Power Device

Measurement Method and Usage of Thermal Resistance RthJC

This application note describes how to measure and use the junction-to-case thermal resistance of a discrete semiconductor device.

About junction-to-case thermal resistance

In the definition of JEDEC Standard JESD51, junction-to-case thermal resistance means “the thermal resistance from the operating portion of a semiconductor device to the outside surface of the package (case) closest to the chip mounting area when that same surface is properly heat sunk so as to minimize temperature variation across that surface.” This is shown in Figure 1.

This clarifies the details and regulations of reproducible measurement methods for junction-to-case thermal resistance in semiconductor devices that have a one-dimensional heat dissipation path from the heat generation junction of the semiconductor to the case surface. One-dimensional means that the direction of heat flow follows a line. However, the direction of heat flow has the ability to diffuse in three dimensions.

Junction-to-case thermal resistance is one of the important thermal characteristics of a semiconductor device. By contacting this surface with a high performance heat sink, the thermal performance limit can be indicated with the best possible cooling conditions on the case surface. The lower this value, the better the thermal performance.

The symbol is RthJC or Theta-JC. If Greek letters can be used, it is $R_{\theta JC}$ or θ_{JC}. ROHM’s discrete products mainly use RthJC and $R_{\theta JC}$.

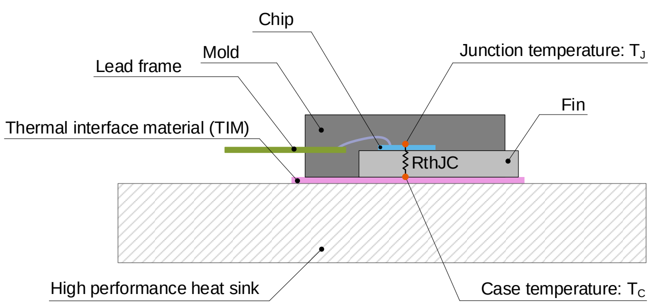

Figure 1. Example showing the definition of RthJC in JESD51

Test method based on MIL-STD-883E

METHOD 1012.1 in MIL-STD-883E describes definitions and procedures for thermal characteristic tests and also describes junction-to-case thermal resistance. This standard was created in 1980 and is now obsolete due to its many problems.

Next, an overview of the test method is provided. Figure 2 shows an example of a test device. Place the semiconductor device to be tested on a water-cooled copper 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. The tip of the thermocouple must be welded and the wire must be electrically insulated. In the figure it is the thermal probe assembly part. 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. In order to achieve reliable thermal contact, silicone grease is used for this interface. In the definition, the case temperature T_C measurement position is described as follows: “The case temperature is the temperature of the specified accessible reference point on the package on which the microelectronic chip is mounted.” Also, in the procedure section, it is described as follows: “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.”

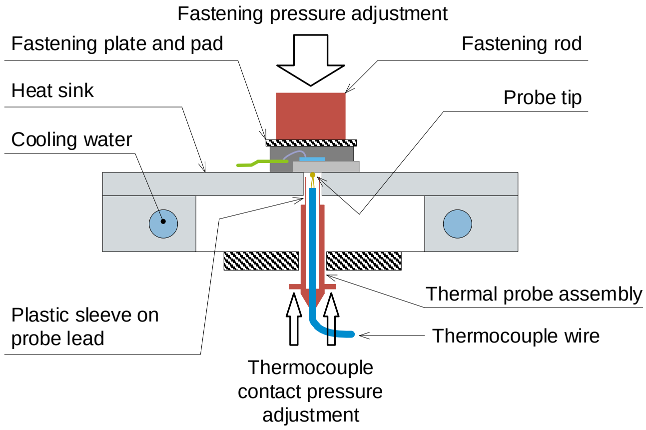

Figure 2. Example of the test equipment in MIL-STD-883E METHOD 1012.1, measuring the case temperature

Problems with testing with MIL-STD-883E

Next the problems with this test method are discussed. Since the measurement of the case temperature with a thermocouple is prone to errors, measurement results have poor reproducibility. First, since there is a temperature distribution over the case, the contact point between the thermocouple and the case may not be the maximum temperature of the case. 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. Further, there is an influence from the drilled holes in the heat sink for the thermocouple. This effect also becomes larger as the device size is decreased. Also, since there are differences in the measurement environment depending on the performance of the thermocouple and heat sink used, the error between each semiconductor vendor becomes larger.

For the thermocouple measurements described in this standard, the junction temperature T_J, case temperature T_C, and heating power loss P_H must be determined while the device is properly dissipating heat from the case to the heat sink. The junction-to-case thermal resistance is calculated using the following equation. Since the case temperature measurement error is large, the RthJC error is also large.

$$\mathrm{RthJC} = \frac{T_J - T_C}{P_H} \quad [°\mathrm{C}/W] \qquad (1)$$

In this measurement, as described above, it is difficult to accurately measure the case temperature using a thermocouple and the surface of the case is in close contact with the heat sink. This means that the value of RthJC may deviate in different measurement environments.

An example of an error occurring at the measurement position is shown in Figure 3. Although point A and point B are only 1 mm apart, there is a temperature difference of 5.1°C. When the thermal resistance is calculated with P_H of 50 W, it will be as follows:

When measuring at point A

$$\mathrm{RthJC\_A} = \frac{170.3 - 138.2}{50} = 0.642\ °\mathrm{C}/W$$

When measuring at point B

$$\mathrm{RthJC\_B} = \frac{170.3 - 133.1}{50} = 0.744\ °\mathrm{C}/W$$

In this example, if the measurement position shifts by only 1 mm, a 16% error in thermal resistance occurs, demonstrating the importance of specifying the measurement position.

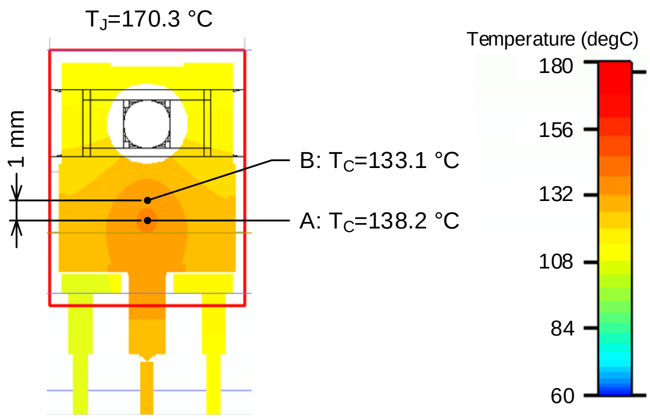

Figure 3. Temperature distribution on the rear of the case Even a slight difference in measurement position causes a temperature difference

JEDEC standard test method

The JEDEC standard JESD 51-14 was created in 2010. 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 RthJC measurements and reduces measurement data errors between companies. This is a common method in current use that replaces MIL-STD.

First, to give an overview of the measurement principle, the thermal impedance or Zth function $Z_{\theta JC}(t)$ of a semiconductor device heated by a constant power P_H starting from time t = 0 while the case surface is properly cooled by the heat sink (cold plate) is defined as follows:

$$Z_{\theta JC}(t) = \frac{T_J(t) - T_J(t=0)}{P_H} \quad [°C/W] \qquad (2)$$

In other words, the thermal impedance is equal to the time-dependent change of the junction temperature $T_J(t)$ divided by the heating power P_H. Even if the cooling conditions of the case are changed, there is no impact on thermal impedance until the temperature of the case that is in contact with the cold plate starts to rise. However, for measurements with different contact resistance between the case and the cold plate, different impedance curves are measured due to changes in total thermal resistance in steady state. Two thermal impedance measurements are taken with different contact resistances, and the cumulative thermal resistance at the point of separation of these two curves is defined as RthJC($R_{\theta JC}$, θ_{JC}). See JESD51-14 for the details of the measurement principle.

As described above, this method is based only on transient measurements of the junction temperature using different contact resistance (cooling conditions) between the cold plate and the case surface. Because it does not require measurement techniques that use a thermocouple to measure the case temperature T_C, all related errors are eliminated. This method only relies on measuring the junction temperature.

Next, an overview of the test method procedure is provided. First, to measure the junction temperature of the device under test (DUT), the temperature parameters of the DUT are obtained in advance. When the DUT is a MOSFET, the body diode is used as a sensing diode. Note that the measurement position differs depending on the type of device. You can measure the temperature characteristic of a pn junction inside the DUT in advance to estimate the junction temperature by utilizing the fact that the temperature characteristic of the forward voltage of a pn junction changes by around -2 mV/°C.

The measurement circuit is shown in Figure 4. At this point, for devices with a wide bandgap, including SiC MOSFET, it is necessary to select a measurement parameter suitable for the device characteristics, such as application of V_{GS} as a reverse bias. Current is applied to the sensing diode and the forward voltage is measured. Using a temperature controller such as a thermostat chamber, the temperature of the heat source device is changed from 25ºC to the maximum junction temperature of the device and the forward voltage is measured at each temperature. After the temperature is changed, it takes time for the heat to be conducted to the chip (junction). Therefore, you should wait until the forward voltage is stabilized. This measurement presupposes that the temperature of the entire device including the junction is the same.

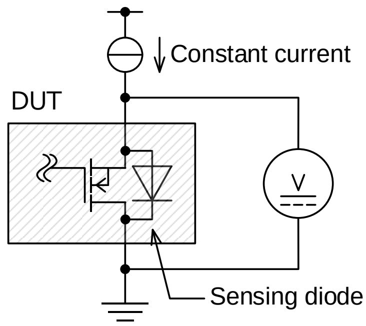

Figure 4. Forward voltage measurement circuit of diode element in DUT

An example of the measurement result is shown in Figure 5. Although the temperature characteristic somewhat depends on the dimensions and material of the element, it generally forms a linear curve with a slope of around -2 mV/°C. This slope is referred to as the K factor.

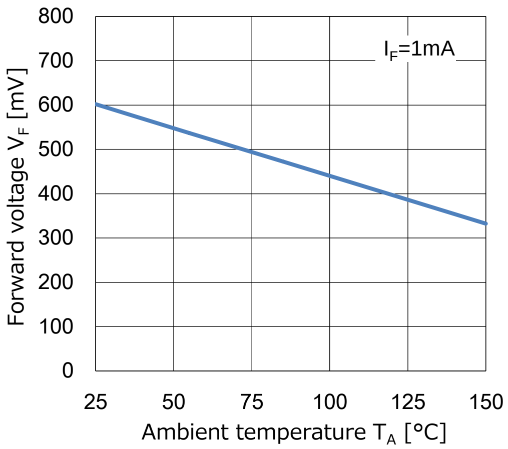

Figure 5. Example of the forward voltage temperature characteristic of a diode element in a DUT

The thermal impedance is measured using a transient thermal measurement equipment. Figure 6 shows an example of a test environment. The DUT is placed on top of a copper cold plate whose temperature is controlled with cooling water.

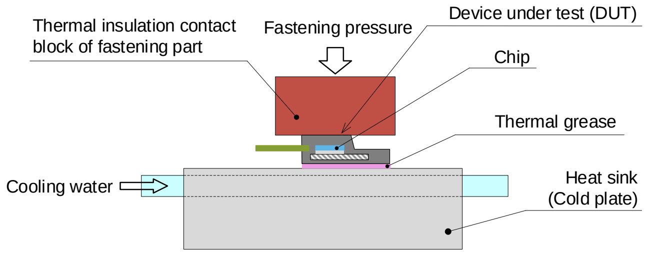

Figure 6. Example of a test environment for the TDI method

At this time, two types are measured: "with" and "without" thermal grease between the DUT and the cold plate as shown in Figure 7.

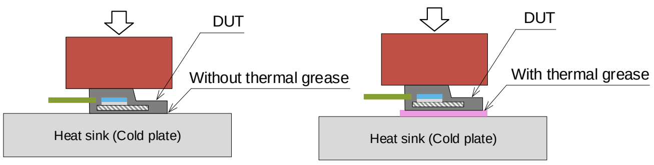

Figure 7. Taking two types of measurements: "With" and "without" thermal grease between the DUT and the cold plate

The procedure for measuring thermal impedance is as follows. Here, we explain the procedure when a general silicon MOSFET is used. For devices with a wide bandgap, including SiC MOSFET, it is necessary to select a suitable circuit configuration and measurement parameter of the heating method and measurement method with the sensing diode for each device used.

1. A constant heating current I_H is supplied to the heating element in the DUT to raise the temperature of the chip. In the case of a MOSFET, the body diode can be used as the heating element. Point A in Figure 8 is the point where the heating current is initially supplied. Heating is continued until the junction temperature is constant and the forward voltage of the sensing diode is monitored for changes in the junction temperature.

2. When the junction temperature is high and stable, the supply of heating current I_H is stopped and measurement is quickly switched to the forward voltage current I_M. Point B in Figure 8 is the point where the current is switched. Next, data is recorded in chronological order until the forward voltage reaches a low temperature steady state (Figure 8 center graph).

3. The recorded forward voltage data is converted to temperatures based on the K factor (Figure 8 bottom graph). This is the transient cooling curve.

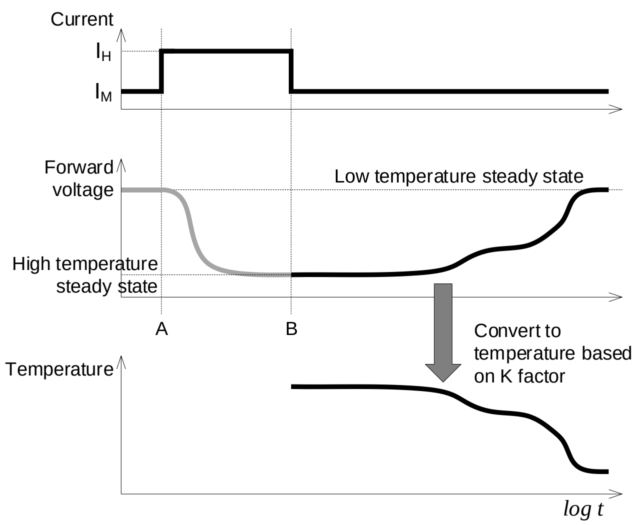

Figure 8. Measurement of transient cooling curve

4. The transient cooling curve data is calculated numerically and converted into a structure function.

The structure function expresses the heat transfer path of the device structure as a one-dimensional thermal circuit of thermal resistance and thermal capacitance and enables the thermal structure of the device to be visualized. An example of a structure function is shown in Figure 9, and its one-dimensional RC thermal circuit network is shown in Figure 10. Also, the device structure at that time is shown in Figure 11.

The structure function obtained from the transient thermal measurement equipment is represented as a network that subdivides the effects of three-dimensional temperature distribution as well as the thermal resistance and thermal capacitance. Therefore, each boundary is not so clear, for example, between the chip and the die bonding in the device structure shown in Figure 11, and each element in Figure 10 does not necessarily have a one-to-one correspondence with the thermal resistance and thermal capacitance present in each element in Figure 11. Nevertheless, here, for the sake of understanding the structure function, boundaries are provided for convenience.

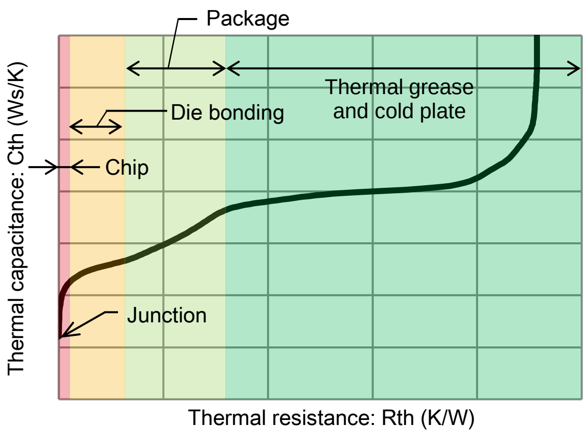

Figure 9. Example of structure function

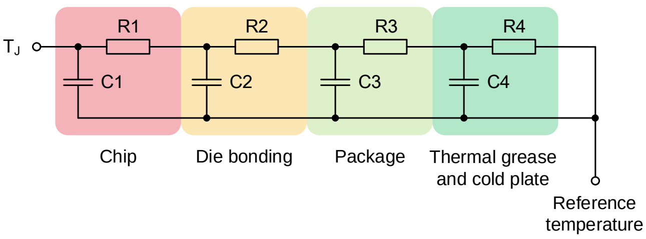

Figure 10. One-dimensional RC thermal circuit network

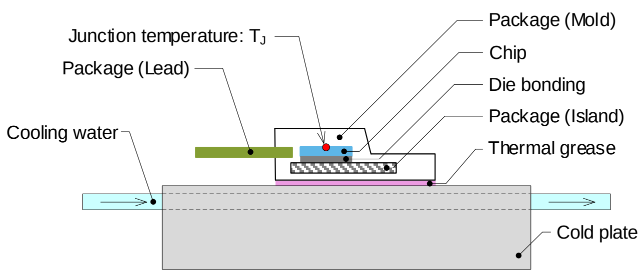

Figure 11. Example of device structure

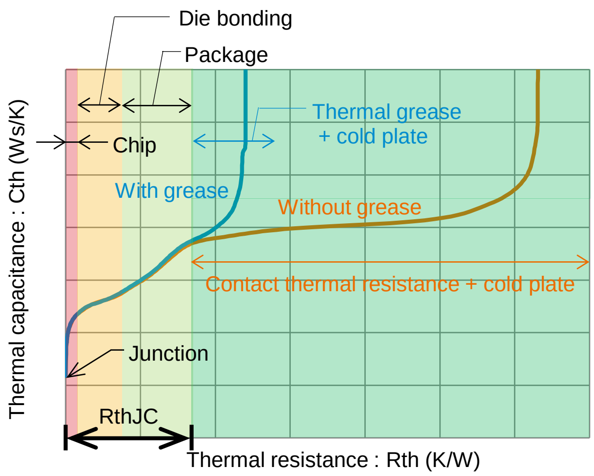

Figure 12. Graph showing superimposition of structure functions "with" and "without" thermal grease

This measurement is performed "with" and "without" thermal grease. Figure 12 shows the measurement results of both cases converted to structure functions and superimposed. It can be seen that without grease there is high contact thermal resistance between the case and the cold plate. In this way, the curve branches from the middle depending on whether grease is used or not. The branching point represents the interface between the case and the thermal grease, meaning that the thermal resistance from the junction to the branching point is RthJC.

As described above, since this method is based only on transient measurements of junction temperature using different contact resistances between the case surface and the cold plate, the technique of measuring with a thermocouple is not required for the case surface temperature T_C. This means that all related errors are eliminated and the method can be used to obtain thermal resistance with good measurement accuracy. RthJC measurements for ROHM discrete products are taken in accordance with JESD51-14.

How to use RthJC

RthJC can be used to compare heat dissipation performance between different packages. For example, if a device mounted on a piece of equipment is replaced with another compatible device, the RthJC values are used to find out how many degrees C the junction temperature will change in relative terms.

A common type of misuse is when the package surface temperature in contact with the heat sink T_C is measured with a thermocouple and the junction temperature is calculated using Equation (3).

$$T_J = RthJC \times P + T_C \quad [℃] \tag{3}$$

The temperature measurement point corresponding to T_C defined by RthJC of JESD51-14 does not exist physically. Be careful not to use Equation (3) to find TJ with an appropriate position of the case as T_C.

Note: “Heat sink” and “cold plate” that appear in the document are synonymous. The terms used in each standard are used.

References

[1] JESD51-1:1995, *Integrated Circuit Thermal Measurement Method - Electrical Test Method*
[2] JESD51-14:2010, *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*
[3] MIL-STD-883E, METHOD 1012.1, *Thermal Characteristics*, 4 November 1980

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