

JEDEC STANDARD

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

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**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**

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Foreword

This document has been prepared by the JEDEC JC-15 Committee on Thermal Characterization. It specifies the details and provisions of a method for the reproducible measurement of the “Junction-to-Case” thermal resistance $R_{\theta JC}$ (θ_{JC}) of semiconductor devices with a one-dimensional conductive heat flow path from the heat dissipating junction of the semiconductor to one case surface of the package. One-dimensional means, that the heat flow direction follows a line. However there is of course heat spreading vertical to that flow direction resulting in a 3-dimensional flow field.

The thermal resistance junction-to-case is one of the most important thermal characteristics of a semiconductor device stating the thermal performance limit under best possible cooling conditions over one package case surface by contacting this surface to a high performance heat sink. $R_{\theta JC}$ should be reported in the data sheet of the device. The lower the value the better is the thermal performance.

Historically the junction-to-case thermal resistance $R_{\theta JC}$ (θ_{JC}) of semiconductor devices has been determined by direct measurement of the temperature difference between junction and the case surface in contact with a water cooled copper heat sink as outlined in MIL Standard 883 [N1]. Since the necessary thermocouple measurement of the case temperature is prone to errors, these results were often not sufficiently reproducible. One problem is a potential temperature distribution at the package case while the thermocouple measures the temperature just at its contact point to the case. This might not be the maximum case temperature. Another reason for a potentially too low case temperature reading is, that thermocouple bead is often not sufficiently insulated against the cold plate and could therefore be cooled from the wire and cold plate side. Further problems arise from considerable clamping pressure to be applied to press the semiconductor device against the heat sink, which closes delaminations. Another source of error is the influence of the drillhole for the thermocouple in the heatsink. This influence increases with smaller devices.

This document specifies a measurement method of the junction-to-case thermal resistance $R_{\theta JC}$ (θ_{JC}) of semiconductor devices without a case temperature measurement by means of a thermocouple at one point. This considerably improves the reproducibility of $R_{\theta JC}$ measurements and allows better comparison of the data and consistent measurements between companies.

The document is an addition to the JESD51 series [N2] of standards for thermal characterization of packaged semiconductor devices. It should be used in conjunction with the electrical test methods described in JEDEC JESD51-1, “Integrated Circuit Thermal Measurement Method - Electrical Test Method (Single Semiconductor Device)” [N3], and document JESD51-12, “Guidelines for Reporting and Using Electronic Package Thermal Information” [N5].

Introduction

The junction-to-case thermal resistance θ_{JC} is a measure of the ability of a semiconductor device to dissipate heat from the surface of the die to a heat sunk package surface. In JESD51-1 [N3] it has been defined as “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”.

The traditional thermocouple measurement as outlined in MIL standard 833 [N1] requires the determination of the junction temperature T_J , the case temperature T_C , and the heating power dissipation P_H , while the device is properly heat-sunk at the case. The junction-to-case thermal resistance is then calculated using

$$\theta_{JC} = \frac{T_J - T_C}{P_H} \quad (1)$$

The result (1) shall be referred to herein as “steady-state θ_{JC} ”, since it is determined under steady-state conditions and relies on a spatial difference of the temperature along the heat flow path from junction to case. Its measurement involves the difficulty to accurately measure the package case temperature with a thermocouple while that case surface is in close contact with a heat sink. Therefore different measurement set-ups are likely to produce deviant θ_{JC} values.

Contrary to the above, the method described in this document is solely based on transient measurements of the junction temperature, with different cooling conditions at the heat sunk case surface. It does not require the knowledge of the case temperature T_C , thus eliminating all errors involved with its determination. The method relies only on the measurement of the junction temperature. It also does not need high pressure to assure good thermal contact to the heat sink.

Transient Dual Interface (TDI) Measurement Principle and Procedure

The thermal impedance or Zth-function $Z_{\theta JC}(t)$ of a semiconductor device which is heated with constant power P_H starting at time $t = 0$ while its case surface is properly heat-sunk shall be defined as

$$Z_{\theta JC}(t) = \frac{T_J(t) - T_J(t=0)}{P_H}, \quad (2)$$

i.e., the thermal impedance equals the time-dependent change of the junction temperature $T_J(t)$ divided by the heating power¹. If the cooling condition at the package case is changed, this should have no influence on the thermal impedance until the temperature starts to increase at the package case where the contact to the heat sink is. A measurement with different contact resistance however changes the total thermal resistance at steady-state and therefore separates the impedance curves of different measurements starting from the point where the external contact resistance contributes, which can be identified as the package case interface.

Two thermal impedance measurements with different contact resistance for cooling the heat sunk package case surface are done to identify this surface in transient measurements. The cumulative thermal resistance at the separation point of these two measurements is defined as $R_{\theta JC}(\theta_{JC})$.

¹ When plotted as a diagram, $Z_{\theta}(t)$ curves are shown in logarithmic time scale. Conversion from linear time scale to logarithmic time scale is relevant from data processing point of view and will be discussed further in detail in the Annexes of this document. When mathematically relevant, linear time and logarithmic time is distinguished by notation t and z respectively, where $z = \ln t$.

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

(From JEDEC Board Ballot JCB-10-59, formulated under the cognizance of the JC-15 Committee on Thermal Characterization.)

1 Scope

This document specifies a test method (referred to herein as “Transient Dual Interface Measurement”) to determine the conductive thermal resistance “Junction-to-Case” $R_{\theta JC}$ (θ_{JC}) of semiconductor devices with a heat flow through a single path, i.e., semiconductor devices with a high conductive heat flow path from the die surface that is heated to a package case surface that can be cooled by contacting it to an external heat sink.

The thermal resistance measured using this document is $R_{\theta JCx}$ or θ_{JCx} , where x denotes the package case side, where the heat is extracted, usually top ($x = \text{top}$) or bottom ($x = \text{bot}$) side.

2 Normative reference

The following normative documents contain provisions that, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

[N1] MIL-STD-883E, METHOD 1012.1, *Thermal Characteristics of Integrated Circuits*, 4 November 1980

[N2] JESD51, *Methodology for the Thermal Measurement of Component Packages (Single Semiconductor Devices)*. This is the overview document for this series of specifications.

[N3] JESD51-1, *Integrated Circuit Thermal Measurement Method - Electrical Test Method*

[N4] JESD51-4, *Thermal Test Chip Guideline (Wire Bond Type Chip)*

[N5] JESD51-12, *Guidelines for Reporting and Using Electronic Package Thermal Information*

[N6] SEMI Test Method #G43-87, *Test Method, Junction-to-Case Thermal Resistance Measurements of Moulded Plastic Packages*

[N7] JESD51-13, *Glossary of thermal measurement terms and definitions*

3 Terms and definitions

For the purposes of this standard, the terms and definitions are given in [N7] JESD51-13, “*Glossary of thermal measurement terms and definitions*” and the following apply:

Further terms and definitions are explained at first occurrence in the text.

4 Junction-to-Case Thermal Resistance Measurement (Test Method)

4.1 Measurement of a transient cooling curve (Thermal Impedance $Z_{\theta JC}$)

4.1.1 Measurement of the junction temperature

The junction temperature T_J of the device under test (DUT) shall be measured as described in document JESD51-1 [N3]. The $Z_{\theta JC}$ curve shall be recorded preferably after the heating power P_H is switched off (cooling curve)². That way the temperature sensitive parameter (TSP) will not be disturbed by the heating voltage or heating current and there is no need to control the heating power during the measurement. This measurement mode can be realized with most product chips as well as thermal test dies. Prior to the measurement of the $Z_{\theta JC}$ curve the TSP of each DUT shall be calibrated individually to account for inter-chip variations of the K-FACTOR, which relates Temperature to the TSP of the device.

Although not recommended, in principle also the heating curve can be used, if constant heating power P_H during the heating pulse time and no electrical cross-talk to a separate TSP device on the chip can be guaranteed¹. Using the heating curve must be reported with the result data.

4.1.2 Recording the transient cooling curve ($Z_{\theta JC}$)

First a constant heating current I_H shall be applied to the chip of the DUT to heat up the device until thermal steady-state is reached, i.e., until the junction temperature remains constant. If the chip does not provide separate structures for heating and sensing to allow monitoring of the TSP during heating, the temperature can either be monitored in dynamic mode (see JESD51-1) or else the heating time must be chosen long enough as to ensure that steady-state is reached. Since the DUT will be in contact with a water-cooled heat-sink during the measurement (see 4.2) a heating time of 100s will be sufficient in most cases. Control and adjustment of the heating time needed to reach steady state can also be done by test measurements.

Once the hot steady-state has been reached the final heating voltage V_H and heating current I_H are recorded and the heating current is switched off completely or to the level of the measurement current I_M , thus creating a sharp ΔP_H power step. Usually I_M is negligibly small compared to I_H , and the power still supplied by I_M to the DUT is neglected. However the measurement principle just requires a well known step of the heating power, i.e., the power dissipated in the device for heating, and considering the power P_M (caused by the I_M measurement current) is the more general and accurate approach. The higher the heating power step $\Delta P_H = P_H - P_M$ the higher the signal-to-noise ratio (SNR) of the measurement and the more accurate θ_{JC} can be determined.

² See also remark 2 in 4.1.5

4.1 Measurement of a transient cooling curve (Thermal Impedance $Z_{\theta JC}$) (cont'd)

4.1.2 Recording the transient cooling curve ($Z_{\theta JC}$) (cont'd)

Consequently the heating current should be as high as possible without over-heating the DUT and the P_M power should be kept as small as possible, however, higher I_M current would result in less initial electrical transients (see 4.1.3). The switching signal at $t = 0$ is used to trigger the recording of the TSP signal as a function of time from $t = 0$ to cold steady-state. The sampling rate shall be at least 50 samples per decade of time.

Based on the K-FACTOR of the DUT the recorded TSP values are converted to junction temperatures $T_J(t)$. Figure 1 shows an example of a measured cooling curve. Switching the heating current off at the beginning of the $Z_{\theta JC}$ -measurement inevitably causes electrical disturbances of the signal, thus rendering the signal useless for short times. In order to reconstruct the junction temperature T_{J0} at $t = 0$, an “offset-correction” has to be performed (ref. N1).

4.1.3 Offset Correction

Due to the electrical disturbances at the beginning of the measurement, the signal has to be discarded for all points of time t smaller than a certain cut-off time t_{cut} . The temperature change $\Delta T_J(t_{cut})$ within this interval of time can not be neglected. However, for short times t there exists an almost linear relationship between temperature change $\Delta T_J(t)$ and the square-root of time $\sqrt{t}$ that can be used to extrapolate the $T_J(t)$ vs. $\sqrt{t}$ graph to $t = 0$ (Figure 2).

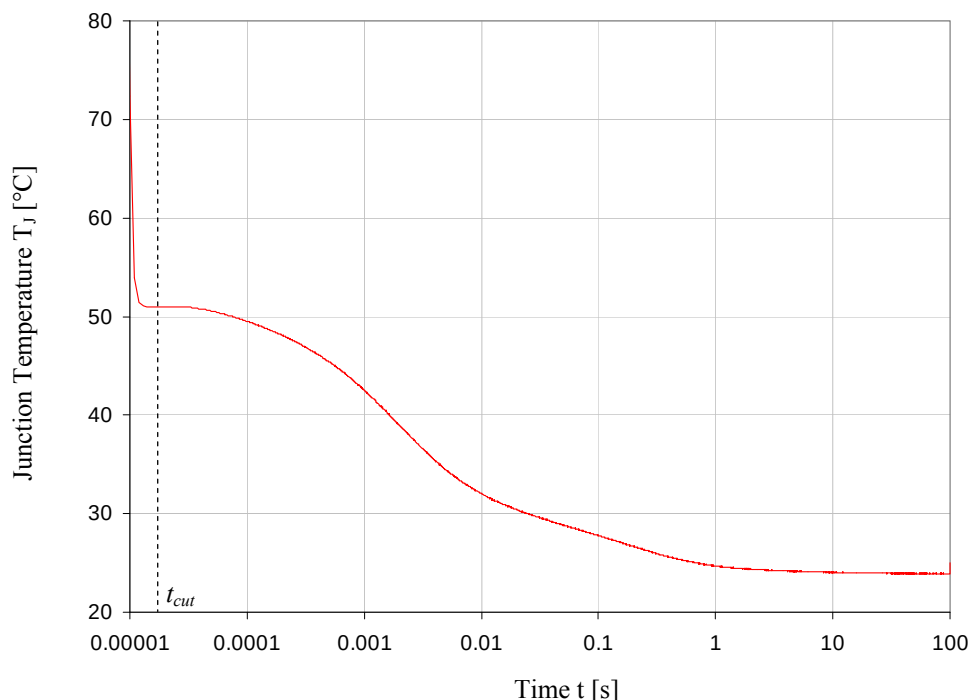


Figure 1 — Semi-logarithmic plot of a measured cooling curve. For short times the signal is disturbed by electrical effects due to switching off the heating current

4.1 Measurement of a transient cooling curve (Thermal Impedance $Z_{\theta JC}$) (cont'd)

4.1.3 Offset Correction (cont'd)

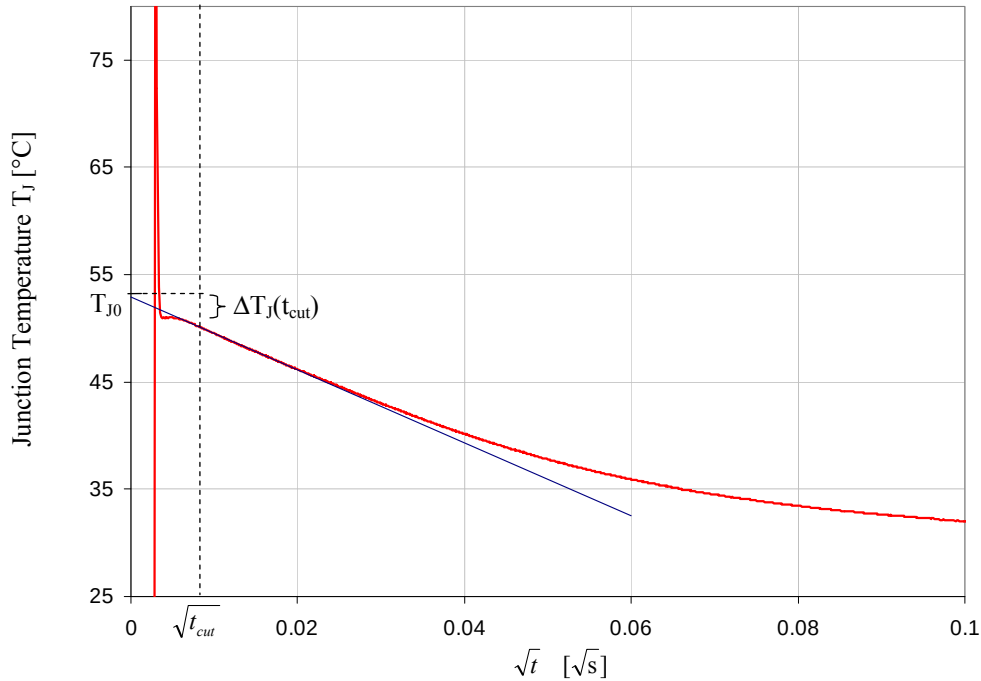


Figure 2 — Determination of the initial junction temperature $T_{J0} = T_J(t=0)$

For a “semi-infinite” plate (i.e., a plate with infinite surface area – ensuring 1-dimensional heat flow perpendicular to the surface – and infinite thickness) of homogeneous material, the surface of which is heated with constant power density P_H/A , it can be shown (see e.g., [1]) that the surface temperature rises/falls linearly with the square root of heating/cooling time when the heating power is switched on/off:

$$\Delta T(t) = \frac{P_H}{A} k_{therm} \sqrt{t}, \quad (3)$$

with

$$k_{therm} = \frac{2}{\sqrt{\pi c \rho \lambda}}, \quad (4)$$

c , ρ , and λ being the specific heat, density, and thermal conductivity of the plate material, respectively. For short times during which the heat propagation inside the silicon chip is approximately 1-dimensional and undisturbed by boundary effects from the chip bottom surface, the “semi-infinite” plate model can be applied to the heating/cooling of the chip surface. This is confirmed by measurements, as shown in Figure 2. The start temperature T_{J0} can be found by extrapolating the $T_J(t)$ vs. $\sqrt{t}$ graph to $t = 0$. As a side benefit an estimate of the active chip area A can be obtained using equation 3 and the slope $m = \Delta T_J(t_{cut}) / \sqrt{t_{cut}}$ of the linear fit:

$$A = \frac{P}{m} k_{therm}. \quad (5)$$

A realistic chip area A calculated this way can serve as cross-check for a reasonable offset correction.

4.1 Measurement of a transient cooling curve (Thermal Impedance $Z_{\theta JC}$) (cont'd)

4.1.4 $Z_{\theta JC}$ curve

The $Z_{\theta JC}$ curve is now computed from the cooling curve $T_J(t)$ using

$$Z_{\theta JC}(t) = \frac{(T_{J0} - T_J(t))}{\Delta P_H} \quad \text{for } t > t_{cut}. \quad (6)$$

4.1.5 Remarks

1. The transient thermal impedance $Z_{\theta JC}(t)$ is commonly used to characterize power semi-conductor devices. Measurement equipment to record the cooling curve is usually available.
2. In case the chip of the DUT provides separate structures for heating the chip and sensing the junction temperature simultaneously (thermal test die) it is also possible to record the heating curve (with constant heating power) instead of the cooling curve. However it must be taken care that the power dissipation P_H remains constant during heating time. The offset correction can be applied analogously, whereas equation 6 has to be replaced by

$$Z_{\theta JC}(t) = \frac{(T_J(t) - T_{J0})}{\Delta P_H} \quad \text{for } t > t_{cut}. \quad (7)$$

3. Due to the temperature dependence of material properties, e.g., electrical and thermal conductivity, $Z_{\theta JC}$ curves derived from cooling and heating curves can be slightly different, which might also have an impact on the resulting θ_{JC} value. The main reason is the slight change of dissipated power during heating, which can be avoided by taking the cooling curve as clearly preferred method. Therefore it shall be reported in case the junction-to-case resistance has been determined using the heating curve.

4.2 Transient Dual Interface Measurement Procedure

4.2.1 Measurement principle

The transient dual interface (TDI) measurement requires two $Z_{\theta JC}$ measurements of the same power semiconductor device in contact with a temperature controlled heat-sink. The first measurement (1) shall be performed without any thermal interface material between DUT and cold-plate. For the second measurement (2) a thin layer of thermal grease or oil shall be applied at the interface (Figure 3). The increased interface resistance in case (1) due to the microscopic surface roughness between package and cold-plate ensures a clear separation of the $Z_{\theta JC}$ -curves (Figure 4) at some point of time t_s . Since the two $Z_{\theta JC}$ curves start to separate as soon as the heat flow enters the thermal interface layer³, the $Z_{\theta JC}$ -value $Z_{\theta JC}(t_s)$ at this point is close to the steady-state thermal resistance θ_{JC} as defined by equation 1. The splitting point and the progression of the $Z_{\theta JC}$ curves are evaluated to obtain θ_{JC} .

³ This description applies to a heating curve. The cooling response of a device is the complement of the heating response, i.e., both curves result in the same $Z_{\theta JC}$ curve.

4.2 Transient Dual Interface Measurement Procedure (cont'd)

4.2.1 Measurement principle (cont'd)

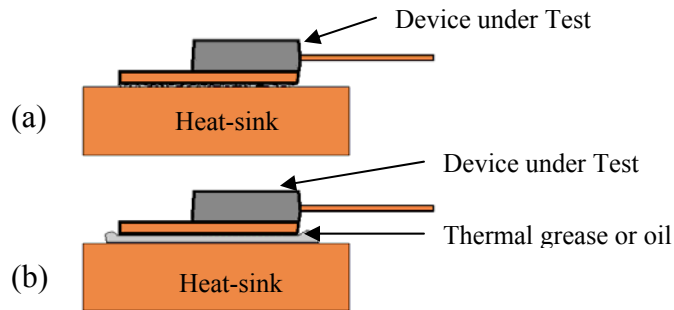


Figure 3 — TDI measurement (a) without and (b) with thermal grease or oil

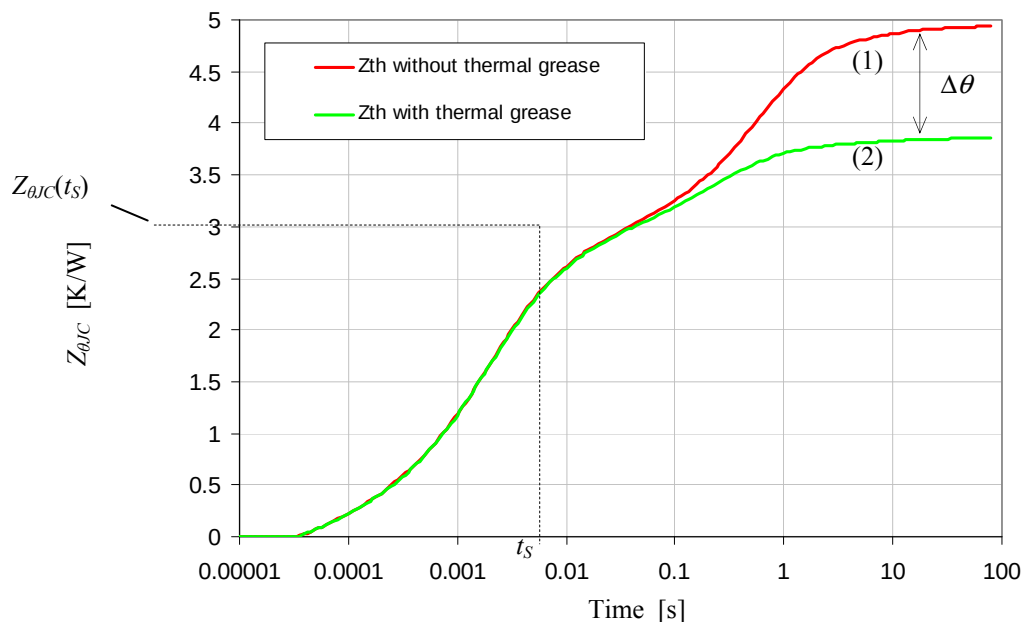


Figure 4 — $Z_{\theta JC}$ curves for a TO-263 package measured with (1) and without (2) thermal grease at the interface between heat-slug and cold-plate

4.2.2 Temperature controlled heat-sink

The device under test shall be mounted on a temperature controlled heat sink so that its primary heat removal surface (referred to herein as “case”) is in contact with the mounting base. To approximate ideal cooling, the heat sink should be very efficient, i.e., the mounting base shall consist of a copper block, the temperature of which is kept constant by a cooling fluid (usually water) passing through drilled holes in the block. The fluid should flow below the mounting base leaving maximum 2 mm Cu-material between drill hole for water cooling and mounting base surface in contact with the cooled package case surface. A thermostat shall be used to control the temperature of the fluid. The temperature of the fluid T_{Fluid} or of the cold plate T_{CP} shall be measured and reported with the results.