

Thermal Design

θ_{JC} and Ψ_{JT}

θ_{JC} and Ψ_{JT} indicate how difficult it is for heat to be conducted. Although both of these are indicators of heat conduction from a junction to a package (case), there may be questions about what their differences are and how they are used in different situations. This application note explains the differences between θ_{JC} and Ψ_{JT} and how to use them correctly.

Definition of θ_{JC} in MIL

Traditionally, θ_{JC} is defined in “MIL-STD-883E, METHOD 1012.1 THERMAL CHARACTERISTICS, 4 November 1980” published by the U.S. Department of Defense. In the definition, θ_{JC} is described as follows: 「Thermal resistance, junction to specified reference point, $R_{\theta JR}$, in °C/W. The thermal resistance of the microcircuit is the temperature difference from the junction to some reference point on the package divided by the power dissipation P_D .」 There is also a description about the case temperature T_C at a reference point saying, “A thermocouple shall be attached as near as possible to the center of the bottom of the device case directly under the chip or substrate.” This is shown in Figure 1.

Place the device to be tested on a water-cooled heat sink and measure the case surface temperature to be contacted directly with a thermocouple. Apply pressure from above to ensure proper contact of the case to the heat sink. In order to measure the case temperature in contact with the heat sink, make a hole in the heat sink and make the thermocouple penetrate through. Since the tip of the thermocouple must be in direct mechanical contact with the case, it is equipped with a pressure adjustment mechanism to make contact with a predetermined force.

The problems with this test method are discussed below. Measuring the case temperature with a thermocouple does not have good reproducibility of results. First, since there is a temperature distribution over the case, there will be an error if the contact point between the thermocouple and the case shifts even slightly (1 mm). In addition, since the tip of the thermocouple is not well insulated against the heat sink, it is cooled from the wires and heat sink and the case temperature readings may be low. Furthermore, there is an influence from the drilled holes in the heat sink for the thermocouple. Also, since there are differences in the measurement environment depending on the devices used and in the skill of the measurers, the error between each semiconductor vendor becomes larger.

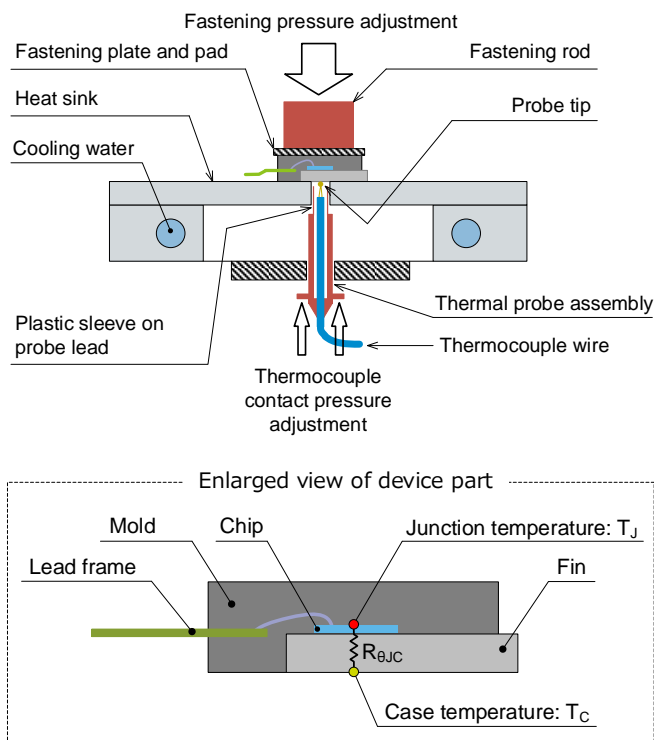


Figure 1. Example of the test equipment in MIL-STD-883E METHOD 1012.1, measuring the case temperature

*Since the words used vary from standard to standard, this application note contains inconsistent descriptions, such as “ θ_{JC} , $R_{\theta JC}$, R_{thJC} ,” “package and case,” and “heat sink and cold plate” that are synonymous.

Definition of θ_{JC} in JEDEC

To solve these problems, JEDEC Standard JESD51-14 was created in 2010 as a new measurement method. It uses the Transient Dual Interface (TDI) test method to achieve junction-to-case thermal resistance measurements without measuring the case temperature with a thermocouple. This improves the reproducibility of θ_{JC} measurements and reduces measurement data errors between companies. This is a common method in current use that replaces the MIL-STD. ROHM currently uses this measurement method.

Figure 2 shows a test environment for the JEDEC TDI method. As in the MIL-STD, place the device to be tested on a water-cooled heat sink and apply pressure from above so that the case makes proper contact with the heat sink. However, instead of using a thermocouple, take measurements in two different environments “with” and “without” thermal grease (Figure 3). Then convert the measurements from their respective thermal impedance curves into structure functions and determine θ_{JC} from the branch point in the graph (Figure 4). For details on the measurement method, refer to References [1], [2], and [3] on the last page.

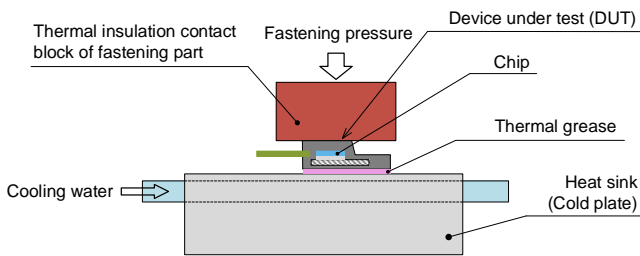


Figure 2. Example of a test environment for the JEDEC TDI method

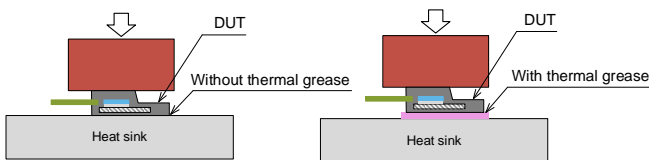


Figure 3. Measurement in two different environments “with” and “without” thermal grease

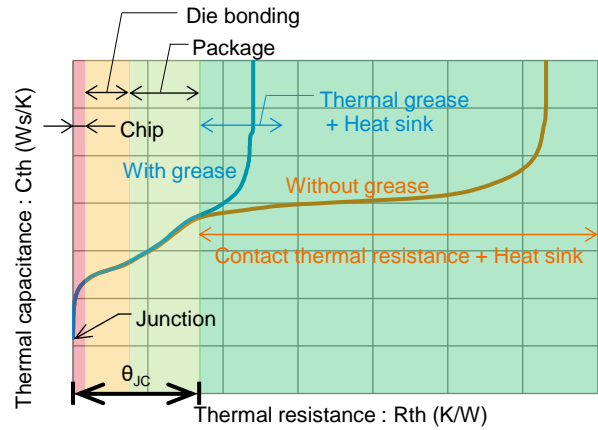


Figure 4. Graph showing superimposition of structure functions “with” and “without” thermal grease θ_{JC} is determined from the branch point.

Figure 5 shows enlarged figures of the device part. A feature of this measurement method is that there is no physical reference point for the case temperature. In the structure function graph, the case temperature c is located near the boundary between “Package” (case) and “Contact thermal resistance” and between “Package” and “Thermal grease” respectively.

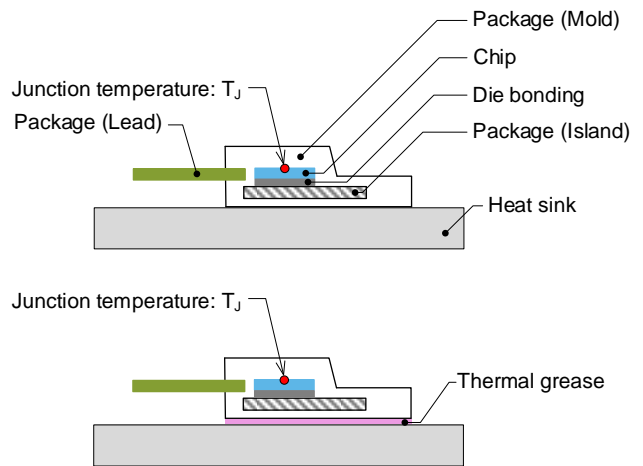


Figure 5. Enlarged figures of the device part There is no physical reference point for the case temperature.

Another feature that must be considered is that most chip heat sources define thermal resistance when heat is dissipated only in one direction (one-dimensional) from the heat sink. Since the upper surface on the opposite side of the heat sink is insulated by a fastening part and furthermore the space between the fastening part and the heat sink is an air layer as shown in Figure 2, almost no heat is dissipated in the

horizontal direction due to high thermal resistance. In applications such as TO packages where a heat sink is installed on the device as in this example, θ_{JC} can be used for thermal design. However, in applications such as SO packages where a heat sink cannot be installed, the condition of heat dissipation is very different from this test environment because the device is mounted on a PCB. Therefore, using θ_{JC} gives an incorrect result.

How to use θ_{JC}

The following shows how to use θ_{JC} .

Example 1:

Comparing θ_{JC} between different products to roughly estimate how many degrees C the junction temperature will change relative to each other.

$$\Delta T_J = (\theta_{JC2} - \theta_{JC1}) \times P_D \quad [^\circ\text{C}] \quad (1)$$

θ_{JC1} : Thermal resistance of Product 1 [$^\circ\text{C}/\text{W}$]

θ_{JC2} : Thermal resistance of Product 2 [$^\circ\text{C}/\text{W}$]

P_D : Power loss [W]

Example 2:

Performing thermal design with a heat sink. As shown in Equation 2, the junction temperature is calculated by multiplying the thermal resistance from the junction to the ambient temperature by the power loss of the device, and then adding the ambient temperature to the product. As shown in Figure 6, the thermal resistance from the junction to the ambient temperature consists of the thermal resistance θ_{JC} from the junction to the case, the contact thermal resistance θ_{CH} from the case including the thermal interface material (TIM) to the heat sink, and the thermal resistance θ_{HA} from the heat sink to the ambient temperature.

$$T_J = (\theta_{JC} + \theta_{CH} + \theta_{HA}) \times P_D + T_A \quad [^\circ\text{C}] \quad (2)$$

θ_{JC} : Thermal resistance from the junction to the case [$^\circ\text{C}/\text{W}$]

θ_{CH} : Thermal resistance from the case to the heat sink [$^\circ\text{C}/\text{W}$]

θ_{HA} : Thermal resistance from the heat sink to the ambient temperature [$^\circ\text{C}/\text{W}$]

P_D : Power consumption [W]

T_A : Ambient temperature [$^\circ\text{C}$]

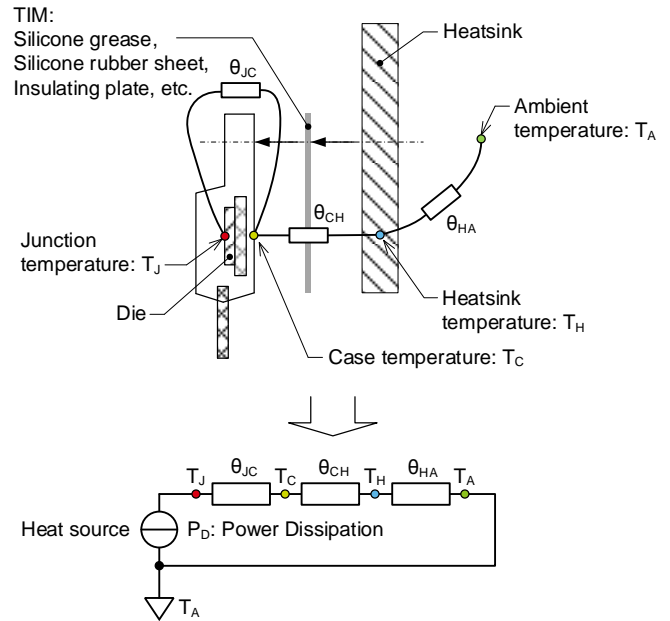


Figure 6. Heat dissipation equivalent circuit from the heat source to the ambient environment

In this example, the case and the TIM are in contact at the boundary. Since this is equivalent to the condition of the JEDEC TDI method, θ_{JC} can be used as a founded value.

Misuse of θ_{JC}

A common type of misuse is to measure the package surface temperature with a thermocouple and use it as T_C in the following equation to calculate the junction temperature.

$$T_J = \theta_{JC} \times P_D + T_C \quad [^\circ\text{C}] \quad (3)$$

P_D : Power loss [W]

Since there is no physical reference point corresponding to T_C as explained above, T_J calculated using this method is an unfounded value. Measurement using the MIL-STD is considered to be incorrect because it uses a thermocouple to measure T_C at a reference point.

Definition of Ψ_{JT}

Ψ_{JT} is defined in JEDEC Standard JESD51-2A "Integrated Circuits Thermal Test Method Environmental Conditions - Natural Convection (Still Air), January 2008." In the definition, Ψ_{JT} is described as follows: 「The thermal characterization parameter to report the difference between junction temperature and the temperature at the top center of the outside surface of the component package, divided by the power applied to the component.」.

For Ψ_{JT} , mount the device on a PCB created to conform to the JESD51-3, JESD51-5, and JESD51-7 standards and measure the temperature at the center of the package surface with a thermocouple under the measurement environment of JESD51-2A.

Figure 7 shows an example of a four-layer PCB for surface-mounted ICs. For details on JEDEC Standard, refer to References [4], [5], and [6] on the last page. These documents contain detailed instructions on PCB dimensions and materials, device mounting positions, copper foil thickness and size, lead wire dimensions, thermal via dimensions, and so on. For an example of the specifications, refer to Reference [7].

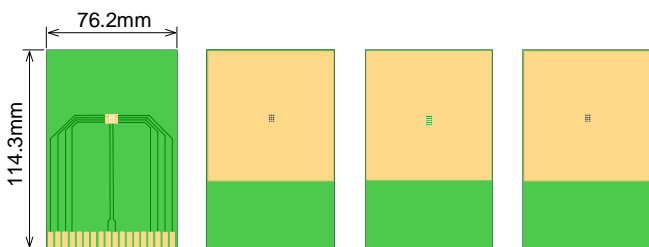


Figure 7. Example of a four-layer PCB for surface-mounted ICs created to conform to the JESD51-3, JESD51-5, and JESD51-7 standards

Implement the measurement environment and method in accordance with JESD51-2A. The description here provides an overview. Refer to Reference [8] for details.

As shown in Figure 8, the measurement environment consists of a PCB-mounted IC fixed in a predetermined position, which is placed in an enclosure (box) made of a material with low thermal conductivity and completely sealed to prevent air flow to and from the outside.

As a preparation for the measurement, measure the forward voltage so as to use a diode in the IC as the sensing diode to

determine the junction temperature. For this diode, as shown in Figure 9, use the body diode of the MOSFET, which becomes the heat source while the IC is operated. Place the IC in a thermostatic chamber and measure the forward voltage at each temperature by applying a minute current that does not cause the diode to get hot. An example of the measurement result is shown in Figure 10. Now it is possible to determine the junction temperature by measuring the forward voltage.

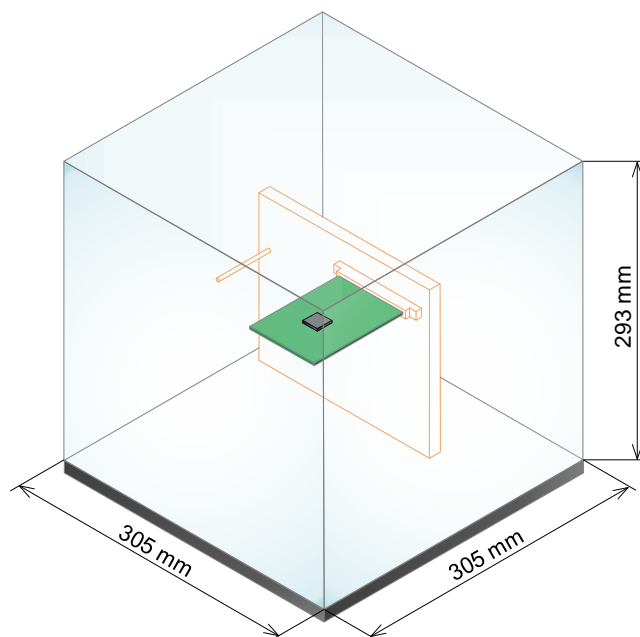


Figure 8. Schematic diagram of the test fixture and enclosure

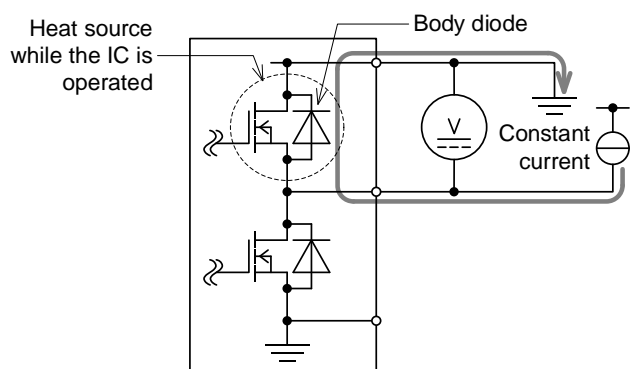


Figure 9. Using the body diode of the heat source MOSFET as the sensing diode to determine the junction temperature

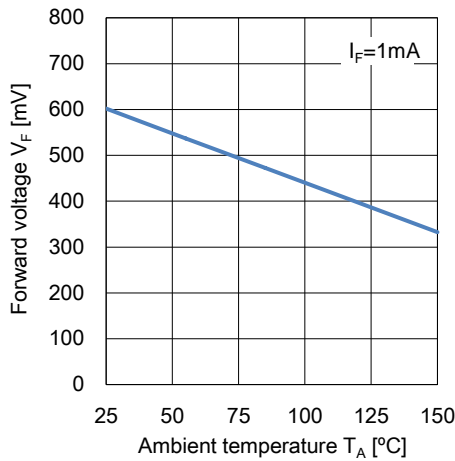


Figure 10. Example of the forward voltage temperature characteristic of the body diode

Start measuring Ψ_{JT} from here. To measure the temperature at the center of the package surface, fix a thermocouple in the center of the package with thermally conductive epoxy adhesive, as shown in Figure 11.

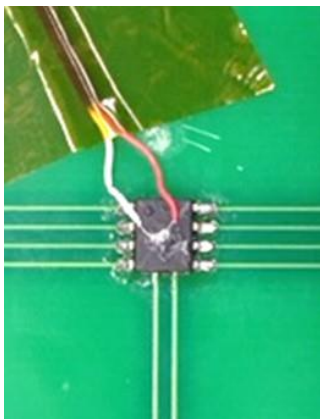


Figure 11. Fixing a thermocouple in the center of the package surface with thermally conductive epoxy adhesive

Next, apply a large current to the body diode in Figure 9 to heat the IC so as to raise the junction temperature by 30°C - 60°C. Then, switch to a minute current, measure the forward voltage, and convert it to the junction temperature using the graph in Figure 10. When the temperature change is stabilized, record the junction temperature and thermocouple temperature. Use the following equation to calculate Ψ_{JT} from the measured value.

$$\psi_{JT} = \frac{T_{Jss} - T_{Tss}}{P_H} \quad [^{\circ}C/W] \quad (4)$$

T_{Jss} : Junction temperature during the steady operation [°C]

T_{Tss} : Temperature at the center of the package surface during the steady operation [°C]

P_H : Consumption power that causes the change in the junction temperature [W]

The thermal characteristics parameter Ψ_{JT} is the temperature difference between the package surface and the junction temperature divided by the consumption power. If the transfer rate of heat flow from the junction to the package surface is constant, Ψ_{JT} is proportional to the temperature difference between the package surface and the junction temperature. Therefore, it is possible to estimate the junction temperature by measuring the package temperature of the device in the actual environment if the temperature characteristics parameters are measured under similar conditions.

Figure 12 shows the heat dissipation path when Ψ_{JT} is measured. Heat is dissipated from the junction in the three-dimensional direction, where thermal conduction is the largest form of heat transfer. Since SMDs (Surface Mount Devices) dissipate most of their heat to the PCB, the heat flow between the junction and the package surface is very small. Therefore, it is found that the temperature difference between T_J and T_T is very small and the value of Ψ_{JT} is also small. When the value of Ψ_{JT} is small, the error in estimating the junction temperature is also small, even if there are differences between the JEDEC board and the actual equipment board.

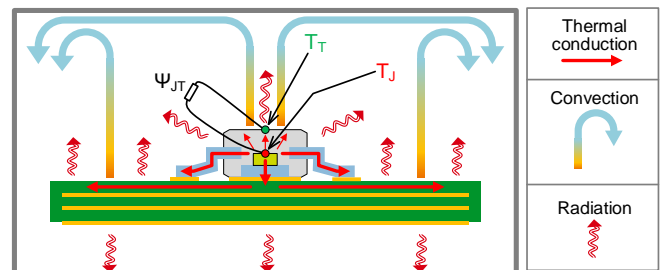


Figure 12. Heat dissipation path when Ψ_{JT} is measured

How to use Ψ_{JT}

The following shows how to use Ψ_{JT} .

Measure the temperature of the package surface and estimate the junction temperature using Ψ_{JT} that is listed in the data sheet.

Use the following equation to calculate the junction temperature.

$$T_J = \Psi_{JT} \times P_D + T_T \quad [^{\circ}\text{C}] \quad (5)$$

Ψ_{JT} : Thermal characteristics parameter from the junction to the package surface [$^{\circ}\text{C}/\text{W}$]

P_D : Power loss [W]

T_T : Temperature at the center of the package surface [$^{\circ}\text{C}$]

Prepare the parameter values required for the calculation.

1. From among the Ψ_{JT} data listed in the data sheet or the thermal resistance application note, select the PCB condition value closest to that of the actual equipment.
2. P_D is the power loss while the applicable device is operated. Determine this by actual measurement or by calculation.
3. Measure T_T by fixing a thermocouple in the center of the package surface with thermally conductive epoxy adhesive. For precautions for the measurement, refer to Reference [9].

Summary

Since θ_{JC} is measured in an environment where the package surface is in contact with the heat sink and furthermore other surfaces are insulated, it is assumed that the device is used in a very good cooling environment where all the heat generated at the junction is transferred (Figure 13). It is ideal for the thermal design of power semiconductor applications using a heat sink.

Since Ψ_{JT} is measured in an environment that includes the board just as in the actual equipment, it is ideal for the thermal design of SMD applications, where most of the heat is dissipated toward the board (Figure 14). Using θ_{JC} for SMDs results in inaccurate thermal design due to the large difference in the heat dissipation direction between the measurement environment and the actual equipment.

	Old standard θ_{JC} MIL	θ_{JC} JEDEC	Ψ_{JT}
Standard	MIL-STD-883E, METHOD 1012.1 THERMAL CHARACTERISTICS, 1980	JEDEC Standard JESD51-14, 2010	JEDEC Standard JESD51-2A, 2008
Definition	Thermal resistance from the junction to the specified reference point, $R_{\theta JR}$ ($^{\circ}\text{C}/\text{W}$)	Thermal resistance from the moving part of the semiconductor device to the outer surface of the package closest to the mounting area of the chip, where the surface must be properly provided with a heat sink to minimize the temperature change across the entire surface	Thermal characteristics parameter indicating the difference between the junction temperature and the temperature at the center of the outer surface of the component package divided by the power applied to the component
Package temperature measurement method	Measurement of the surface with a thermocouple	Transient Dual Interface (TDI) test method	Measurement of the surface with a thermocouple
Package temperature position	Specified reference point on the package	<ul style="list-style-type: none"> Boundary between the package surface and the TIM There is no physical measurement point. 	Center of the package surface
Data compatibility between manufacturers	Low <ul style="list-style-type: none"> Measurement conditions vary from manufacturer to manufacturer. 	High	High
Measurement environment	Cool the case temperature measurement surface and insulate other surfaces. Thermal resistance measurement when heat is dissipated in only one direction (one-dimensional) from the junction to the case (Figure 13 shows JEDEC.)		Thermal characteristics including the board, when heat is dissipated from the junction in the 3-dimensional direction with the device mounted on a board conforming to JEDEC (Figure 14)
Applications	<ul style="list-style-type: none"> Comparing θ_{JC} between different products to estimate how many degrees C the junction temperature will change relative to each other Thermal design of applications using a heat sink, such as TO packages 		<ul style="list-style-type: none"> Thermal design of SMD applications Measuring the temperature of the package surface and estimating the junction temperature
Junction temperature estimation	$T_J = (\theta_{JC} + \theta_{CH} + \theta_{HA}) \times P_D + T_A$ θ_{CH} : Contact thermal resistance [$^{\circ}\text{C}/\text{W}$] θ_{HA} : Thermal resistance of the heat sink [$^{\circ}\text{C}/\text{W}$] P_D : Power loss [W] T_A : Ambient temperature [$^{\circ}\text{C}$]		$T_J = \Psi_{JT} \times P_D + T_T$ P_D : Power loss [W] T_T : Temperature at the center of the package surface [$^{\circ}\text{C}$]

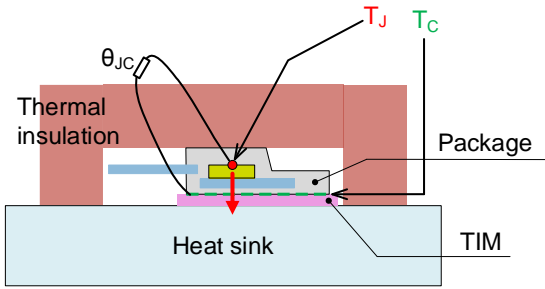


Figure 13. Schematic diagram of the measurement environment for θ_{JC} (JEDEC)
 T_C indicates the temperature at the boundary between the package surface and the TIM.

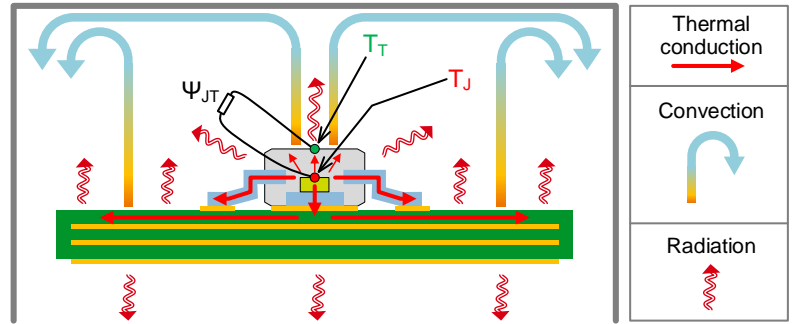


Figure 14. Schematic diagram of the measurement environment for Ψ_{JT}

References

- [1] MIL-STD-883E, METHOD 1012.1, Thermal Characteristics, 4 November 1980
- [2] [JESD51-14](#), Transient Dual Interface Test Method for the Measurement of the Thermal Resistance Junction to Case of Semiconductor Devices with Heat Flow Through a Single Path, November 2010
- [3] Application Note "[Measurement Method and Usage of Thermal Resistance \$R_{thJC}\$](#) ", ROHM CO., LTD., 2020, 2022
- [4] [JESD51-3](#), Low Effective Thermal Conductivity Test Board for Leaded Surface Mount Packages, 1996
- [5] [JESD51-5](#), Extension of Thermal Test Board Standards for Packages with Direct Thermal Attachment Mechanisms, 1999
- [6] [JESD51-7](#), High Effective Thermal Conductivity Test Board for Leaded Surface Mount Packages, 1999
- [7] Application Note "[HTSOP-J8 Package Thermal Resistance Information](#)" page 3 to 4, ROHM CO., LTD., 2022
- [8] [JESD51-2A](#), Integrated Circuits Thermal Test Method Environmental Conditions - Natural Convection (Still Air), January 2008
- [9] Application Note "[Notes for Temperature Measurement Using Thermocouples](#)", ROHM CO., LTD., 2020

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