Component Thermal Characterization: Transient to Steady State

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Contents

Foreword

This document was built upon the *Fundamentals of Thermal Resistance Measurement*, originally written 1995 by Dr. John Sofia. It includes a more substantial treatment of transient thermal phenomena, new material and techniques and substantial rewriting.

1. Introduction

This document presents the background of methods and analysis related to the application of the electrical method of junction temperature measurement for thermal characterization of packaged semiconductor devices. Knowledge of this technical background is essential for anyone involved in the collection, interpretation, or application of semiconductor component thermal data.

> **Thermal characterization** of a semiconductor device (component) is the determination of the temperature response of the semiconductor circuit junctions due to internal self-heating under a specific set of environmental cooling conditions.

This internal self-heating is a byproduct of electrical current flow in the electronic device during operation; the heat generated elevates the temperature in the semiconductor junctions as it conducts from the junction area through the die, through the package, and eventually into the ambient. This flow of heat is described by the laws of thermodynamics and the principles of heat transfer. Accordingly the temperature within the package is the highest in the heat generating junctions on the semiconductor die. It is this temperature elevation of the semiconductor junctions that drives the need for thermal characterization of packaged semiconductors since higher semiconductor junction temperatures are associated with reduced operating life. [Kraus, et. al., 1983]

Component heat generation is concentrated in a small region in the semiconductor die from which it diffuses outward into the package where it becomes progressively less concentrated.

> **Heat flux**, defined as the heat flow per unit area perpendicular to the temperature gradient (ie., the direction of heat flow), is greatest in the heat generating region of the semiconductor. As the heat flows further and further from the source, the heat flux becomes lower and the local temperature gradient becomes smaller.

From the perspective of the entire electronics cooling network, the component is the critical, initial link for all heat leaving the die. Minute differences in component package design, material selection, and quality of manufacture can have enormous impacts on junction operating temperatures and time-to-failure. Measurement of component thermal performance is critical for development of reliable, long-lived electronic systems.

2. Thermal Resistance

The primary goal of thermal engineering in electronics-cooling is the control of operating junction temperatures. The measurement of component **thermal resistance** is a common approach to junction temperature determination and includes the effects of environmental conditions and the component power dissipation. Thermal resistance provides a simple and convenient means for estimating junction temperatures.

R*esistance* as generalized physical property is the ratio of applied *force* to the resultant *flow*.   For thermal phenomena, the *force* is the temperature difference which causes heat energy to *flow*. For fluid mechanics, the *force* is the pressure difference which causes fluid to *flow*. For electrical phenomena, the *force* is voltage difference which causes electrical current to *flow*.

The electrical analogy is popular due the general familiarity of electric conduction in wires. The serious shortcoming of the electrical analogy is that it promotes notions of one-dimensional flow between discrete points, familiar in electrical circuits. In contrast, thermal conduction in electronic components is often highly three-dimensional with continuously distributed thermal resistances and heat capacitances. Thus the electrical analogy tends to yield one-dimensional interpretations of an inherently three dimensional phenomena. The precise definition of thermal resistance is critical to its correct measurement and application.

> **Thermal Resistance** is defined as the difference in temperature between two closed isothermal surfaces divided by the total heat flow between them. It further requires that all of the heat which flows through one surface also flows through the other and that no net thermal energy accumulation occurs in the volume between the surfaces. It should be noted that these "surfaces" are not physical, solid surfaces but rather imaginary surfaces of constant temperature. Defining T_j and T_x as the hot and cold isothermal surface temperatures, respectively, and the total heat flow rate between them as P, the thermal resistance between them is
>
> $$R_{jx} = \left(T_j - T_x\right) / P$$
>
> The units of thermal resistance in electronic applications are °C / Watt. If mass flow occurs across these isothermal surfaces, there must be no net mass accumulation within the volume enclosed between the two surfaces since that would comprise an accumulation of thermal energy in the form of heat capacity of the accumulating mass. Likewise, there can also be no net thermal accumulation due to latent heat that may result from phase change effects.

In addition to being surfaces of constant temperature, isothermal surfaces experience heat flow in a perpendicular direction. Lines drawn parallel to the heat flow are called "heat-flux-lines" which comprise paths along which heat flows (but never crosses) leading from the component junction to the environment. Taken together, these lines form a map-like network of heat flow paths that provide an effective visualization tool. Isothermal surfaces do not intersect but rather form "nests" of concentric, closed volumes around a heat source. Isotherm nests and heat-flux-networks are directly related: a complete description of either one contains all the information necessary to construct the other since heat conducts perpendicular to isotherms and parallel to heat-flux-lines.

Isothermal surfaces are uniquely defined by size and shape. Thermal resistance is *isotherm specific*: changing the size or shape of the isothermal surfaces used in the above definition will change the computed thermal resistance. Thermal resistance is specific to the heat flux network; any alteration of the network will change the thermal resistance.

To avoid confusion, it is important to distinguish the difference between thermal resistance and thermal resistivity.

> **Thermal Resistivity** is defined as the ratio of thermal gradient to the heat flux in strictly one-dimensional heat conduction. Thermal resistivity is the reciprocal of thermal conductivity. It is a material property indicating the resistance of the material to thermal conduction or insulative quality. For measurement, the one-dimensional heat flow condition can be imposed by two parallel isothermal surfaces, T1 and T2 separated by a uniform layer of material of thickness with thickness x. If the heat flux (heat energy flow per unit area) is defined as q, the resistivity of the material separating the isothermal surfaces is
>
> $$r = q \cdot (T_1 - T_2) / x$$
>
> Thermal resistivity is expressed in units of K * meter / Watt. The reciprocal of resistivity, conductivity, k, is more commonly used. Thermal resistivity is a material property independent of the geometry in which the material is used. By contrast, thermal resistance is a function of material resistivities *and* geometry. Thermal resistivity is used for evaluating the thermal-quality of materials for used in component packaging applications. By contrast, thermal resistance is a figure of merit for evaluating of the thermal transport capability of component packaging configuration.

3. Electrical Junction Temperature Measurement

The measurement of junction temperatures is essential for evaluating thermal performance for design, application and manufacture of semiconductor components. The electrical method for junction temperature measurement is a widely used method today. It is a direct, non-contact technique since it utilizes the junction itself as an electro-thermal temperature sensor. Although methods such as infrared and liquid crystal sensing [Azar, 1991] can be used to measure junction temperatures, their application is limited to junctions that are directly visible. In contrast, the electrical method is a direct technique that can be performed at-a-distance using only the electrical-temperature properties of the semiconductor junction.

The most common implementation of the method uses the forward voltage drop of a junction as the temperature sensitive parameter (TSP) and is variously known as the "diode-forward-drop" method or the "V_{be}" technique from historical applications with power diodes and bipolar power transistors. The method was implemented soon after the invention of semiconductor electronics and continues to be used extensively today.

Although the diode forward voltage is the most commonly used temperature sensitive parameter (TSP), other parameters can also be used depending on the specific device under test. An excellent reference on the electrical method is contained in reference [Oettinger, F.F., Blackburn, D.L., 1990].

The electrical method of junction temperature measurement is based on a temperature and voltage dependency exhibited by all semiconductor diode junctions. This relationship can be measured and used to compute the semiconductor junction temperatures in response to power dissipation in the junction region.

> **Voltage-temperature relationships** are intrinsic electro-thermal properties of semiconductor junctions. These are usually smooth, often linear, relationships between junction temperature and junction voltage generated by a small, induced sense currents which ideally generate an insignificant amounts of junction self-heating. These relationships are specific to the sense current used and the selected junction. This is also called the temperature sensitive parameter or TSP.

Once the specific temperature-voltage relationship is measured, the junction can be used to measure its temperature. This relationship is specific to the chosen junction and sense current used. The measurement of the calibrating relationship is discussed in the next section.

4. Junction Calibration Technique

Device junction calibrations are performed by collecting TSP data at various known junction temperatures. These generally chosen to be equally spaced temperature-voltage data points be taken over range of junction temperature of interest.

4.1 Performing Device Calibrations

Figure 1 illustrates a method for measuring the calibrating relationship for a diode junction using a dielectric oil bath. Since the sense current does not significantly heat the junction, the case temperature will nearly equal the junction temperature if sufficient time allowed for the case and junction to reach isothermal equilibrium.   In this case, the bath is used to effectively control the device temperature and maintain the isothermal equilibrium between the case thermocouple and sense junction when data is collected.

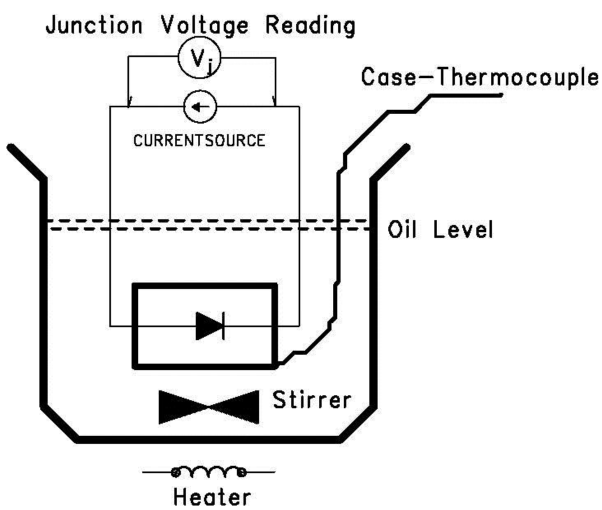


Figure 1: Illustration of bath-method for measurement of TSP

Alternatively, an oven can be used for this purpose although the device must be thermally connected to a conductive mass (heat sink) to prevent he device case temperature from changing too quickly and violating the isothermal equilibrium requirement. The oven approach is desirable for parts that cannot be easily cleaned of residual dielectric oil. In all cases, the condition of isothermal equilibrium must exist whenever data is collected.

Although diode junction forward voltage is the most commonly used temperature sensitive parameter (TSP), others do exist. For example, the "transistor saturation voltage" is a TSP with characteristics similar to the diode forward voltage TSP.   Devices such as IGBTs and darlington transistors use this TSP since their structures do not offer a suitable diode junctions. Other TSPs also exist but are not widely used.

4.2 Linear Junction Calibrations

Figure 2 shows a graph of junction TSP calibration data having good linearity. When the data is sufficiently linear, it can be expressed in a straight-line equation,

$$T_j = m \cdot V_j + T_0$$

where *m* (ºC/V) is the slope of the temperature sensitive parameter and *T0* is the Y-intercept or offset, collectively referred to as the *calibration parameters* determined from the data by simple linear regression. The slope is normally negative with the junction voltage decreasing with increasing junction temperature. The quality of the linear fit is evidenced by the deviation of this line from the data.

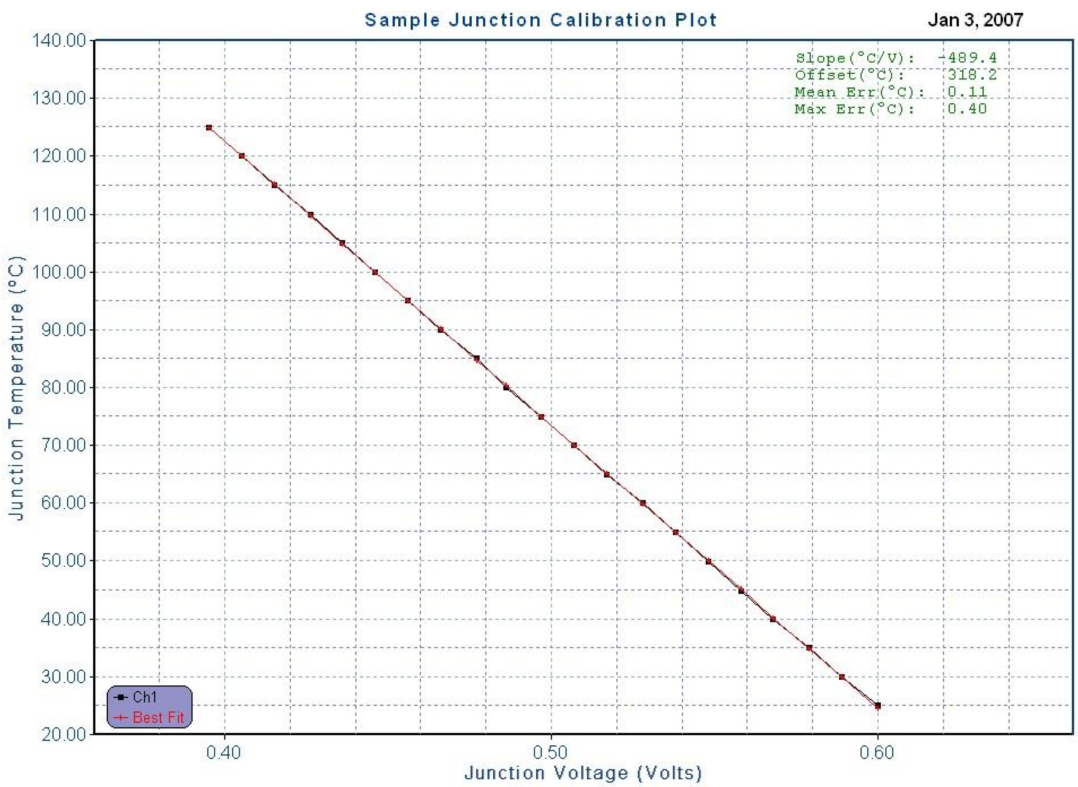


Figure 2: Sample linear temperature sensitive parameter plot

Once the slope and intercept, have been determined, the junction can be used as a temperature sensor by directly computing the junction temperature from the measured junction voltage. The reciprocal of the slope is sometimes termed "K factor" (mV/°C).

4.3 Non-linear Junction Calibrations

If the Tj calibration data is not sufficiently linear, the use of a linear calibrating relationship will produce test data with undesirable systematic errors. Figure 3 illustrates a non-linear calibration of this type. In such cases, the determination of junction temperature can be best be performed by direct interpolation of the voltage versus temperature data. This is essentially a table-lookup of the junction temperature from the measured junction voltage. Linear interpolation is generally adequate if temperature increments are sufficiently closely spaced.

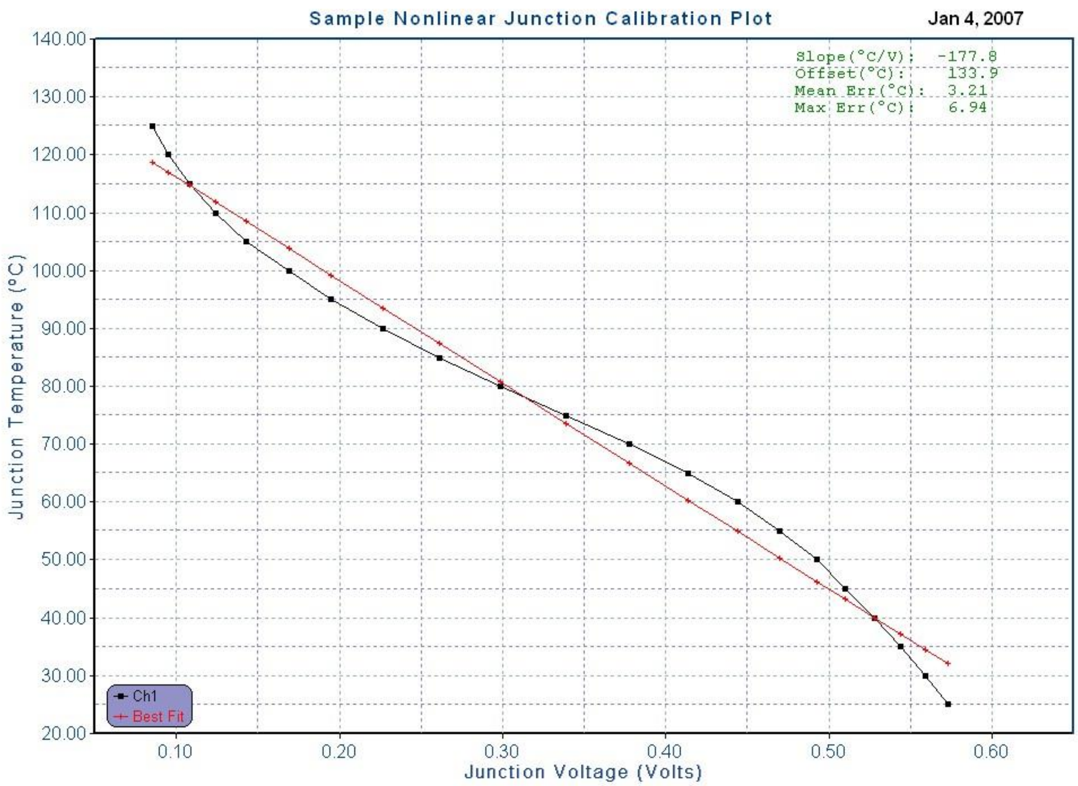


Figure 3: Sample of non-linear Tj calibration data

Nonlinear calibrations are certainly less desirable than linear ones and are generally associated with a lower accuracy test results. Before a nonlinear calibration is used for testing, the calibration should be repeated at a higher sense current or with a different junction selected. Non-linear calibrations generally require that each device be individually calibrated, unlike linear calibrations as discussed below.

The most common cause of nonlinear calibration is insufficient sense current. Figure 4 presents Tj calibration plots for one LED calibrated at 3 different sense currents: 1, 5, and 10 mA. The most linear data shown is for 10mA. This behavior is most common in schottky diodes, thryristors, and LEDs although can be observed in almost any device if the sense current is low enough. Generally, the larger the junction under calibration, the higher the sense current should be. Multiple Tj calibrations are sometimes needed to establish the most linear calibration or to find the junction with the most linear calibration when more than one sense junction is available.

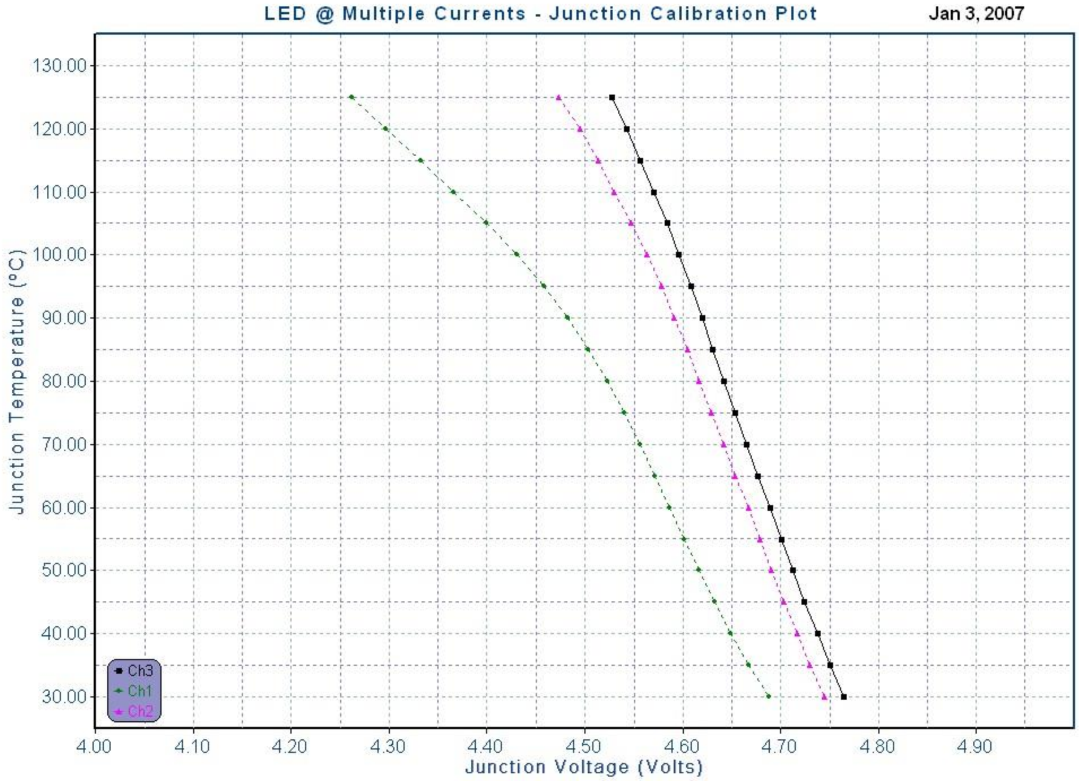


Figure 4: Sample LED calibration @ sense currents 1, 5, 10 mA

4.4 Sense Current Level Selection

Sense current selections typically range from 1 to 50 milliamps. Determination of the correct sense current level is subject to some limit considerations:

Lower limit - conduction: The sense current must be sufficiently large to establish conduction in the body of the junction rather than just superficial surface leakage or non-uniform conduction. This is often the cause of non-linear calibrations due to insufficient sense current. Typically, the larger the junction, the higher this lower-limit becomes.

Upper limit - thermal: Ideal sense currents generate no internal heating in the sense junction. Real sense currents generate a self-heating temperature rise in the sense junction which results in a systematic junction calibration error. This temperature error can be upper-bounded by computing the product of sense current, the highest Tj sense voltage and the maximum estimated thermal resistance for the device under test.

Lower Limit - electrical: All semiconductor junctions have parasitic electrical capacitances. These capacitances cause the measured junction temperatures to briefly lag actual junction temperatures during thermal testing. Larger sense currents shorten this temperature measurement delay and improve the Tj measurement accuracy. Larger, more capacitive junctions will test better with larger sense currents. (See Active Dice under **Device Types and Test Methods**)

Generally, the larger the device junction, the larger the sense current should be. Sense currents below 1 mA are rarely necessary. Although the Tj calibration is specific to the selected sense current level used, the choice of the sense current level is not critical provided it is sufficient to provide a linear calibration.

4.5 Identical Device Calibrations

Figure 5 compares Tj calibration data from a sample group of "identical parts". As shown, the calibration slopes are very consistent although the intercepts (temperature offsets) have a part-to-part variation. The range of this offset variation is a characteristic of the specific part.

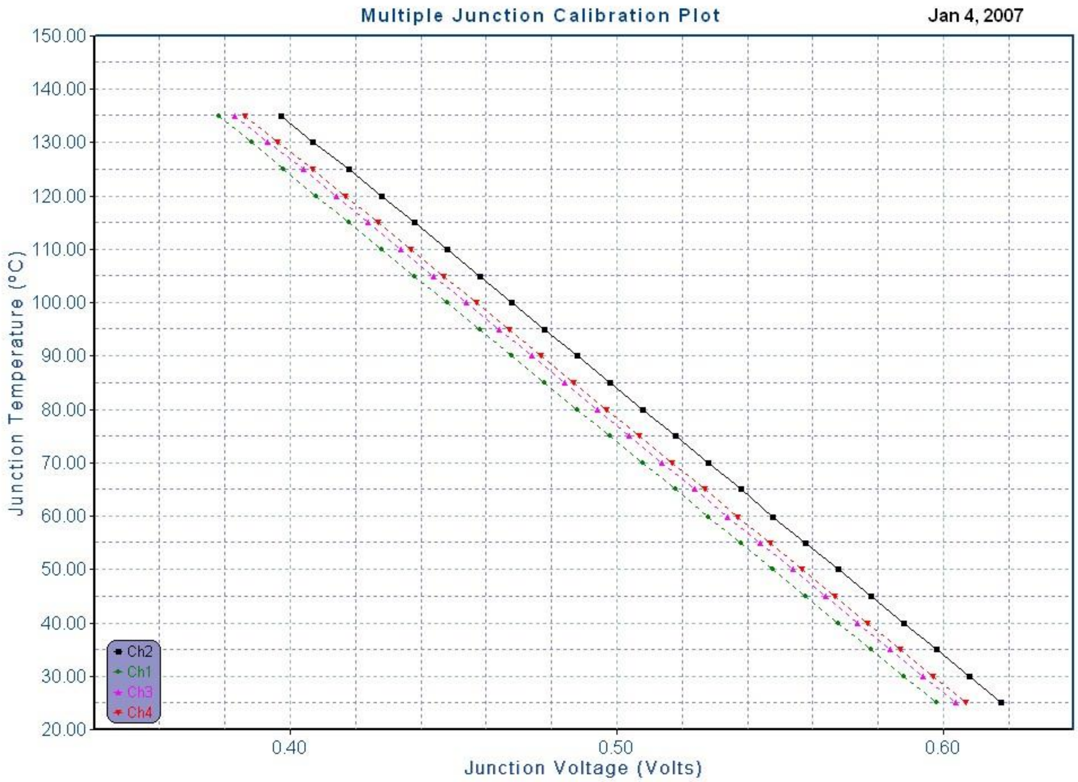


Figure 5: Device calibrations from a group of "identical parts"

The fact that the calibration lines for "identical parts" are parallel but with different intercepts leads to a generally accepted and useful tool when using the diode voltage TSP: device calibration must be performed only once for a group of identical parts to establish the Tj calibration slope. The temperature intercept can then be computed for identical parts which were not calibrated by using one measured voltage-temperature data point. This method is called *one point recalibration* or *"recal"* and dramatically reduces the number of components that must be calibrated. It is generally implemented prior to the commencement of a test when the device is at ambient equilibrium with the die at the same temperature as the thermocouple reference.

The correct intercept for any part can be computed by simply allowing the component to reach unpowered steady state equilibrium at room temperature and then measuring the sense voltage and case temperature. This one data point combined with the calibrated slope for an identical component permits the corrected computation of the temperature intercept. Once a part has been calibrated, recalibration on identical parts is normally sufficient rather than a full device calibration on every “identical” part tested. This is generally *not* true for non-linear calibrations. One point recalibration is effective for the diode voltage and transistor saturation voltage TSPs but not for the gate-turn-on TSP.

When a previously calibrated die is mounted in different packages, the calibration need not be repeated. Care should be taken to ensure that the correct electrical connections are bonded out for the chosen sense parameter each time the die is used in a different package. If device calibrations are correctly performed, it does not matter in what package a calibrated die is mounted since a given junction will have the same calibration regardless of the package.

5. Application of Thermal Resistance Concepts

According to its definition, thermal resistance is specific to the chosen isothermal surfaces, specified by size and shape. Practically, it would be quite difficult to specify an isothermal surface that does not correspond to a physical surface by describing its particular size and shape. Even if such a description could be provided, it would be nearly impossible to utilize such information in a real-world test situation.

The application of thermal resistance measurement to electronic component applications requires a practical perspective in addition to an understanding of the basic definition. Thermal resistance is generally based on junction temperature (hotter isotherm) and any one of a variety of different choices for reference temperatures (colder isotherm). Thermal resistances are frequently cited as thermal resistance, *junction-to-reference*, Rjx, or θjx, where, x, the reference site, could be local ambient air, a specific site on the component case, specific site on a component lead, or other well-defined reference site

Applying the definition of thermal resistance to practical application is instructive: The "junction" is considered to be tightly enclosed by a very small, "hot", isothermal surface through which all of the internally generated heat is dissipated. The "cold" isothermal surface, the reference isothermal surface, is much more problematic. Each of the above reference temperature sites is a physically defined location without regard to the shape and size of the isothermal surfaces in the immediate vicinity. Under any precisely defined set of cooling conditions, each reference site corresponds to one point on a particular, vaguely specified, isothermal surface. But, under different component cooling conditions, heat flows from the component in a different pattern of paths and forms different isothermal surfaces. (Note: isothermal surfaces are defined by size *and* shape) Since no practical method exists for specifying the shape and size of these isothermal surfaces, the above thermal resistances, based on fixed reference sites, require complete specification of the component cooling conditions. Expressed simply, *any thermal* *resistance based on physically fixed temperature sites is specific to the cooling conditions under which the measurements are taken*. Thermal resistances measured under significantly different cooling conditions are simply *different* measured thermal resistance parameters.

For junction-to-ambient thermal resistance measurement, the size and shape of the isothermal surfaces in the vicinity of the component leads to significant variation in measured thermal resistance with variation in cooling condition. As examples of this variation; junction-to-local-ambient thermal resistance exhibits appreciable variation with the velocity of the air flow on the component; natural convection is influenced by the orientation of the component and its power dissipation; forced convection is affected by the local air pressure gradient.

Junction-to-case thermal resistances (Ψjx) are likewise specific to the cooling conditions implemented during measurement. The case temperature is usually measured at a specific accessible site on the outside of the component case, most often, the hottest point on the case. Popular locations include case top (Ψjt) and a package lead (Ψjl). The temperature difference between the junction and the case is dramatically affected by variations in heat flux network from the junction. Factors such as heat dissipation from adjacent components, nearby materials and thermal pathways, test coupon size and construction, power level, air flow, and component mounting can radically affect the junction-to-case thermal resistance. Components with a wide variety of cooling-condition alternatives will likewise offer a wide variety of thermal resistances. Conversely, components designed for strictly defined cooling configurations with little variation in the overall heat flow patterns will have few meaningful thermal resistance varieties.

Junction-to-case thermal resistances are often mistaken for fixed parameters that are independent of the specific heat flow configuration. This stems from the misconception that junction-to-case thermal resistance is solely a function of the component package and does not depend on the cooling environment imposed when the thermal resistance is measured.

Integrated circuits are a good example of components which typically experience a variety of heat flow patterns. Some of the primary paths typically include case-to-PWB, direct case-to-air, and a sequence of case-to-leads and leads-to-PWB. Heat flow patterns are also affected by board-heating from adjacent components and local airflow irregularities. Each set of cooling conditions *defines* a different thermal resistance.

By contrast, some components with integral metal plates which are always cooled by attachment to a significant heat sink have very few variations in heat flow pattern. Component packages of the type TO220, TO202, and TO247 are good examples of this. These packages are specifically intended to be used with a significant heat sink. Nearly all of the heat that leaves the junction exits the component through the integral cooling plate regardless of the specific application. For this reason, there are very few varieties of thermal resistances for these components.

In summary, thermal resistances must be reported with precise descriptions of the cooling conditions and the power dissipations that were used during the measurement. This description should ideally be as simple as possible yet sufficiently accurate to enable detailed reconstruction of the test configuration.

5.1 Thermocouple Measurements

Thermocouples are generally used to measure thermal resistance reference temperatures. Ideally, the reference temperature measurement should be non-invasive, i.e., report the same site-temperature as that which existed prior to the installation of the thermocouple. This goal is never perfectly achieved since thermocouples inherently involve contact measurement. Some heat conduction invariably occurs in the thermocouple, thus "wicking" the heat away and cooling the reference site. This error elevates the temperature difference between the reference and the junction and yields an erroneously elevated thermal resistance measurement. This error is most severe when measuring component case temperatures on low thermal conductivity (ie., high resistivity) packaging materials such as plastic molding compounds. For example, if high conductivity 30 gauge thermocouple wire (type T) is used to measure a typical plastic integrated circuit case temperature, the error can be as high as 40% of the difference between the ambient and the actual case temperature depending on the means of thermocouple attachment. Although precise error predictions are not practical, the following recommendations generally apply:

1) Wire thermocouples should be no larger than 30 gauge, preferably, 36 gauge.
2) Wire thermocouples should be thermally grounded to the surface measured.
3) Type K offers the lowest wire-conductivity and thus the "wicking" error but requires adhesive attachment; type T offers solder-attachment but with more "wicking" error.
4) Use wire thermocouples for metal and highly conductive surfaces; use thin-foil type thermocouples for surfaces of low conductivity materials.
5) Larger thermocouples are desirable for measurement of bulk air temperatures since the larger bead-heat-capacitance will stabilize unwanted fluctuations.
6) Infrared temperature sensors for the measurement of non-conductive surface temperatures avoid heat "wicking" errors but can present problems due to surface emissivity variations and larger-than-desired spot size.

5.2 Specific Thermal Resistance Measurement Methods

Standard environmental specifications for measurement of junction-to-case and junction-to-ambient thermal resistances are available as Military Standards, SEMI Packaging Standards and JEDEC Industrial Standards. Such standards offer a valuable means of technical communication and documentation. When applying such industry standard methods, critical examination must be exercised to independently evaluate the validity of the recommended methods. Some "standards" have been later found to be deeply flawed based on the underlying physical principles or tainted by the effects of commercial bias in the standards creation process. There is no substitute for a critical investigation of any unfamiliar method regardless of how widely recognized or standardized. Care should always be taken to ensure that the method employed generates data which is useful for the intended purpose.

The following example underscores the caution must be exercised before embracing any "standard" method. The obsolete SEMI Standards, G30-88 and G43-87 use a liquid bath environment for junction-to-case measurements. These specious methods measure junction-to-case thermal resistance by suspending the component in an agitated fluid. According to the method, the high thermal conductivity of the fluid combined with the agitation effectively creates infinite heat sinking conditions and thereby assures that the entire surface of the case will be isothermal. Any cautious implementation of this method quickly reveals that the component is far from isothermal and that the fluid selection (within the range of specification) and degree of agitation dramatically affect the resulting measurement. These methods do not sufficiently specify the essential liquid cooling parameters but rather rely on fictitious infinite heat sinking. This example illustrates the hazards of *assuming* that a standard method is technically sound.

Another popular junction-to-case thermal resistance measurement standard is found in Mil Std 883, method 1012 as well as SEMI Std G30-88. Here the integrated circuit component is thermally grounded to a very significant heat sink so that almost all of the heat flows directly into the heat sink. The case temperature is usually the surface temperature of the component that is in contact with the heat sink. The resulting junction-to-case thermal resistance value is quite valid and repeatable since the heat flow patterns and cooling conditions are well specified. This variety of junction-to-case thermal resistance is directly applicable to components which are cooled in this manner, i.e., by heat sink attachment in the same manner as the test configuration where the entire contact surface is nearly an isothermal surface. For components which are not intended to be cooled in this way, this data cannot be used directly. It *can* validly be used for development of thermal models but not directly to predict the operating junction temperature in other cooing cooling configurations. This distinction is critical for anyone intending to use test data from these methods.

Much of the latest standards work on thermal characterization has been done by JEDEC committees on JESD51-x. These standards are available from Global Engineering Documents, 877-413-5184 or http://global.ihs.com/.

6. Delivery of Heating Power

The heating power dissipated in a component is computed as the product of the current flow through the component times the voltage difference between the in-flowing and out-flowing leads. With the voltage, in volts, and the current, in amps, the heating power, in Watts, is

$$P = I \cdot (V_{in} - V_{out})$$

Ohm's law relates voltage, current, and resistance:

$$V = I \cdot R$$

Current flow through any resistor generates a voltage difference and thus heat. Since the wires which carry heating power to a component-under-test have resistance, they generate heat that should not be included with the total heat dissipation of the component for thermal resistance measurements. This error can be easily avoided by measuring the heating voltage difference at the points where the current enters and leaves the package. This method is called a "Kelvin connection" or a "four-wire connection".

Figure 6 illustrates the two-wire connection with its attendant power measurement error. Figure 7 illustrates the four-wire connection. In the four-wire method, the leads which serve to deliver the heating current are often called the "force" connections; the leads which serve to measure the voltage are called "sense" or "voltage sense" connections. For thermal characterization of components, the voltage sensing leads and the current delivery leads should be joined at a site as close to the die as possible to minimize this error in computing the component heat dissipation.

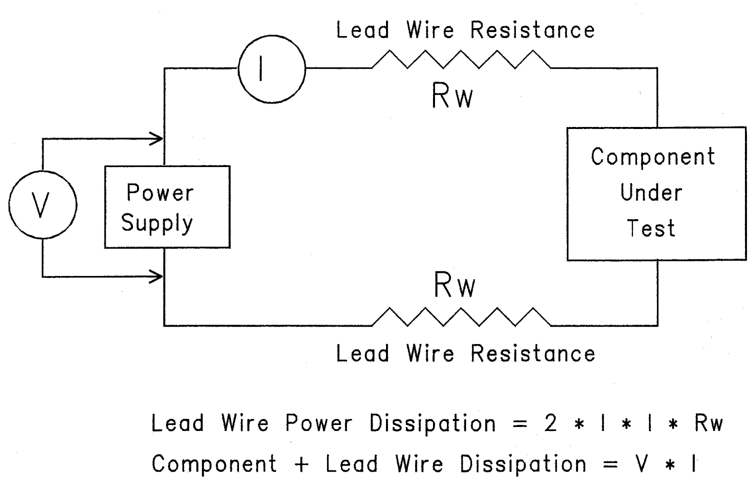
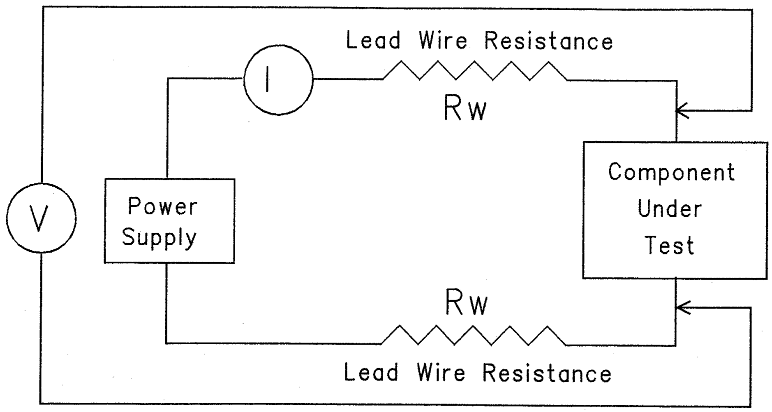


Figure 6: Illustration of 2 wire power measurement with attendant error



Component Power Dissipation = V * I

Figure 7: Illustration of 4 wire power measurement

A four-wire connection measurement is sometimes used on the junction temperature sensing connections. The concept here is that voltage difference across the temperature sensing junction should not include the voltage drops across the wires which carry the sense current to the sense junction. Using Ohms law to examine this perspective, the voltage drop in the lead wires, Vs is

$$V_s = I_{sense} \cdot R_{leads}$$

Assuming high-range numerical values to estimate a "large" lead voltage-drop (lead wire resistance: 0.3 ohms per meter, lead wire length (round trip): 1 meter, sense current: 20 mA) yields a, lead voltage drop, Vs = .005 volts. Although voltages of this magnitude *are* significant in electrical junction temperature measurement, these sense-lead voltage drops are essentially constants that are nulled out when the electrical method is properly implemented:

1) Normal use of one-point recalibration to adjust for variations in the temperature intercept within a collection of identical components will automatically compensate for variations sense lead length.
2) A component should be calibrated using sense-current lead-lengths approximately the same as those intended for thermal resistance testing
3) The variation in lead electrical resistance with temperature insignificant here.

In summary, four-wire connections are only recommended for heating power delivery and not for junction temperature sensing connections. The inconvenience of four-wire connection for the junction temperature sensing has nearly zero benefit. For delivery of heating power, the higher the current and the higher the resistance of wires carrying that current, the more important careful 4-wire connections become.

7. Test Methodology

7.1 Active Device Testing

Active (functional) devices are most commonly used for thermal testing. Here the heat dissipation is *not* electrically independent from Tj sensing which requires that the otherwise continuous heating power to be interrupted for the measurement of the junction temperature. Thus heating and sensing are separated into two intervals:

Temperature sampling interval is the period of time when the heating power has been interrupted, the sense current is been applied to the sensed junction, and the temperature sensitive voltage is measured. During the temperature sampling interval, the junction cools passively until the heating power is restored. The temperature sampling interval is usually less than 0.01% of the heating interval, for steady state thermal testing.

Heating Interval is the period of time when the heating power is being delivered to the component under test. Active dice are tested with a succession of heating intervals and temperature sampling intervals. Heating intervals are much longer than the sampling intervals for thermal resistance measurement.

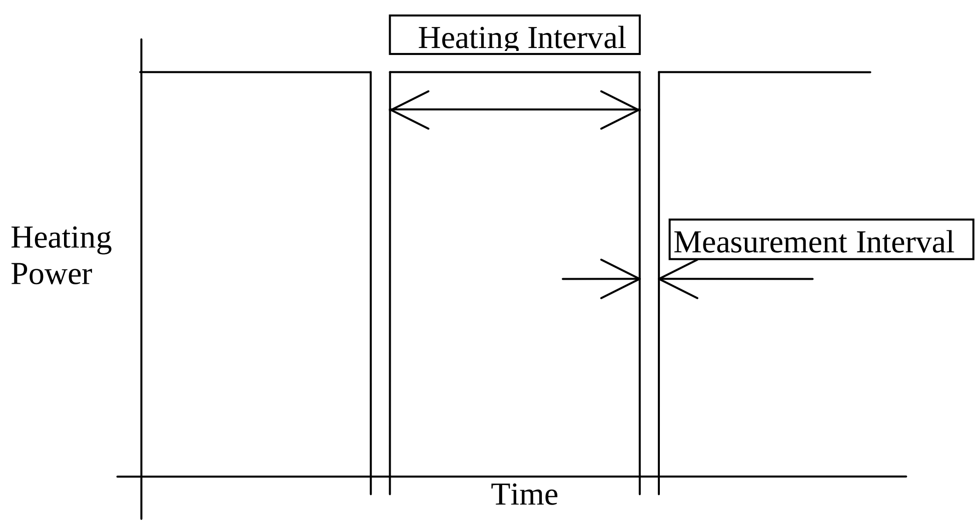


Figure 8: Graphic illustration of the heating and measurement intervals

This general method is illustrated for diode testing in Figure 9. Here the diode junction serves as both the heat dissipater as well as the temperature sensor.

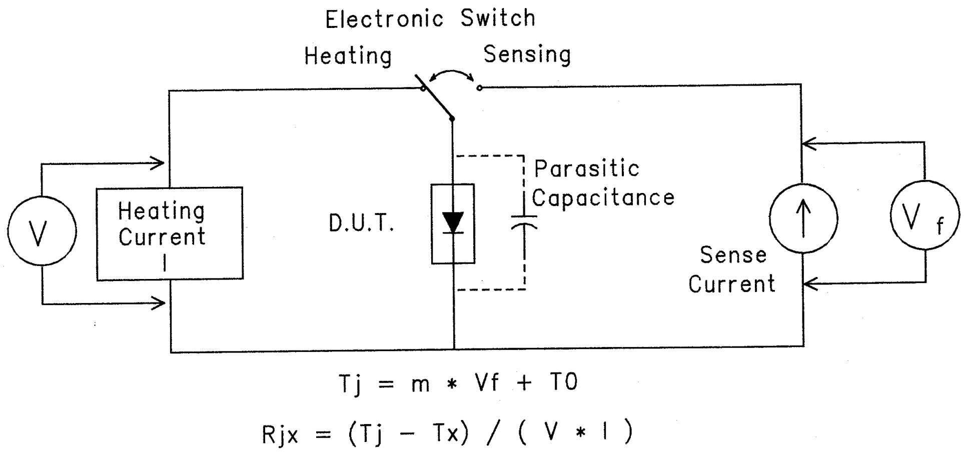


Figure 9: Illustration of diode test method concept

The electrical switching between heating and Tj sensing stimulates electrical transients which vary depending on the device tested. Figure 10 shows electrical transients from 0 to 30 microseconds after the end of the heating interval.

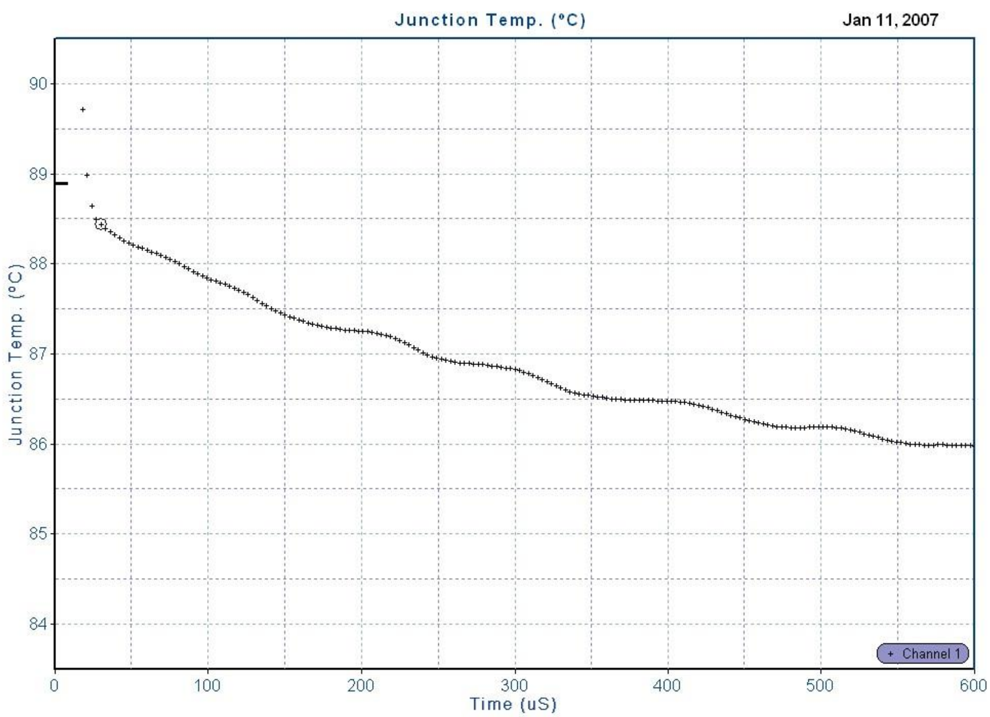


Figure 10: Typical electrical transient for rectifier diode

Measurement delay interval is the initial portion of temperature sampling interval between the instant of heating power interruption and acquisition of the first valid, temperature dependent voltage reading. This interval always begins at the instant of power interruption and lasts until the electrical switching transients have subsided. The typically range is from 0 to a few hundred microseconds for larger junctions. The correct measurement delay interval is often junction-temperature sensitive. During this interval, the temperature-sensitive-voltage measurements do not accurately represent the junction temperature.

Since the goal is to determine the junction temperature at the instant that the heating interval ends, Tj samples are taken rapidly and then extrapolated back to the instant of power interruption, ie., the end of the heating interval. This also overcomes the effects of junction cooling and electrical switching transients as discussed below.

7.2 Integrated Circuits and Thermal Test Die

Thermal test dice are specifically designed for thermal characterization of integrated circuit packages. These dice are available in a variety of sizes and can be mounted into any desired package to create a thermal test vehicle. Thermal dice can offer accurate thermal characterization with a minimum of measurement hardware. The basic concepts of device calibration, junction temperature measurement, power delivery, and wattage control are a direct application of the concepts presented previously.

Care must be taken to ensure that the thermal test die size is very close to that of the intended functional die. The die attachment may also be different for the thermal die versus the active die since one is a prototype process and the other a production process. Accordingly, device characterizations utilizing thermal test dice should include a specification of the thermal test die size and the type of die attachment.

Integrated circuit components are best characterized using the functional die since the die size and die attachment *is* the final production version, unlike thermal test dies. The simplest technique utilizes the substrate isolation diode that is present on integrated circuit dice. The substrate isolation diode is electrically accessed by reverse-biasing the power and ground pins and normally used as the heat dissipater thereby creating die-heating that is uniform much like that of the thermal test die. The sense junction can be either this heated junction or another junction present on the die. The disadvantage of using the substrate isolation diode method **or** the thermal test die method is that the heat dissipation on the die is uniform which can be quite different from that which exists during functional operation of the integrated circuit. This difference can create higher application-junction-temperatures in functional dies than that measured in thermal test.

8. Component Thermal Impedance: Transient vs. Steady State

Non-equilibrium, transient thermal effects are important in applications where the component never reaches steady state during the course of operation. Transient thermal analysis can also predict the component performance in response to non-steady or cyclic heating waveforms as well as revealing performance of component inner-construction details such as die attachment quality.

When a constant level of power is applied to a component for long period of time, the component temperature undergoes a progressive transition toward to a new, powered steady state equilibrium condition:

> **Steady state thermal equilibrium** is the thermal condition where the previous temperature history of the component no longer influences the present temperature condition of the component. At thermal equilibrium, the only variables that control the temperature of the component are the fixed power dissipation and the thermal environment; when both of these are constant for a sufficient period of time, the part approaches thermal equilibrium and heating-time become irrelevant. Prior to equilibrium, the component is considered to be in thermal transition or a transient thermal state.

During thermal transition, the temperatures within the component package are changing toward a new equilibrium. The definition of thermal resistance requires the same total heat flow across both of the two isothermal surfaces. This can only occur when all of the heat capacitances existing between the two isothermal surfaces are no longer changing their thermally stored energy. The greater the heat capacity or thermal mass of the material contained between the isothermal surfaces, the longer the transition period that ends with the onset of thermal equilibrium. While the thermal capacitance of the component is being "charged" to a different set of temperatures, the attempted computation of thermal resistance yields thermal *impedance*.

> **Thermal impedance** is defined as the difference in temperature between two isothermal surfaces divided by the rate of heat flowing across the hotter isothermal boundary. Thermal impedance at thermal equilibrium is synonymous with thermal resistance. Thermal impedance requires the specification of the powering condition *and* duration whereas thermal resistance is only defined at thermal equilibrium where powering duration is irrelevant. Defining Tj and Tx as the hot and cold isothermal surface temperatures respectively, and the total heat flow rate entering the isothermal surface at temperature Tj as P, the thermal impedance referenced to these two surfaces is

$$Z_{jx} = \left(T_j - T_x\right) / P$$

Thermal impedance is simply thermal resistance without the condition of equal heat flux across both isotherms. This inequality occurs when heat capacitances between the isothermal surfaces are changing their stored heat energy during transient heating prior to thermal equilibrium.

The thermal impedance concept is analogous to electrical impedance. Electrical impedances include resistances and energy storage elements in the form of capacitance and inductance. (Note: there is no thermal analog of electrical inductance.) These energy storage elements only manifest themselves during periods of transition. Once electrical steady state has been reached, only the presence of resistance is apparent.

Table 1 illustrates the difference between thermal resistance and thermal impedance for a device that is at unpowered thermal equilibrium with the ambient at 25 °C at "time-zero". Beginning at "time-zero", a constant heating power of 3 Watts is initiated. After 5 seconds, the junction temperature of the part is measured at 35 °C. and power continues to be applied for a total of 3000 seconds. The junction-to-ambient thermal impedance for this part would be computed:

Duration, sec	Power, W	T_{j-ref} °C	T_{ref} °C	Z @ t (°C/W)
5	3	35	25	3.33
15	3	49	25	8.00
30	3	55	25	10.00
1000	3	60	25	11.66
2000	3	61	25	12.00
3000	3	61	25	12.00

Table 1: Example of distinction between thermal impedance and resistance

By the time the component has been powered for 2000 seconds, it has reached steady state and therefore the impedance at 2000 seconds is actually equal to the thermal resistance of the component, 12.00 °C/W. For any given power level, selected temperature references, and cooling environment, a component can have an unlimited number of thermal impedances but can have only one thermal resistance. For practical considerations, the isothermal surfaces that define the particular thermal resistance of interest are defined by the selection of reference temperature site.

9. Heating Characterization

Conceptually, heating characterization begins with a component in an unpowered equilibrium condition. Heating is then initiated and held constant for a duration that is sufficient to ensure complete thermal equilibrium. The junction-to-reference temperature difference climbs steadily from its initial value of zero to the final equilibrium value as heating progresses. During this heating power step, the component thermal impedance, computed at any instant, continuously changes until equilibrium is reached and thermal resistance is measured.

9.1 Heating Curve: Impedance versus Duration

Figure 11 illustrates a plot of thermal impedance versus heating duration after a step change in power dissipation. Thermal impedance data taken during transient response to a step-change in power is often called "heating characterization" or "heating curve," since a plot of the data plot details the transient heating of the device.

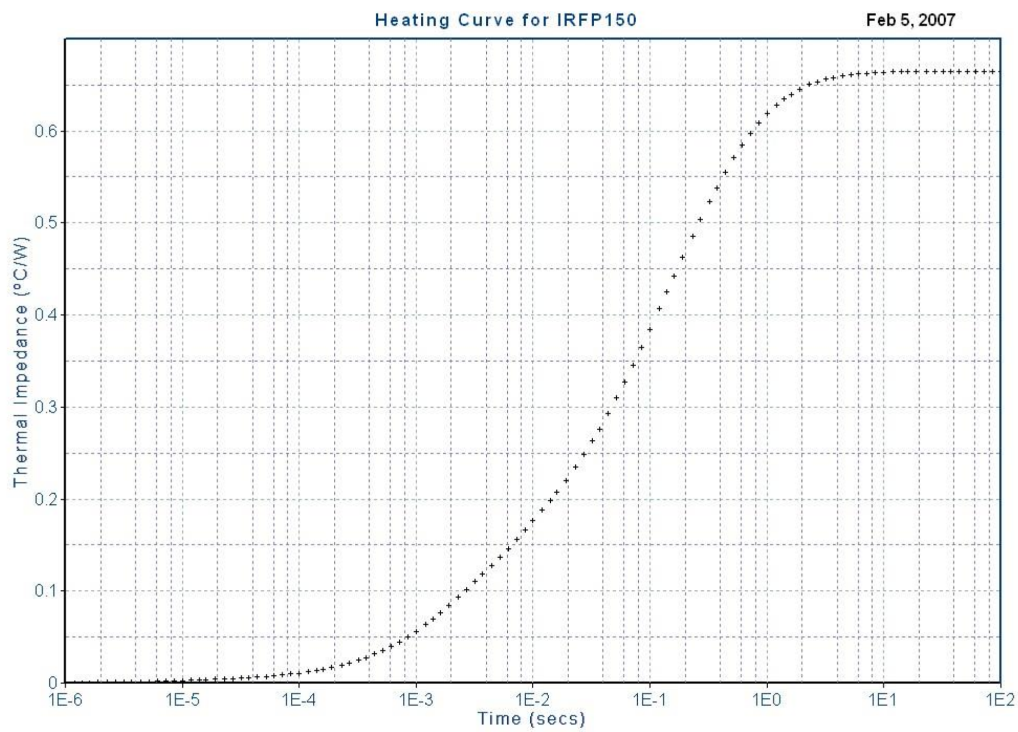


Figure 11: Example of log-time heating characterization plot or "heating curve"

> **Heating Characterization** is the complete response of a component to a step-heating condition. It details the relationship of thermal impedance versus heating duration and contains a complete signature of the thermal behavior of the device ranging from transient to steady state.

The heating curve represents a type of cross sectional view of the internal thermal resistances and capacitances of a component. To appreciate this fact, it is helpful to envision the flow of heat in the component beginning at the instant that the power-step commences: As heat initially spreads through the die and into the die attachment region, the initial temperature rise is governed by thermal spreading in the die region before significant heat has reached the package; therefore, the short duration impedances are overwhelmingly representative of the heat flow in the die region. The mass of the component package, with its larger heat capacitance, responds only after further heating when sufficient energy has accumulated and its temperature rises. Larger heat capacitances, located at larger resistances from the heat source require longer the heating durations before their influence on junction temperature will be manifested. Thus heating curve plots reflect internal thermal resistances as a function of distance from the die: effectively a thermal resistance cross section of the component [Sofia, J.W.,1995, D.L. Blackburn, 1975, D.L. Blackburn, F.F. Oettinger, 1974, C. Neugebauer, [et al.], 1986].

The heating curve X-axis normally uses log-time. The vertical impedance axis can be either linear or logarithmic and the data presented as actual or normalized to the steady-state thermal resistance. A logarithmic impedance axis is ideal for short-duration impedances. The normalized impedance axis allows easy application of the impedance data over some variation in component thermal resistance with *reasonable* accuracy.

9.2 Dynamic Thermal Models

Heating characterization data can be simulated by a mathematical model comprised of thermal resistances and thermal capacitances as shown in figure 12. If the resistance and capacitance values are correctly chosen, the simulated response of the model to a particular heat input will match the measured heating characterization data. Once such a model is determined, it can be used to predict the thermal behavior of the component to any desired thermal input, transient or steady state.

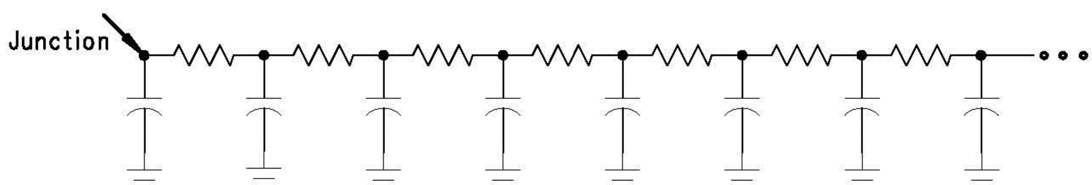


Figure 12: Discrete multi-stage RC model dynamic model of component

Each resistor/capacitor pair comprises a "stage" in the model. Each stage is characterized by the exponential time constant equal to the R x C product. Each RC stage of the model contributes to the overall response of the model. Inevitably, the smallest (shortest) RC time constants occur closest to the heat-source-junction with progressively larger (longer) time constants appearing as the heat flows away from the junction. This range of time constants from short to long forms a "spectrum" of RC time-constants called the “time constant spectrum” or “METS” for “Multi-Exponential Time-constant Spectrum”.

Compact transient RC models can also be generated by optimizing for a minimal number of discrete RC stages. Such compact models provide a simplified and effective dynamic model with high fidelity to the original heating curve data. Figure 13 presents a heating curve with the associated optimized compact-model-simulation overlaid in red. At equilibrium, all of the thermal resistance stages between the die and the reference site are summed in the final thermal resistance. The black-dot-plot represent the results of a 90 stage RC-model and the red-dot-line represents the result of a 4 stage compact RC-model.

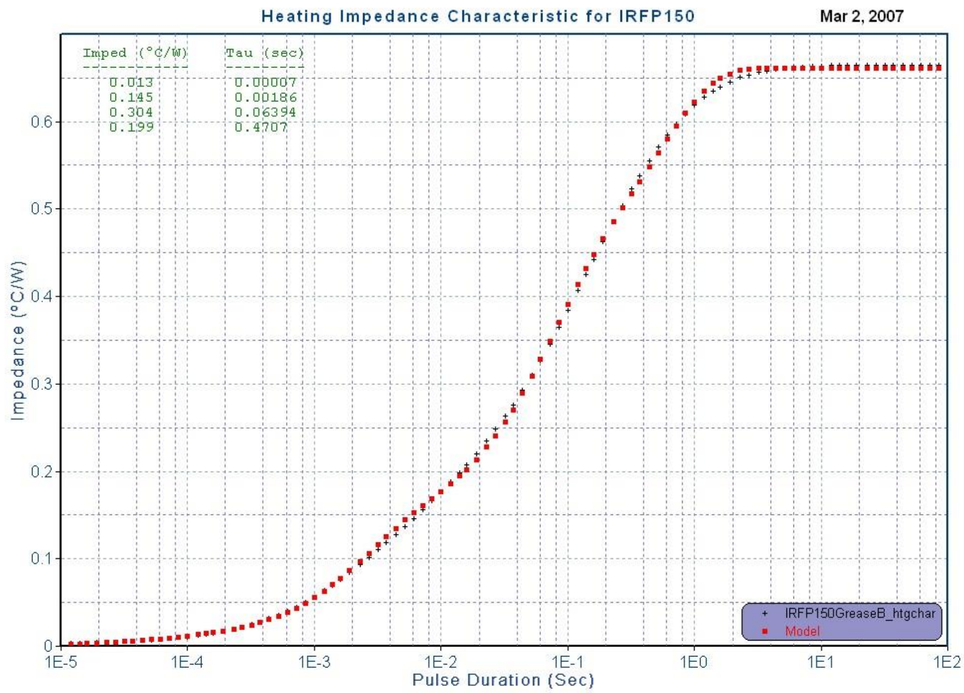


Figure 13: Heating curve with discrete 4-stage RC model simulation overlaid

These RC models are provided in two alternative but equivalent forms: the Cauer (physical) form and Foster form. Figure 13a and Figure 13b illustrate electrical representations of the Cauer and Foster models respectively.

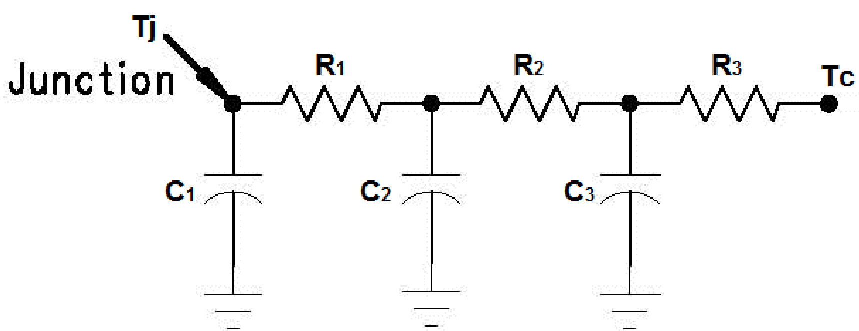


Figure 13a: Cauer Form compact 3-stage model

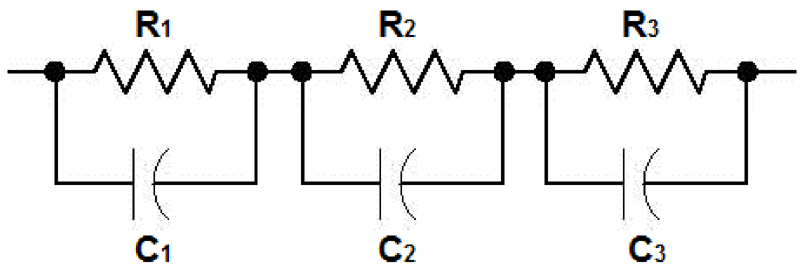


Figure 13b: Foster Form compact 3-stage RC model

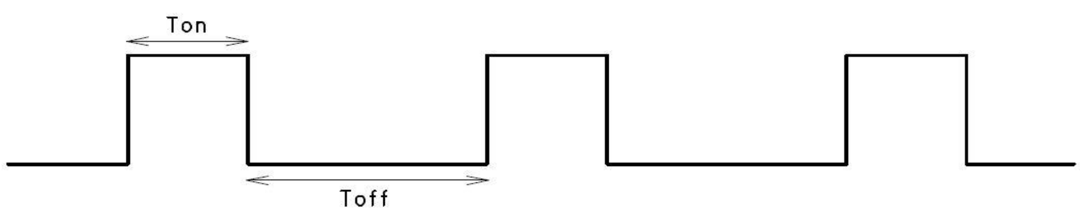
The benefit of the Foster model is that it can be arithmetically exercised. This means that a simple arithmetic equation can be used to determine the impedance, Z, for any heating duration, t :

$$Z(t) = \sum_{i=1}^{N} R_i\left(1 - e^{\frac{-t}{R_i C_i}}\right)$$

where

a) Stage "1" is the junction node.
b) The number of stages in the model is "N".
c) "i" is the index of a stages between 1 and "N".
d) The sum of resistances from the junction to stage "i" is defined as ∑Ri and is equal to the steady state thermal resistance.

Once the model is properly formulated, it can be used to predict the performance of the component in response to the any heating input. Figure 15 presents an example of the model simulation for a *quasi-steady* train of square wave heating pulses of various duty cycles (figure 14). This is called quasi-steady state since the train of pulses is continuous and the device may never reach steady state equilibrium. Rather, it undergoes the identical temperature excursion for each cycle of the heating input with each cycle having the same maximum and minimum junction temperatures. The plot is based on the maximum junction temperature experienced after a *quasi-steady* state has been reached. The Y-axis for "Peak Power Impedance" is based on the heating power during Ton and assumes that zero heating power exists during Toff. Similar plots can be created using Ton (pulse duration) as the X-axis parameter.



Ton = power-on duration = pulse duration
Toff = power-off duration
T = Ton + Toff = "cycle period"
Duty Cycle = Ton / T

Figure 14: Simulated square-wave heating input to compact 4-stage RC model

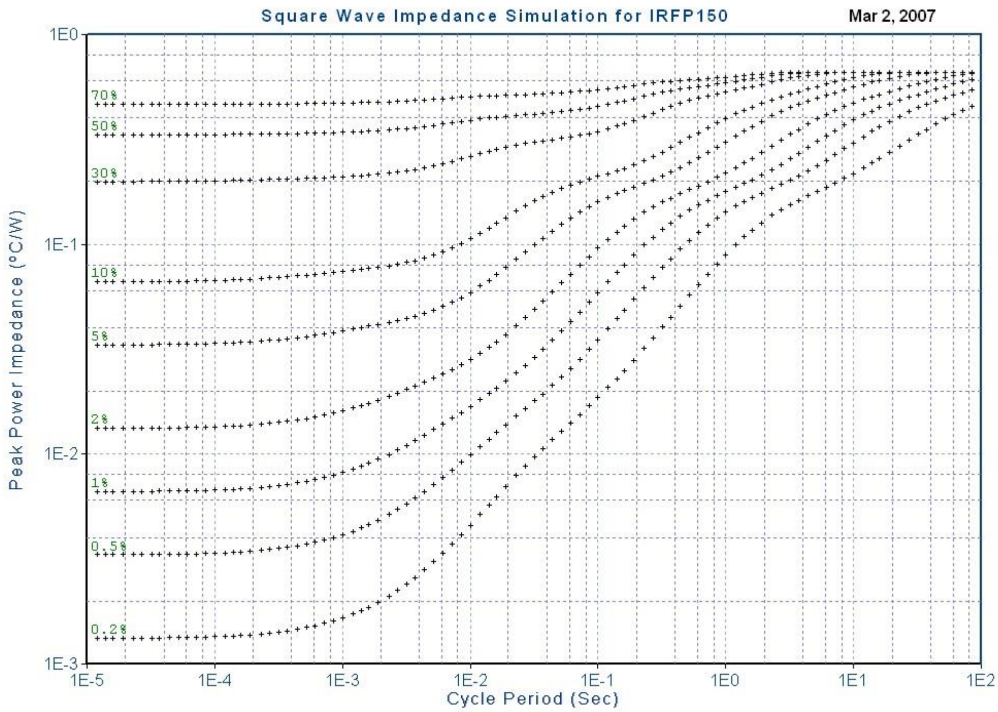


Figure 15: Model simulation for quasi-steady square-wave heating

9.3 Impedance Testing and Die Attach Screening

When heat is delivered to a junction, the observed temperature rise decreases with radius from junction. This is due to the fact that *sum total* amount of the heat capacity of the surrounding packaging material increases with radius. Short heating pulse impedances are dominated by the packaging in the immediate vicinity of the junction. Longer pulse impedances are sensitive to areas of the package further from the die. By proper selection of the pulse duration, a particular package thermal interface can be evaluated, non-destructively, with a high degree of sensitivity to the package-depth of interest.

One of the most popular applications of "tuned" impedance measurement is the die attachment test [F.F. Oettinger, R.L. Gladhill, 1973] used to evaluate the thermal resistance of the mechanical/thermal bond between the die-attachment and the package. The die attachment is a vital thermal pathway, crucial to ensuring good thermal performance. Incomplete die-attachment offers a poor heat-conduction path from the chip to the chip-package causing higher junction temperatures and possibly shortened life expectancy.

The die attachment test is totally transient, typically 10 to 200 milliseconds in heating pulse duration. Longer heating durations can be used to test internal component-interface layers, for example, header attachments with durations from 50 to 500 milliseconds. Such a test is sensitive to the quality of the header attachment *and* the die attachment since the longer pulse measures the thermal impedance elements from the die through the die attachment, the header, and the header attachment, respectively. If the pulse duration is too short, the junction temperature rise it will be insensitive to the package feature of interest due to insignificant propagation of the pulse heat. If the pulse duration is too long, the measured impedance will reflect the thermal impedance of additional features, thus diminishing the sensitivity to the primary feature of interest. Pulse powers used in die-attachment tests are also usually higher than for steady state so that a substantial temperature rise can be achieved with a brief pulse

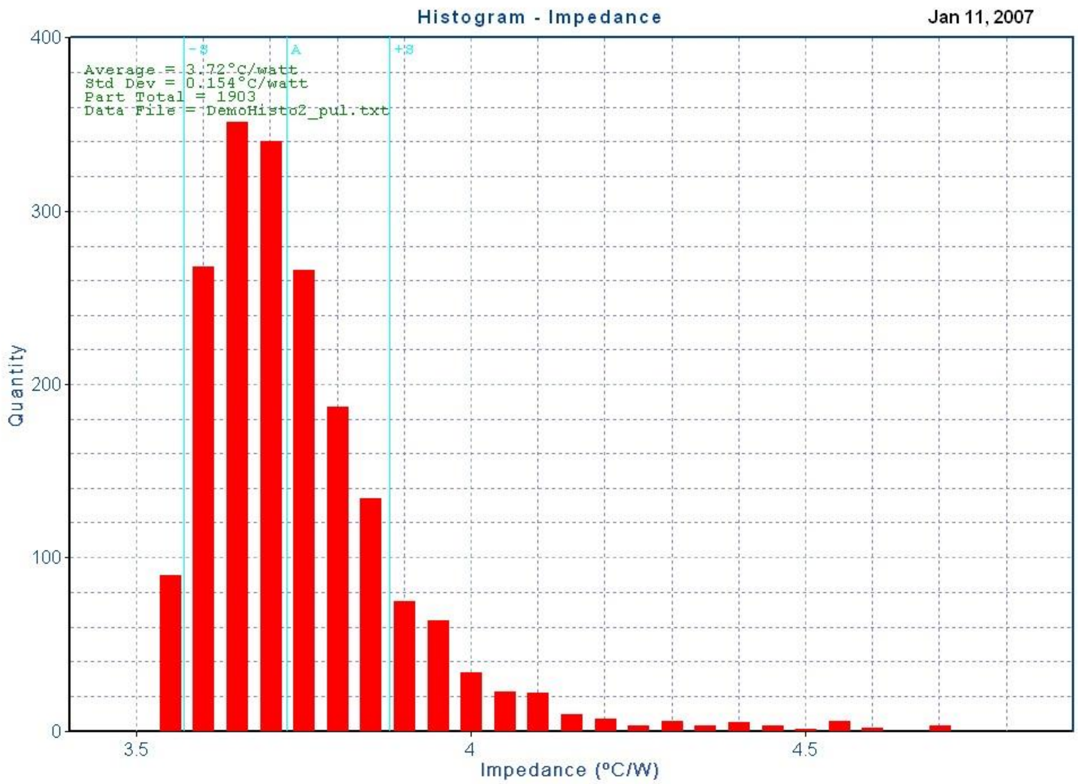


Figure 16: Histogram of impedance testing for die attachment quality

In production environments, large quantities of devices can be screened for die attachment and presented as a histogram such as Figure 16. The shape of these curves is often an asymmetrical bell curve with an extended right "foot". Parts that fall into the extended right "foot" have the worse thermal performance.

10. Transient Thermal Analysis

The transient thermal data analysis uses heating curves and structure function plots; two alternative ways of viewing the transient heating data. Ultimately, multiple tests are required with some variation in cooling configuration between tests to correlate the details of the configuration to the plots. See Section 10.1 - 10.3 for examples.

10.1 Heating Curve Analysis

Recognizing that heating duration correlates to distance-from-the-die, heating curves easily identify where the most significant thermal resistances lie with respect to the die. For example, components with heating curves which rise sharply for short durations have most of their internal thermal resistance close to the die, such as the die attachment. Looking at the heating curve in figure 17, the abrupt rise in impedance that starts at about 2 seconds (2E0) is related to some aspect of the thermal design that is quite far from the heat generating region and is causing a significant increase in the thermal impedance as heating time continues after 2 seconds. Such interpretation can aid in the development of improved component thermal performance.

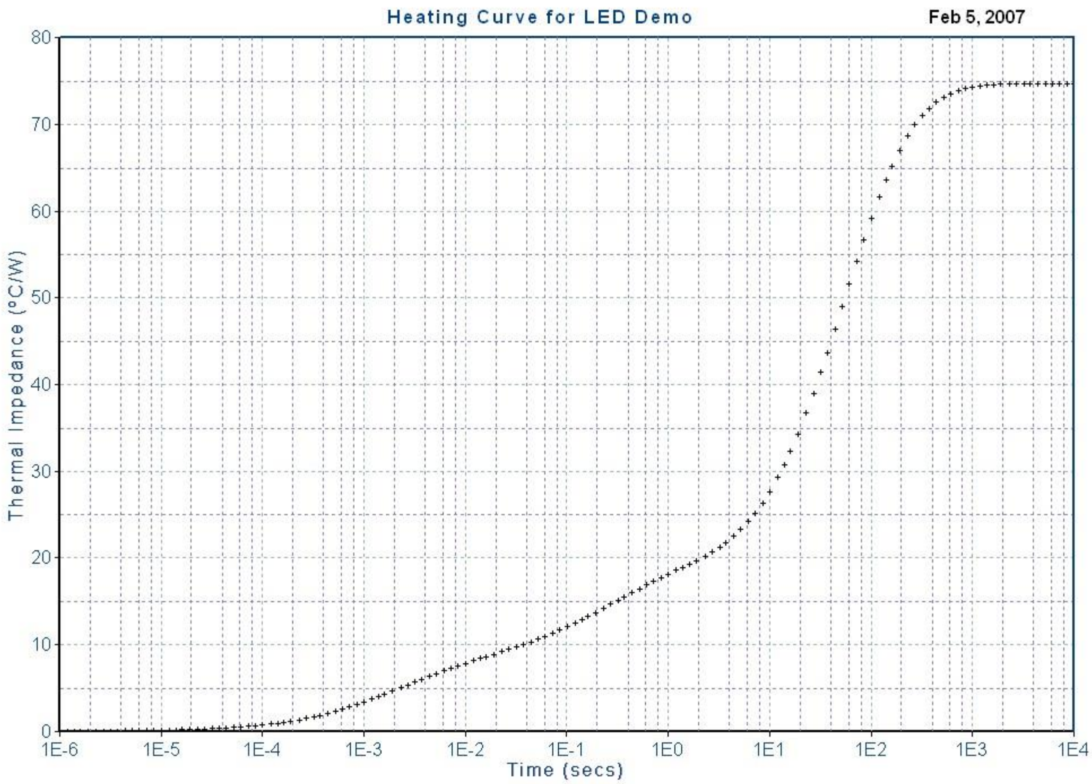


Figure 17: Heating curve plot

Examination of the device design suggests that this is probably related to the heat sink upon which the component is mounted where heat is significantly starting to reach the heat sink after about 2 seconds of heating at a thermal impedance of about 20 °C/W.

It should be noted that interpretation of the heating curve relies on knowledge of the internal structure of the device and is somewhat speculative until additional test data is collected on variations of the thermal structure. Data from such physical variations will aid and solidify the interpretation.

10.2 Structure Function Analysis

The structure function provides an alternative view of the transient heating data and can offers some unique capabilities. Like the direct heating curve analysis, structure functions can help clarify package thermal performance and help to suggest where package improvements would be most effective.

A discussed in section 9.2, the data that is collected from transient heating characterization can be analyzed by creating a multi-stage model RC model. The simulated response of a properly composed model is nearly identical to the measured transient data. A detailed examination of the RC stages that comprise the model provides the basis for structure function analysis. For this, the following nomenclature is useful:

a) Stage "1" includes the junction node.
b) The number of stages in the model is "n".
c) "i" is the index of a stage between 1 and "n".
d) The sum of resistances from the junction to stage "i" is defined as ∑Ri.
e) The sum of capacitances from the junction to stage "i" is defined as ∑Ci.
f) The difference between the Rs in stage "i-1" and stage "i" is defined as ∆Ri.
g) The difference between the Cs in stage "i-1" and stage "i" is defined as ∆Ci.

It should be noted that the sum of all stage resistances from 1 to n is ∑Rn which equals the steady state thermal resistance. All structure function plots utilize ∑Ri as the X-axis parameter. Therefore the maximum value plotted on the X-axis is the steady state thermal resistance, occurring as a vertical asymptote.

The Y-axis has two alternate forms depending on whether it is a "*cumulative*" or a "*differential*" structure function. The cumulative structure function Y-axis is simply ∑Ci. This makes the cumulative structure function a plot of ∑Ci versus ∑Ri for each stage of the model, one point per model stage from 1 to n. The differential structure function plots the *slope* of the cumulative structure function at each ∑Ri. Accordingly, the differential structure function Y-axis is the ratio ∆Ci / ∆Ri.

The Y-axes of structure functions are generally useful only as relative, not absolute, parameter. In this regard, the peaks and valleys of the structure function are of interest not for their Y-axis values but for the thermal impedance (X-axis) where the peaks occur. The structure functions have the following features:

a) Structure functions are derived from the heating curve which includes all the transient thermal response starting from unheated equilibrium and terminating at steady-state heated equilibrium; the heating curve and structure function provide different perspectives on the same transient phenomena.

b) Structure functions can sometimes be useful for understanding the performance of the multiple thermal interfaces and pathways existing in a packaged electronic component. The peaks and valleys of the differential structure function are associated with differing material properties or heat flux geometry encountered at the leading edge of the transient heat flow at a particular heating duration, corresponding to a particular impedance as provided by the heating curve.

c) Like the heating curve, details of structure function plots that are closer to the Y-axis are associated with thermal pathways closer to the die; the further the details are to the right, the further from the die region these pathways and structures are located.

d) The right end of the structure functions tend toward a vertical asymptote located on the impedance axis at the steady state thermal resistance.

e) Like the heating curve, the benefits of structure function interpretation rely heavily on comparison between similar component designs or implementations. The association of structure function plot details with various structures within the component is almost entirely subjective unless it is grounded on comparisons of very similar component designs.

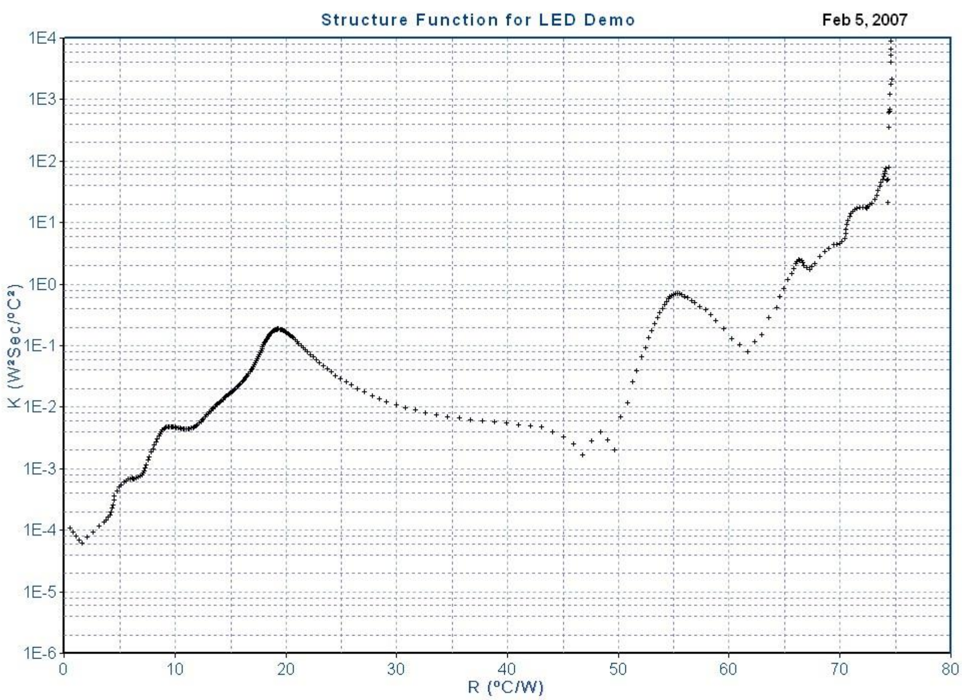


Figure 18: Differential structure function plot for figure 17 heating curve data

Figure 18 presents the differential structure function for the heating curve data of figure 17. We have previously surmised that the heat is beginning to enter the heat sink after 2 seconds at a cumulative impedance of about 20°C/W. If we look at the first significant bump on the left side of the heating curve, it appears to have its peak at an impedance of about 19°C/W. This corresponds to the same instant of time when the heat is first entering the heat sink where the heating curve shows the beginning of a steep rise in thermal impedance. Looking further to the right on the structure function plot of figure 18, a second major bump is noticed before the curve begins its asymptotic climb toward an asymptote of about 75°C/W which equals the steady state thermal resistance shown in the figure 17 heating curve. The origin of the bump that occurs at an impedance of about 55°C/W is not immediately clear. Experience indicates that this bump is the end of initial transient heat spreading within the heat sink and the beginning of heat rejection to the surrounding air.

It should be noted that a single structure function cannot uniquely distinguish between thermal effects associated with transitions in heat conduction geometry versus transitions in material properties (conductivity and heat capacity) encountered during transient heat propagation. Structure function interpretation relies on having multiple similar designs to compare as well as knowledge of the interior package construction.

10.3 Transient Analysis with Comparative Data

Figures 19 and 20 present transient data for a TO247 MOSFET mounted on three different PWBs, sandwiched between the MOSFET and a heat sink. The data for each of the three configurations is plotted both as a heating curve and as a structure function allowing comparisons of the data from both analyses.

The case configurations are labeled A, B, and C and are defined:

Case A: MOSFET on large-sized PWB with two inner copper layers
Case B: MOSFET on small-sized PWB with two inner copper layers
Case C: component on small-sized PWB with no inner copper layers

All testing utilized the same interfacial material between the component and the PWB and the PWB and the heat sink.

Figure 11 shows the heating curve for the MOSFET attached directly to the heat sink without any PWB sandwiched between. Here, the steady state thermal resistance is 0.66°C/W starting at about the 1 second mark. In the heating curve of figure 19, the 1 second mark is also where we see that the impedance is about 0.8°C/W, close to 0.66°C/W but expectedly less since the component does not have the benefit of an isothermal heat sink surface when mounted on a PWB. This makes sense since we should be able to see the transient characteristics of the MOSFET occurring prior to the transient effects of the PWB. After about the 1 second mark when heat has certainly started flowing across the first interface layer between the component and the PWB, the impedance rises abruptly as heating continues. This makes sense since owing to the higher resistance of the PWB material.

Figure 20 shows the associated differential structure function plot with the figure 19 heating curve. Here we see that all three curves have a common peak at about 0.2°C/W which is associated with thermal interface between the die and the copper heat spreader. This same die-interfacial peak can be seen in more detail in figure 20 at 0.15°C/W which presents the differential structure function plot of the TO-247 MOSFET directly attached to the heat sink. (Figure 11 heating curve) The figure 21 differential structure function expectedly shows no peaks once the heat has left the die attach interface region since heat flow in this region characterized as geometrically uniform in a consistent material.

After the die-attach peak at 0.2°C/W on the figure 17 structure function, an anti-peak occurs at about 0.6-0.7°C/W which is indicative heat flow transitioning out of the component's copper spreader. The peak at 1.0°C/W is indicative of the transient transverse heat flow into the PWB. Continuing further to the right, a broad anti-peak occurs between 2-3.5°C/W which is indicative of the transient two-dimensional spreading within the PWB. Note that all three cases show identical structure function plots from 0 to 3.5°C/W despite that fact that from 1 to 3.5°C/W heat is substantially flowing within the three PWBs, each with very different thermal properties.

On the differential structure function plot, data for A and B diverge at about 3.5°C/W and the data for B and C diverge at about 4.3°C/W. Looking at the heating curve, we see a similar divergence at 8 seconds between cases A and B at an impedance of 4.0°C/W and a divergence between B and C at about 10.5 seconds at about 5.5°C/W. So there is a slight disagreement between the structure function and the heating curve. This result is expected because the differential structure function detects divergences in the heat flux patterns which occur *before* the heat reaches the interface of interest. (see section 10.4) Despite the sensitivity of the differential structure function, the reported cumulative resistance at divergences are slightly distorted by this sensitivity. At impedance above 3.5°C/W, the three cases are diverging, each shows a similar peak but at different impedances. This peak indicates that transient lateral spreading within PWB has essentially been saturated and is beginning to move out of the PWB in a transverse direction. Looking further to the right, the vertical asymptotes of 7.7, 9.5, and 10.5°C/W agree with the steady state thermal resistances shown on the heating curve.

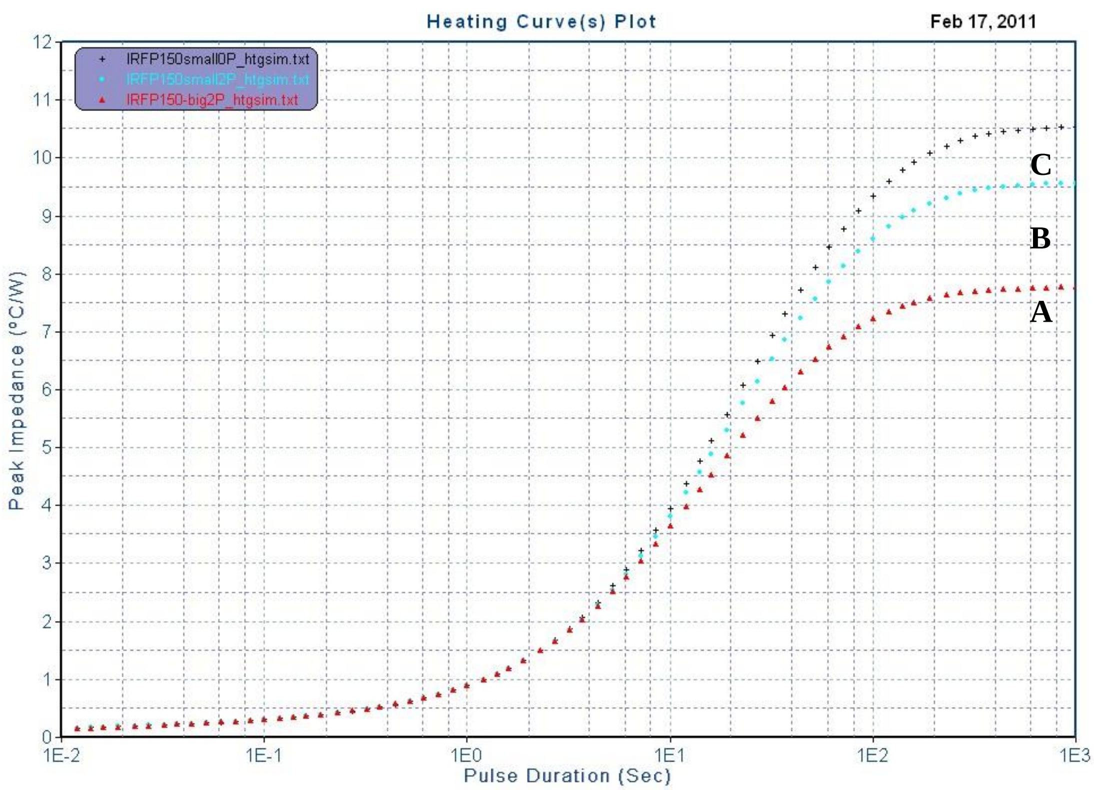


Figure 19: Heating curve for TO-247 MOSFET on 3 different mounting PWBs

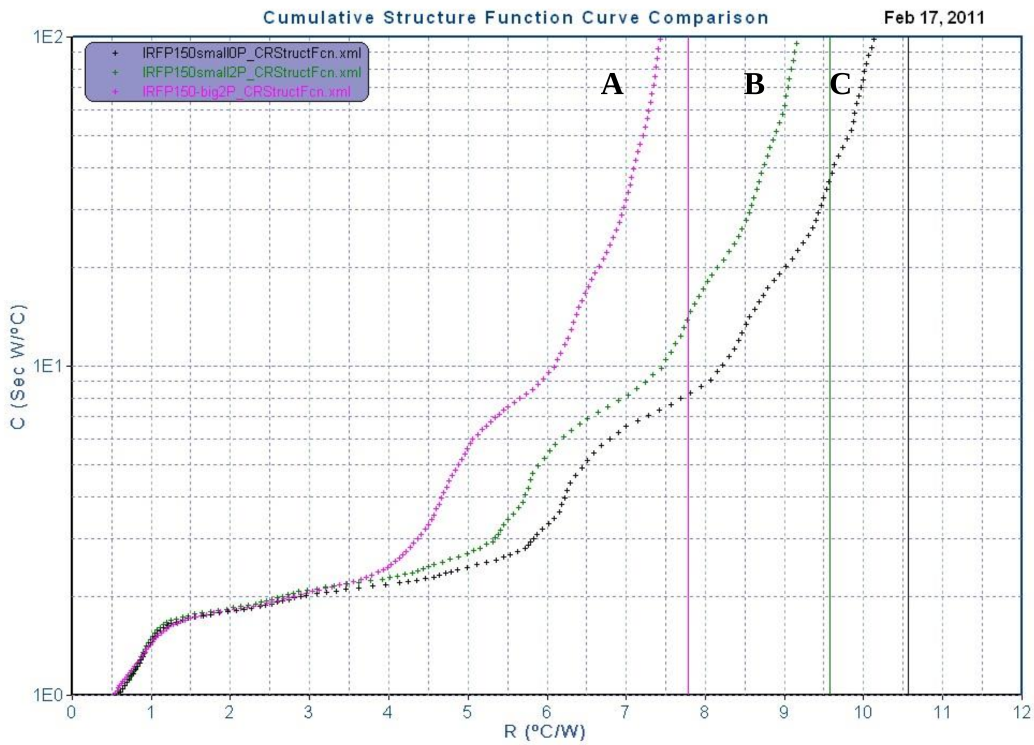


Figure 20: Cum. Structure function - TO247 MOSFET, 3 different mountings

Figure 21: Diff. Structure function - TO247 MOSFET, 3 different mountings

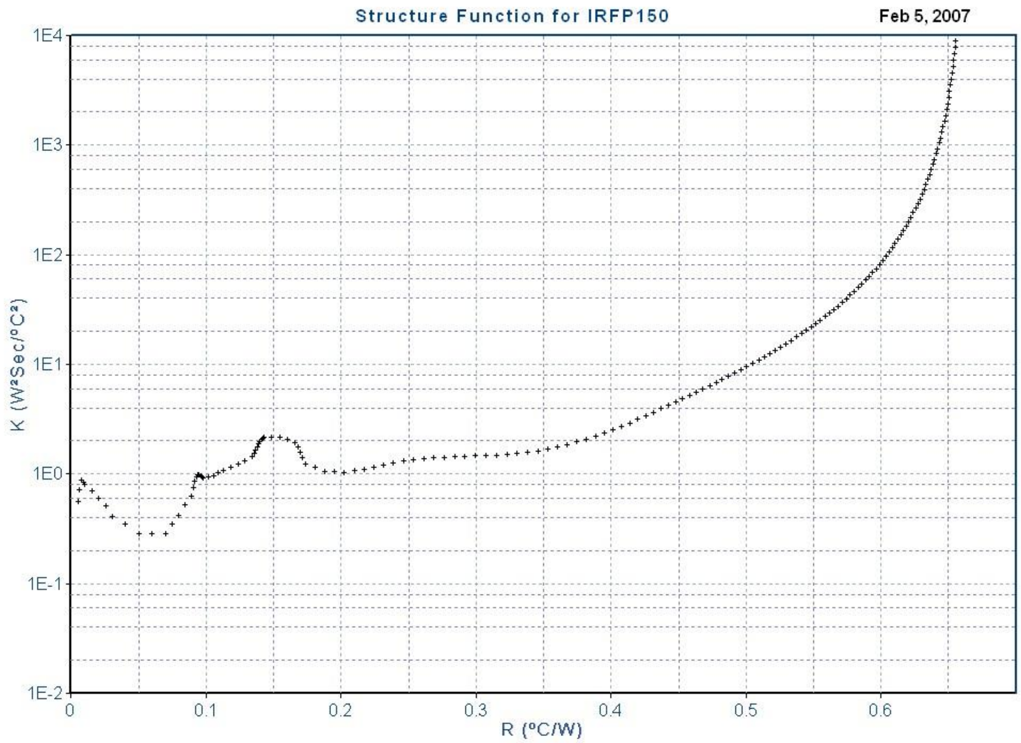


Figure 22: Diff. Structure Funct. for heating curve of TO247 MOSFET on heat sink

In summary, the combination of heating curve and structure function analysis when applied to a few variations of component design allow accurate interpretation of the thermal performance of various thermal designs implementations. It is most important to appreciate that the structure function does not differentiate between changes in transient heat-flow geometry within a consistent material and consistent transient flow-geometry within a body composed of material with different thermal properties, namely conductivity and heat capacity. The peaks and anti-peaks of the structure function are indicative of both changes in material properties and flow-geometry. The final vertical asymptote of the structure function is simply the steady state thermal resistance of the component in the particular cooling configuration.

Finally, when comparing similar cooling configurations, it should be noted that the three-dimensional heat flow patterns “upstream” of a particular thermal structure can be influenced by conduction patterns and thermal structure “downstream”. This will generate some structure function divergences *prior* the actual transition of interest. The intensity of these secondary divergences will depend on the severity of the structural differences being compared.

10.4 Cumulative versus Differential Structure Functions

The cumulative and differential structure functions are both directly based on the multi-stage exponential model derived from the heating curve. The differential structure function is uniquely sensitive to detecting the differences in the heat flux networks between two different configurations. For example, two package designs with internal spreaders made from different conductivity materials can be compared with the differential structure function measured for each. It might be assumed that resistance at the point where the two DSF (differential structure function) curves diverge is the resistance at first interface to the header. This assumption would be incorrect. The divergence of these two DSF plots occurs at a cumulative resistance *smaller* than that of the cumulative resistance at the first header-interface. This is true because the header conductivity influences the shape of the heat flow pattern prior to (ie., upstream of) the heat actually reaching the interface. This gives rise to the divergence at cumulative resistance less than that of the first header-interface as would be associated with a cumulative resistance somewhere in the material closer to the die than the first header interface. This is a fundamental issue with the use of the DSF. Comparisons using heating curves or cumulative structure function (CSF) are less sensitive indicators of divergence and therefore reduce the impact of this issue. For this reason, direct use of heating curve comparisons or cumulative structure functions often provides a more accurate estimate of the cumulative junction-to-interface resistance. The following photo shows three samples that were compared for transient thermal response. There two FR4 PWBs with different pad design and one alumina PWB.

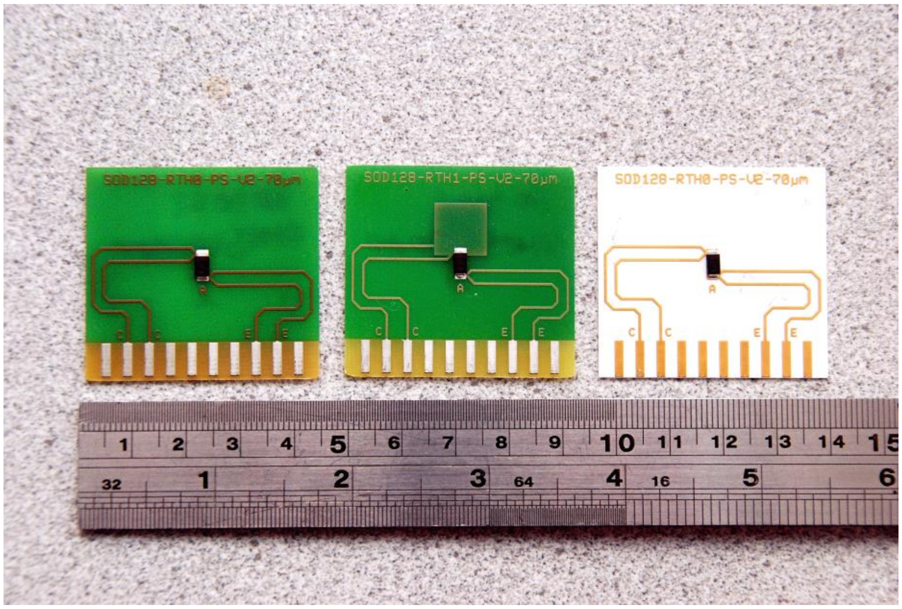


Figure 23: Three sample SOA diodes on different substrates

It should be noted that these three samples will generate significantly different heat flow patterns upstream of the mounting pads which will cause the divergence point for their transient responses to be in some disagreement as to the correct value of Rjc.

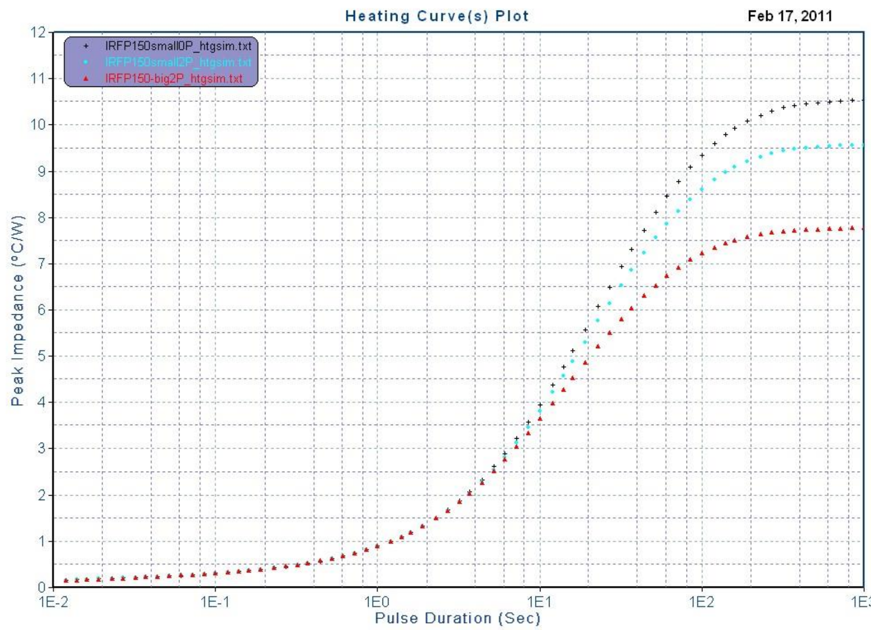


Figure 24: Comparison of three heating curves

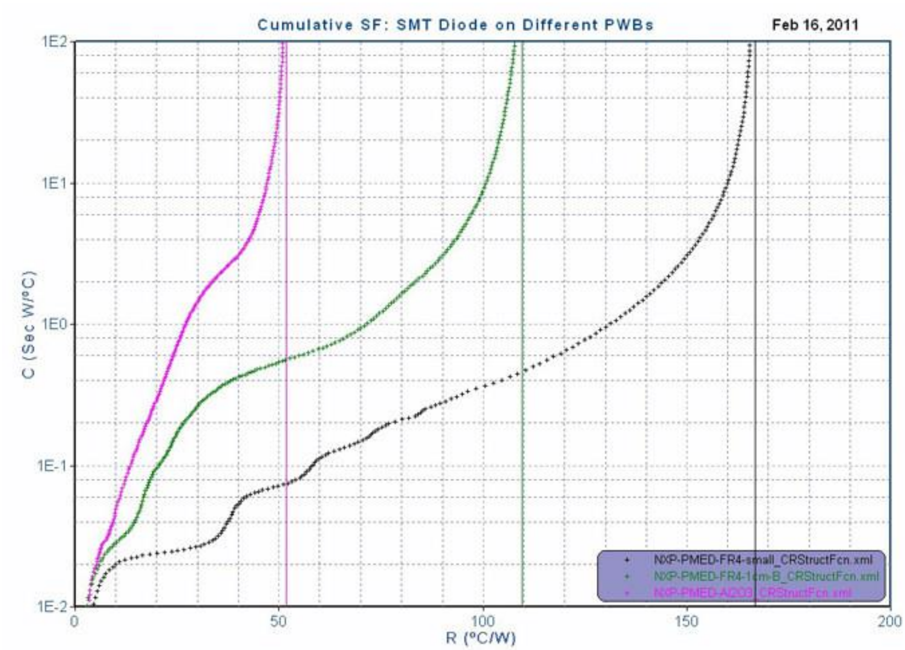


Fig. 25 Comparison of three cumulative structure functions

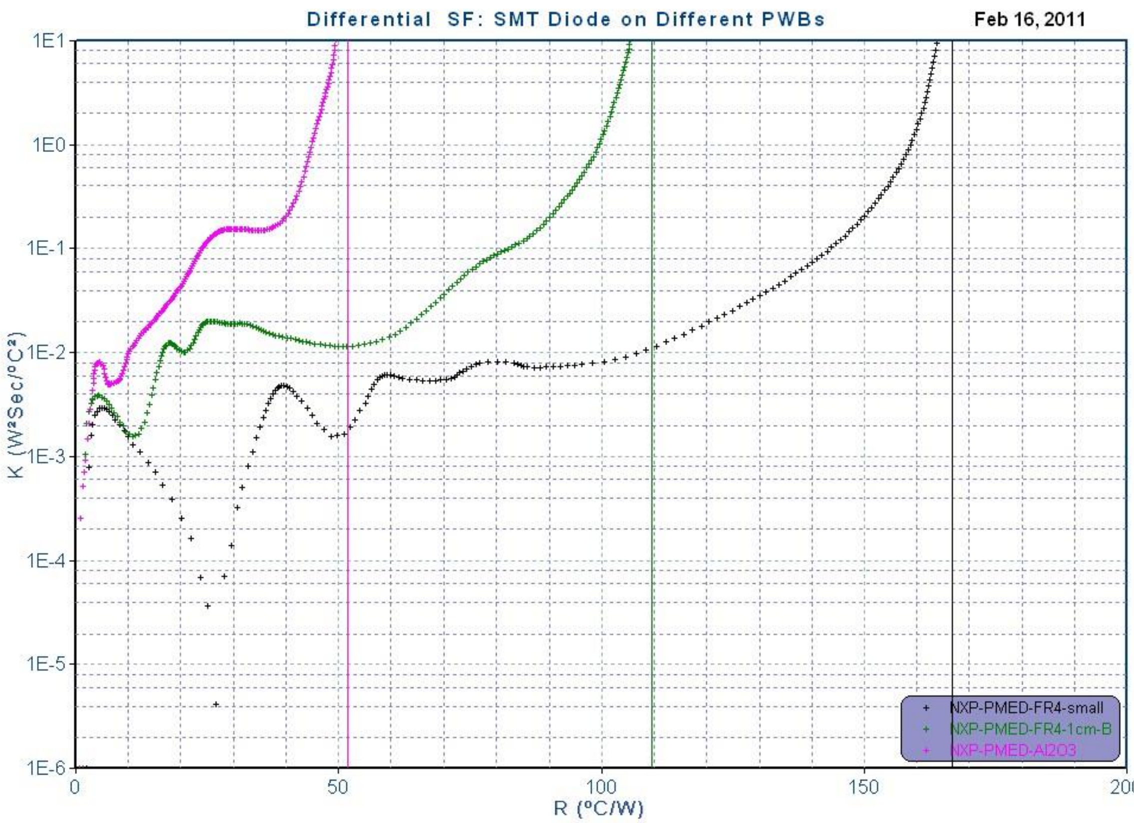


Fig. 26: Comparison of three differential structure functions

Clearly the thermal resistance for this part is somewhere between 2 and 10 °C/W. This amount of uncertainty is not surprising considering that samples have substantial different heat flow geometries.

This method of comparing transient performance as a means of determining Rjc, junction-to-case thermal resistance, has been enshrined in JEDEC Std 51-14 discussed below.

10.5 Rjc Measurement Using Transient Methods

JEDEC 51-14 entitled "Transient Dual Interface Test Method for Measurement of Rjc for Semiconductor Devices with Single Heat Flow Path" uses the comparison of two transient tests on a component that has a single, dominant, conduction-heat-flow path. One test is performed with a low resistance case-to-sink thermal interface material (TIM) and another with a high resistance TIM. The point at which the two transient profiles diverge corresponds to the case-to-heat sink interface. The resistance at this point is thus the thermal resistance, junction-to-case, or Rjc.

This method compares the two transient characteristics using both the cumulative structure functions (CSF) and the heating curves (HC) to determine the impedance at the transient divergence point. The impedance at the divergence is assumed to be the junction-to-case thermal resistance, Rjc, since the divergence is caused exclusively by a difference in the case-to-sink interface. The reference temperature for this method is the temperature controlled cooling liquid temperature that supplies the heat sink. This reference temperature choice avoids an interface-thermocouple which is commonly influenced by minute mechanical positioning which can be difficult to consistently control.

This standard recommends using comparisons of “thermal grease” to “dry contact” interfaces. The problem with dry contact is that the contact interface resistance is extremely variable depending on the flatness of the mating surfaces and the particular interface contact pattern. The cause of this variability is simply that air is an excellent thermal insulator and small variations in the *location* and amount of this thin air layer causes substantial and unpredictable variations in the contact resistance. This in turn can create anomalous transient comparisons due to variations in the geometry of the heat flow across the air-entrained irregular interface. Logically, it would seem that a comparison based on high-performance grease and low-performance grease would offer better consistency by reducing the potential variations of the dry contact within the conduction interface.

Figure 27 presents the heating curves for an TO-247 device pressed onto a liquid cooled heat sink with 5 pounds (20 nt) of force via a thick Teflon actuator (Teflon k = 0.28 W/mK). The three interface materials used make two JEDEC Rjc determinations:

a) Dow Corning TC5026, k = 2.9 W/mK, termed “gray”
b) Dow Corning DC340, k = 0.5 W/mK, termed “white”
c) Dow Corning DC200-1000 silicone oil, k = 0.1W/mK, termed “oil”

Ideally, comparison tests should be conducted at the same heating wattage to eliminate power dependency on the Rjc measurement. Although the determination of Rjc from transient data is a numerical procedure, the associated graphical comparisons are presented below for the two pairs of TIMs.

Fig 27: JEDEC 51-14 Rjc HC comparisons for Gray & Oil TIMs

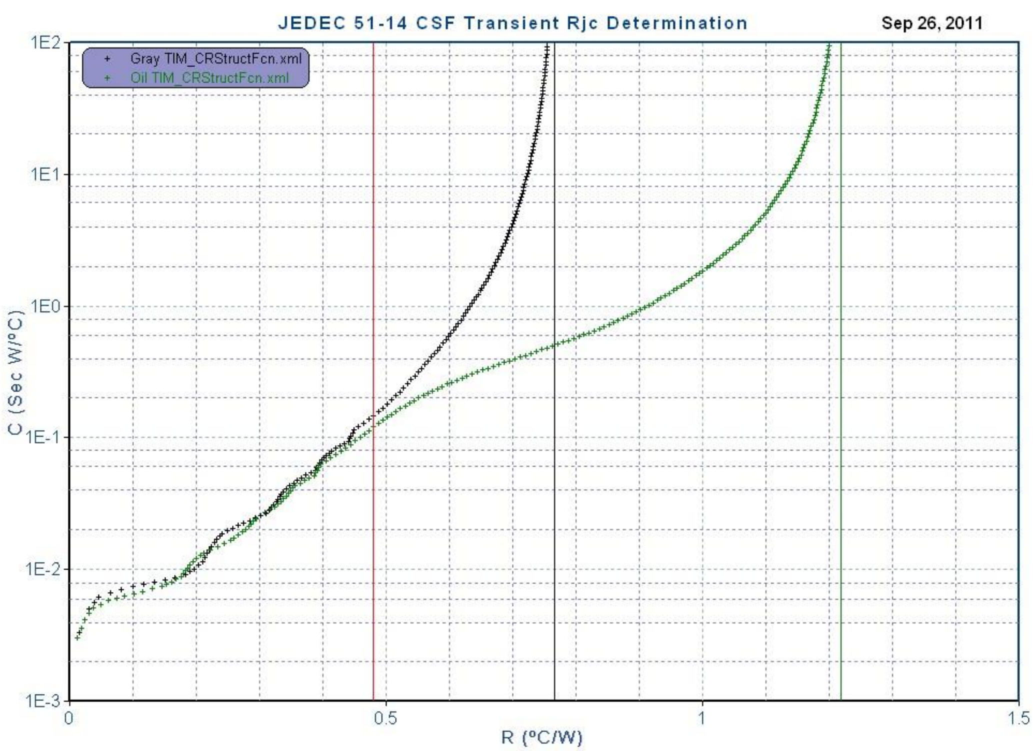


Fig 28: JEDEC 51-14 Rjc CSF comparisons for "Gray & Oil" TIMs

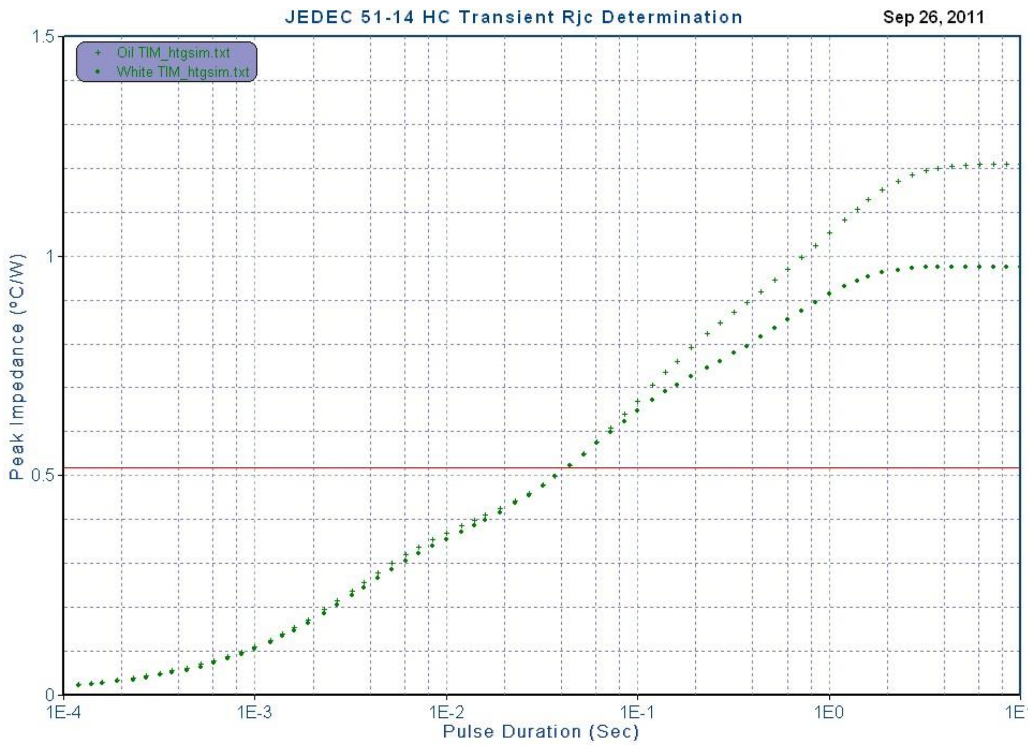


Fig 29: JEDEC 51-14 Rjc HC comparisons for "White & Oil" TIMS

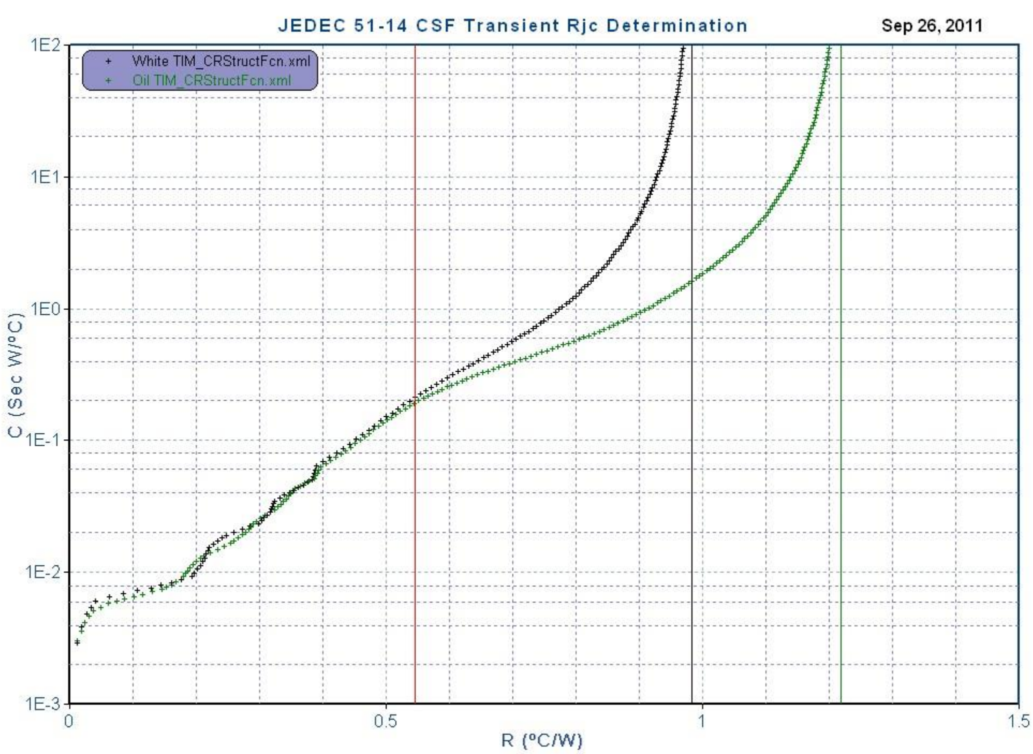


Fig 30: JEDEC 51-14 Rjc CSF comparisons for "White & Oil" TIMs

JEDEC Std 51-14 includes a precise computational means for determining the divergence point for Rjc from the heating curves. Determination of the Rjc from the cumulative structure function is somewhat less explicitly defined. Comparisons are required for both the heating curves and the cumulative structure functions according to the standard. For this example case, the resulting Rjc for this two pairs of comparisons is presented below. This suggests that the JEDEC transient Rjc depends somewhat on the particular selection of interface greases used in the comparison tests:

Interfaces Compared	**Rjc, °C/W**
Gray and Oil using CSF	0.480
Gray and Oil using HC	0.486
White and Oil using CSF	0.546
White and Oil using HC	0.518

In summary, the choice of the TIMs chosen for the JEDEC Rjc transient measurement method should favor TIMs with the greatest performance difference to make the divergence impedance easier to identify. Some degree of Rjc dependency on the specific selection of TIMs for the JEDEC Rjc determination is to be expected.

11. References

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