation.

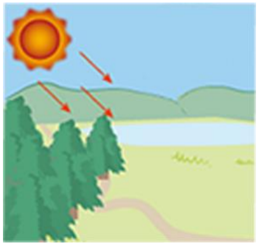
- Thermal conduction: Heat is transferred from a high temperature point to a low temperature point within an identical object due to movement of molecules composing the material. No movement of the material is involved.



- Convection (heat transmission): Heat is transferred by flow of a fluid when there is a temperature difference between the surface of a solid and a fluid, such as air or water, that is in contact with the surface. The convection can transfer a larger amount of heat compared with the thermal conduction.

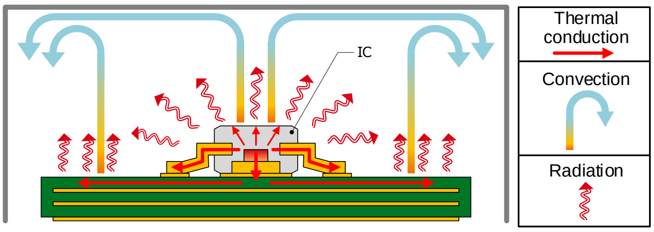


- Heat radiation: From the surface of an object, an electromagnetic wave is emitted with a wavelength corresponding to the surface temperature. The electromagnetic wave is transmitted through a space and hits the destination object. The vibration energy of the electromagnetic wave causes vibration of molecules on the surface of the destination object, transferring heat and changing the temperature of the destination object. Through the heat radiation, heat may be transferred without any medium between objects (even in a vacuum). Therefore, it causes no change in the surrounding air temperature.



Heat dissipation path

Generated heat is dissipated to the ambient air via various paths through the conduction, radiation, and convection. In this section, an IC mounted on a printed circuit board (PCB) is used as an example for explanation.



The heat generating source is the chip (die) of the IC. The heat is conducted to the die attach (die bonding), lead frame, case (package), and PCB. The heat is transferred from surfaces of the PCB and the IC package to the atmosphere through the convection and radiation. This is represented with a circuit network of resistance elements as follows.

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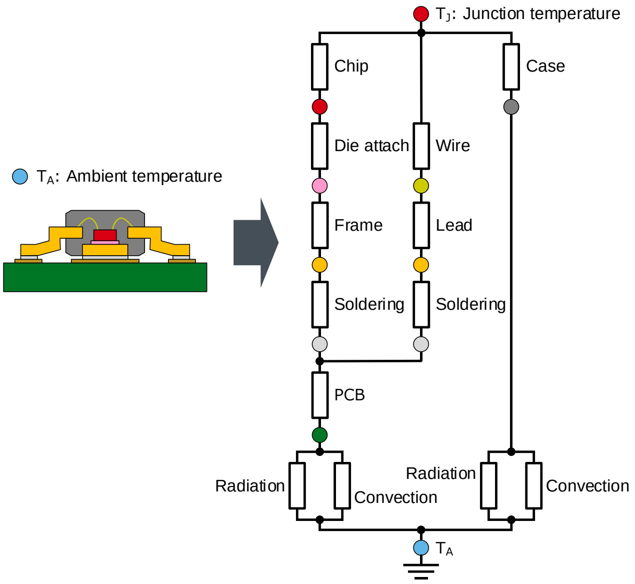
Example of simplified steady thermal circuit network



Note: Except for those for radiation and convection, all thermal resistances are for thermal conduction.

The colors of the respective parts in the IC cross section (the left figure above) correspond to the colors of the circles in the circuit network. For example, the chip is represented in red. Junction temperature T_J of the chip reaches ambient temperature T_A through the thermal resistances as shown in the circuit network.

The heat dissipation path runs from the chip to the exposed heat-pad via the die attach and frame, and reaches the PCB via soldering on the copper foil land of the PCB. Then, the heat is transferred to the atmosphere (T_A) through the convection and radiation from the PCB.As another possible path, the heat can be transferred from the chip to the lead frame and the PCB via the bonding wire, and convected and radiated to the atmosphere. It is also possible that the heat is convected and radiated from the chip to the atmosphere through the package.

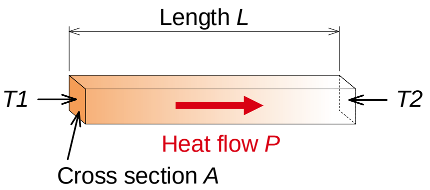
If the thermal resistance of these paths and the power loss of the IC are known, the temperature difference (between T_J and T_A in this case) can be calculated with the equation for the thermal resistance as mentioned above.

Thermal design is intended to reduce each thermal resistance described here, that is, to reduce the thermal resistance of the heat dissipation path from the chip to the atmosphere. This reduces T_J and improves reliability.

In the following sections, we explain basic formulas required for reducing each thermal resistance.

Thermal resistance for thermal conduction

Thermal resistance for thermal conduction is represented with the following figure and equations.



$$Temperature\ difference\ (T1 - T2)$$
$$= Thermal\ resistance\ Rth\ \times Heat\ flow\ P$$

$$Thermal\ resistance\ Rth$$
$$= \frac{Length\ L}{Thermal\ conductivity \lambda\ \times Cross\ section\ A}$$

The figure shows that temperature T1 at one end of an object with cross section A and length L is transferred to the opposite end through the conduction, changing into temperature T2.

The first equation is the equation for the thermal resistance described in the first section, showing that the temperature difference between T1 and T2 is the product of thermal resistance Rth multiplied by heat flow P.

The second equation represents Rth with the parameters of the object.

As it can easily be imagined from the figure and the terms in the equations, the thermal resistance for thermal conduction can be considered basically in the same way as the sheet resistance of a conductor. The sheet resistance can be calculated with an equation where the thermal conductivity is replaced with the resistivity. As the resistivity has a value specific to the conductor material, the value of thermal conductivity is also specific to the material.

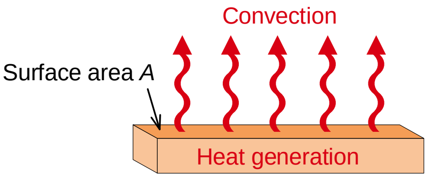
Based on the equation for Rth, in order to reduce the thermal resistance for thermal conduction, it is necessary to increase the cross section of the object, decrease the length of the object, or select a material with a higher thermal conductivity.

Thermal resistance due to convection (heat transmission)

There are several types of convection. Their definitions are shown below together with definitions of terms.

Fluid	Material that flows, such as gas or liquid
Convection	Heat transfer phenomenon where heat is transferred by a fluid that receives the heat. Note: No heat transfer through convection is expected to occur without any fluid (in a vacuum).
Natural convection	Upward flow generated by temperature difference in fluid
Forced convection	Flow generated by an external factor, such as a fan or pump

Thermal resistance due to fluid is represented with the following figure and equations.



$$(Surface\ temperature - Fluid\ temperature) = Thermal\ resistance\ Rth \times Heat\ flow\ P$$

$$Thermal\ resistance\ Rth = \frac{1}{\text{Convective heat transfer coefficient } hm \times Surface\ area\ A}$$

$$Convective\ heat\ transfer\ coefficient\ hm$$

$$Natural\ convection\ hm = 2.51 \times C \times \left(\frac{\Delta T}{L}\right)^{0.25} \quad [W/m^2K]$$

C: Coefficient (Varies with shape and installation conditions)

ΔT: Temperature difference [℃]

L: Representative length $[m]$

$$Forced\ convection: laminar\ flow\ hm = 3.86 \times \left(\frac{V}{L}\right)^{0.5} \quad [W/m^2K]$$

$$Forced\ convection: turbulent\ flow\ hm = 6 \times \left(\frac{V}{L^{0.25}}\right)^{0.8} \quad [W/m^2K]$$

V: Air velocity $[m/s]$

L: Representative length $[m]$

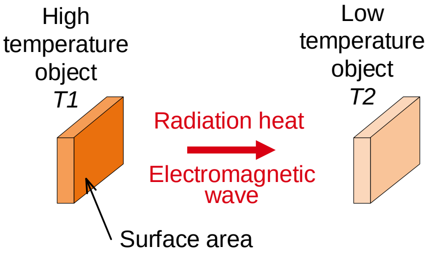
The thermal resistance for convection is represented as the reciprocal of the product of the convective heat transfer coefficient (hm) and the surface area (A) of the object that generates heat. Based on the equation, it is found that the convective thermal resistance is decreased as the surface area of the object is increased.

The convective heat transfer coefficient (hm) depends on the types of convection. For the natural convection, a larger temperature difference facilitates the convection, decreasing the thermal resistance. For the forced convection, it is found that a higher air velocity decreases the thermal resistance.

Thermal resistance for heat radiation

The heat radiation occurs by a different mechanism from the thermal conduction or convection (heat transmission) where heat is transferred via molecules. Through the heat radiation, heat can be transferred in a vacuum where no object or fluid exists.

Thermal resistance for heat radiation is represented with the following figure and equations.



$$Temperature\ difference\ (T1 - T2) = Thermal\ resistance\ Rth \times Heat\ flow\ P$$

$$Rth = \frac{1}{Radiative\ heat\ transfer\ coefficient \times Surface\ area}$$

$$Radiative\ heat\ transfer\ coefficient = \sigma \times Emissivity\varepsilon \times (T_1^2 + T_2^2)(T_1 + T_2)$$

σ: Stefan – Boltzmann constant $5.67 \times 10^{-8}\ [W/m^2K^4]$

Emissivityε: Emissivity of material surface 0 to 1

The thermal resistance for heat radiation is represented as the reciprocal of the product of the radiative heat transfer coefficient and the surface area of the object that generates heat. As shown in the equation, the surface area, temperature, and emissivity of the object affects the thermal resistance for heat radiation.

Based on the equation for Rth, in order to reduce the thermal resistance for heat radiation, it is necessary to increase the surface area of the object or select a material with a high emissivity.

Material	Emissivity
Polished aluminum wheel	0.05
Alumina	0.78
Polished copper	0.03
Oxidized copper plate	0.78
Polished cast iron	0.21
Oxidized cast iron	0.57
Polished brass	0.04
Oxidized brass	0.60
Resin	0.79-0.83
Rubber	0.86-0.92
Coating: matte white	0.91
Coating: matte black	0.88
Coating: gloss black	0.90

Reference: Emissivity of Solids, Heat Exchanger Design Handbook, ISBN: 978-1-56700-423-6

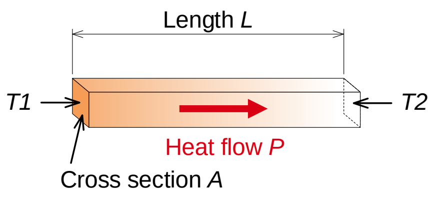
For the three forms of heat transfer, namely, thermal conduction, convection (heat transmission), and heat radiation, the equations of the respective thermal resistances have been shown. In all cases, since keys to decrease the thermal resistances can be obtained from the basic formulas, check the relationships of the parameters.

Summary

Finally, we summarize the calculation formulas for the thermal resistances in the three forms of heat transfer and the methods for decreasing the thermal resistances.

Conductive thermal resistance

$$Rth = \frac{Length}{Thermal\ conductivity \times Cross\ section}$$

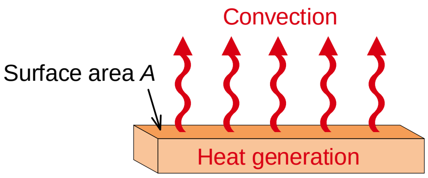


To decrease the thermal resistance:

- increase the cross section of the object,
- decrease the length of the object, or
- select material with a higher thermal conductivity.

Convective thermal resistance

$$Rth = \frac{1}{Convective\ heat\ transfer\ coefficient \times Surface\ area}$$

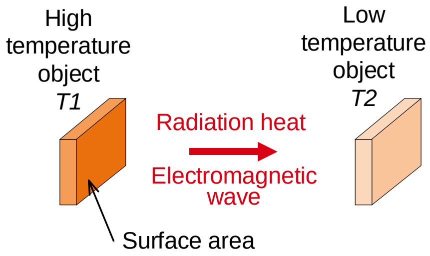


To decrease the thermal resistance:

- increase the surface area of the object,
- for the natural convection, consider the configuration so that the temperature difference is increased, or
- for the forced convection, increase the air velocity.

Radiative thermal resistance

$$Rth = \frac{1}{Radiative\ heat\ transfer\ coefficient \times Surface\ area}$$



To decrease the thermal resistance:

- increase the surface area of the object, or
- select material with a high emissivity.

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