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An Introduction to Diode Thermal Measurements

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1. Introduction

This handbook provides a brief overview of the electrical test method for diode thermal resistance measurements. It is designed to aquatint the reader with the basics of the measurement and, as such, is general in nature. Specific diode types (i.e., rectifier, signal, RF, LED, laser, etc.) each have their own peculiarities and require extension of this document to address these special cases.

It should be noted that many non-diode-specific devices (such as integrated circuits, MOSFETs, bipolar junction transistors, etc.) can also be tested as diodes. While this not optimum for transistors, because the heat is generated differently in the diode mode as compared to transistor mode, practical considerations may dictate the use of the diode mode in testing these devices. In the case of large complex-circuit integrated circuits (ICs), it is nearly impossible to test the IC in an application mode. Thus, most ICs meeting this requirement are thermally tested using the substrate isolation diode usually inherent in the IC for both heating and sensing. All of these devices also may require certain extensions to the measurement description below.

The key thermal parameter that is most common is thermal resistance, with the symbol θ and units of °C/W. The symbol has two subscripts – J for diode junction and X to indicate where the heat flow is being delivered. For example, θ_{JC} is the parameter that provides a measure of heat flow capability from the junction to the device case (or package) when the heat is forced to directly flow to case.

2. Temperature Sensing

Diodes make excellent temperature sensors. At low values of forward current (usually refereed to as measurement current [I_M] or sense current [I_S]), the junction temperature [T_J]– junction forward voltage [V_F] correlation is very nearly linear to the second order. Thus a change in junction temperature produces a corresponding change in junction forward voltage with a constant correlation factor of the form –

$$\Delta T_J = K \times \Delta V_F$$

where the correlation factor is referred to as the K Factor. The units of K are in °C/mV and the value is typically in the range of 0.4 to 0.8 °C/mV.

No one value of I_M is suitable for all diodes. The selection of I_M is based on the diode size and type. Industry practice is to use a value of I_M that corresponds to the break in the diode's forward voltage curve as shown in Figure 1. Choosing a too low a I_M value will cause problems in measurement repeatability for a specific diode and potentially large variations between devices of the same part number. Too large a values of I_M will cause significant self-heating within the diode junction area and give rise to potentially large temperature measurement errors. When ever possible, I_M is selected to some nominal value, such as 0.1, 1.0, 5.0 or 10.0 mA, the exact value depending on the current-handling capabilities of the diode to be calibrated.

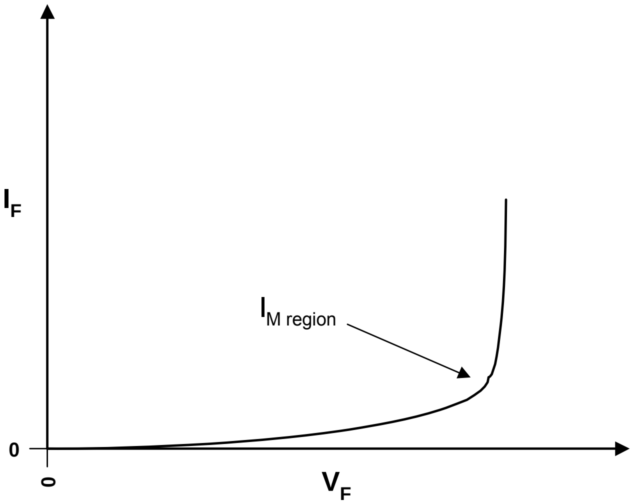


Figure 1

Typical practice is to calibrate five or more devices at a single time. Batch calibration serves two purposes. First, it reduces the time necessary to calibrate all the devices individually. The initial temperature and the final temperature stabilization periods, which can take 30 minutes or more depending on the temperature environment used for the calibration, only has to be done once instead of for each diode. Second, making measurements in batch form helps to reduce potential errors if the data is averaged.

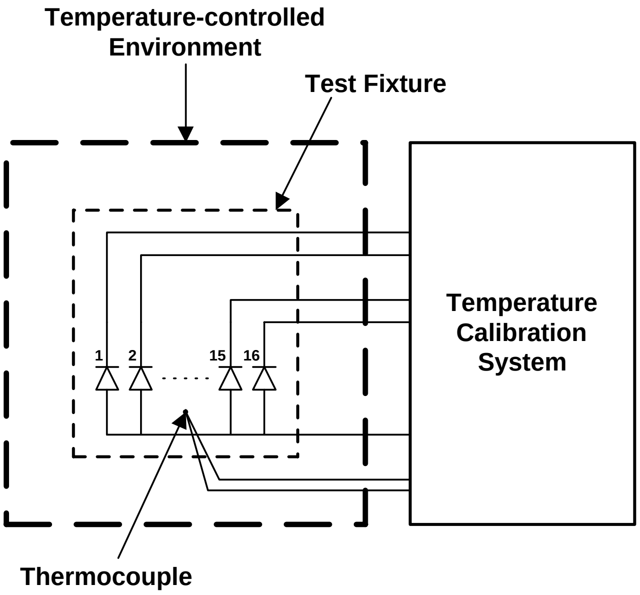


Figure 2

The equipment setup for performing K Factor calibration measurements is shown in Figure 2. The temperature-controlled environment can be a small oven that maintains uniform temperature in an area large enough to contain the test fixture. The test fixture only has to provide electrical connection to the individual diodes to be calibrated. The temperature calibration system provides the measurement current and measures the environment temperature and the diode forward voltage. The diode forward voltage is read and recorded for each device once the environment temperature has stabilized at a fixed value. Temperature stability has occurred when neither the diode voltage(s) nor environmental temperature measurements shows any significant fluctuations.

Once the diodes are mounted in the test fixture, the fixture is inserted into the temperature–controlled environment, and the fixture is connected to the measurement system, the next step is to wait for initial temperature stabilization at the low temperature [T_{low}]. This temperature is usually near room temperature, something in the 23 °C range. After readings are obtained at this temperature, the temperature is increased to a higher value [T_{high}], typically in the 100 °C range, stabilization allowed to occur, and a new set of voltage readings is taken.

Figure 3 shows graphically the results of the two different temperature conditions. K Factor [K] is defined as the reciprocal of the slope of the V_F – T_J line, and is usually in the range of 0.4 to 0.6 °C/mV for a single diode junction. The equation is –

$$K = \left| \frac{T_{high} - T_{low}}{V_{low} - V_{high}} \right| \text{ °C/mV}$$

To save thermal testing time, the results of calibration batch testing are usually averaged (K_{avg}) and the standard deviation (σ_K) is determined. If the ratio of σ_K/ K_{avg} is less than 1.03, then thermal testing on the batch units can proceed using the K_{avg} for all units without causing a significant error in the thermal test results. A ratio of greater than 1.03 requires using the individual values of K for thermal testing. The higher ratio also indicates potential process control problems in the fabrication of the diodes.

The K Factor is highly dependent on the value chosen for I_M. It is imperative that the same value of I_M be used during the thermal testing.

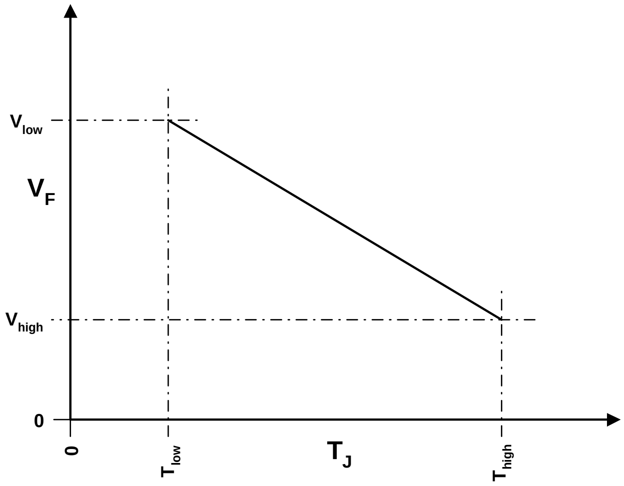


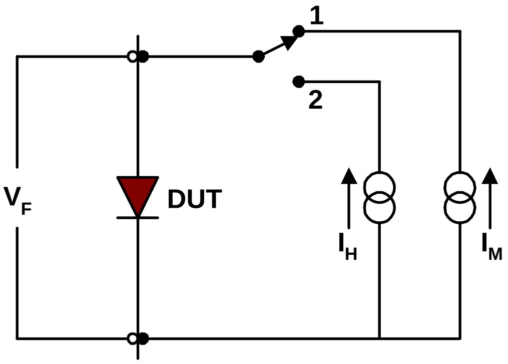
Figure 3

The average value and standard deviation of the K values from a group of the same samples provides a measure of sample uniformity. If the ratio of standard deviation to average K is less than 0.03, then industry practice dictates that the average K can be used for all the devices in the lot. However, if this ratio is greater than 0.03, then the sample-specific value must be used for each sample. Most silicon-based samples will typically have a ratio of 0.01 or better, while devices fabricated from III-V compound material (i.e., laser diodes, LEDs, etc) will typically exceed the 0.03 ratio requirement.

The discussion above is generic in that it applies to any diode – PN Junction, Schottky Junction, Substrate Isolation diode in an integrated circuit, Source-Body diode in a MOSFET, etc. Also, the V_F-T_J relationship is usually assumed to be linear (hence, the two point measurement of K) but may actually be slightly non-linear (second or third order effect) but usually not enough to significantly affect thermal data.

3. Measurement Procedure

When the T_J sensing technique is combined with the application of Heating Power (P_H), the measurement of junction temperature rise (ΔT_J) resulting from applied P_H leads directly to the T_J, thermal resistance (θ_{JX}) or thermal impedance ($Z_{\theta JX}$) of the diode for a specific set of environmental and time conditions; the X subscript defines the reference environmental condition.



The electrical test method (ETM) for diode thermal measurements uses a three-step sequence of applied current levels to determine a change in junction voltage (ΔV_F) under Measurement Current (I_M) conditions. The setup for the measurement is shown in Figure 4. First, I_M is applied and the diode-under-test junction voltage is measured - the measurement value is referred to as V_{Fi}. Second, I_M is replaced with a desired amount of Heating Current (I_H) for a time duration consistent with the steady-state or transient data required. During this time the diode voltage (V_H) is measured for determining the amount of power (P_H) being dissipated in the diode. Third, I_H is removed and quickly replaced with I_M and a final junction voltage measurement is be made - this voltage is referred to as V_{Ff}. The three-step operation shown graphically in Figure 5.

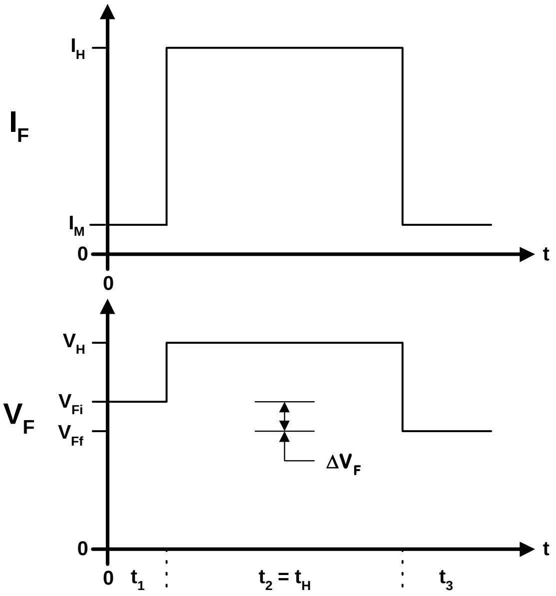


Figure 5 Current and Voltage waveforms for diode thermal measurements.

Once this three-step measurement process has been completed and the appropriate data collected, the next step is to use the data to compute T_J and θ_{JX} (or $Z_{\theta JX}$) as follows:

$$\Delta V_F = \left| V_{Fi} - V_{Ff} \right|$$

$$\Delta T_J = K \times \Delta V_F$$

$$T_J = T_{Ji} + \Delta T_J$$

where T_{Ji} is the initial temperature of the diode junction before the start of the measurement. Then

$$\theta_{JX} = \left[\frac{K \times \Delta V_F}{I_H \times V_H} \right] = \left[\frac{\Delta T_J}{I_H \times V_H} \right]$$

where - θ_{JX} is the thermal resistance for the defined test condition and thermal environment

ΔV_F is the change in the TSP change (in this case diode forward voltage)

I_H is the applied heating current

V_H is the applied heating voltage

K is the K Factor

The three-step process described above produces a data point for a single value of Heating Time. This single data point is usually difficult to interpret and understand. A better approach is to generate a Heating Curve by making multiple three-step measurements with successive iteration having a longer value of Heating Time. Shown in Figure 6, the resultant curve shows how the heat propagates from the heat source (i.e., junction) on the left to some other physical location, such as the device package on the right.

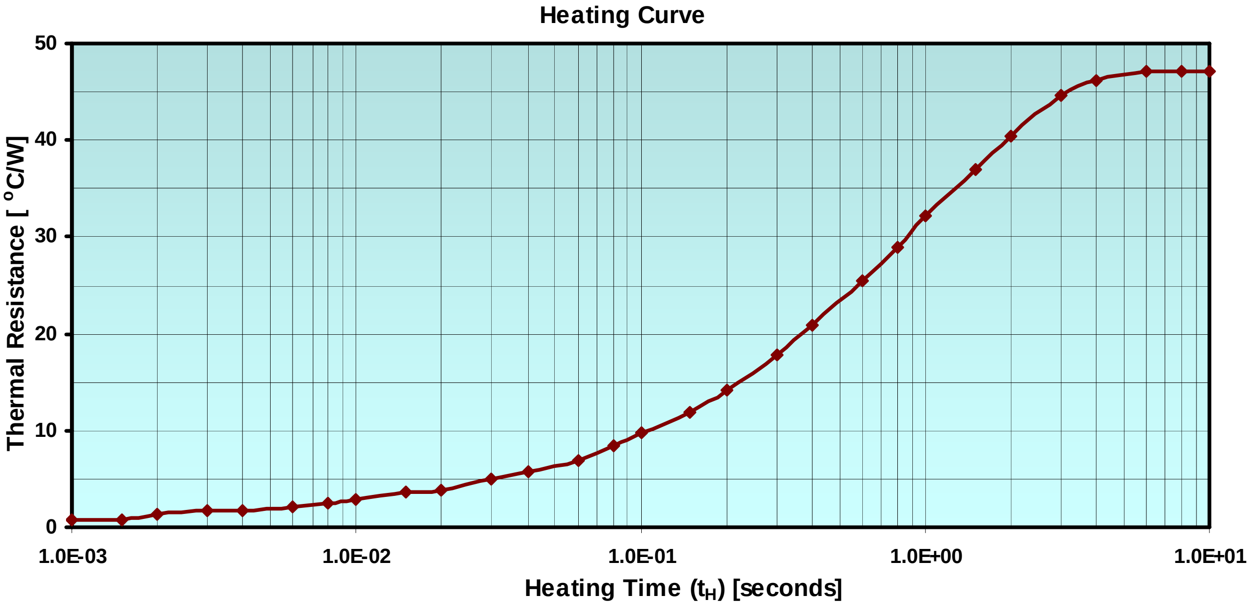


Figure 6 Heating Curve generated by iterative measurements

4. Junction Cooling

The electrical method for semiconductor thermal measurements relies on the ability to quickly measure the TSP (temperature-sensitive parameter) of the device-under-test (DUT) after removing power applied to the DUT. The DUT junction temperature (T_J) starts decreasing immediately but measurement difficulties usually make reading the TSP at the exact cessation of applied power next to impossible. Thus, if measurement data is not corrected for junction cooling, then the resultant junction temperature thermal resistance values will be too low - in some cases by a significant amount.

While the waveforms in Figure 5 are idealized for demonstrating the basic concept, the actual waveforms are shown in Figure 7. The instant heating power is applied to the DUT, the voltage starts to decrease. The extent of the decrease is determined by both the level of power applied (relative to the current handling capability of the DUT) and the amount of time (t_H) the heating power is applied. Similarly, the junction starts to rapidly cool down when the heating power is removed. The speed of the temperature decrease is dependent on the initial junction temperature and the physical size of the active junction.

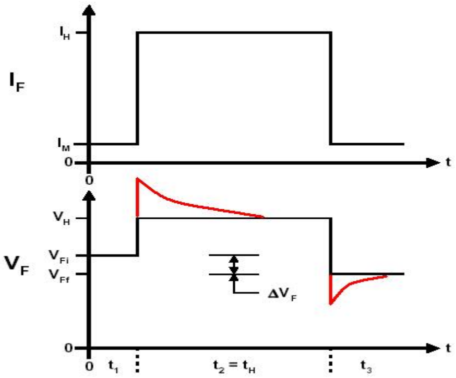


Figure 7 Actual Current and Voltage waveforms for diode thermal measurements.

The Cooling Curve, shown in Figure 8, is a tool for correcting the measured results for junction cooling effects. It is based on the exponential nature of junction cooling. When T_J (or some related parameter) is plotted on the logarithmic axis of a semi-log graph with Measurement Delay Time (t_{MD}) - defined as the time from cessation of applied heating power to the start of the TSP measurement - on the linear axis, the data should result in straight line with a negative slope. However, as shown in the graph below, until non-thermal switching effects (associated with test system limitation, DUT switching capabilities, and inductance in the test leads from the system to the DUT) are overcome, the curve declines at a steep non-exponential pace. Use of data taken in this range (up to 40 µs in the graph shown below) will lead to T_J and thermal resistance values considerably higher than real values.

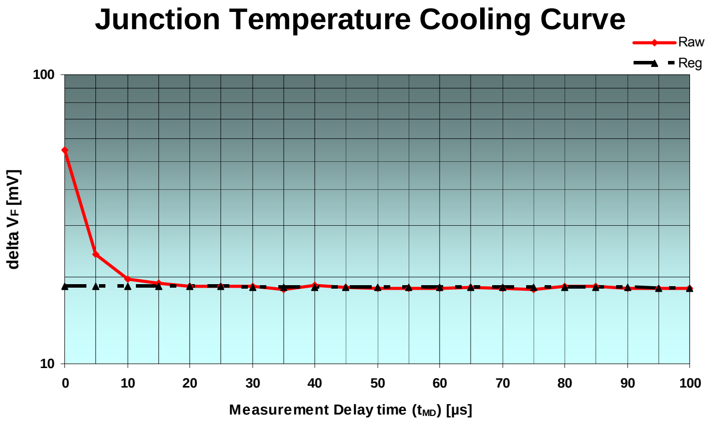


Figure 8 Cooling Curve

Once TSP data is taken as a function of different t_{MD} values and plotted on a semi-log graph, it should be reasonably obvious where the curve flattens out into a straight line. The t_{MD} value at this point or just beyond should be used for thermal resistance and T_J measurements.

The next step is to use the data from this t_{MD} point on to create a best-fit (regression) line and extrapolate that line back to the Y-axis. Then the Y-axis intercept point value (labeled 'a' on the graph) is divided by the t_{MD} value used for testing (referred to as 'b'; using 40 µs in this example). This ratio of a/b is used to correct the data for junction cooling effects.

The measurement data can be corrected in two ways. It can be manually corrected after data collection. Or it can be corrected automatically during the testing so that the final data reflects the correction. The easiest way to do this is by modifying the K Factor value. Then K' can be programmed into the thermal test system to yield corrected data values directly.

$$\theta_{JX} = \left[\frac{\left(\frac{a}{b}\right) \times K \times \Delta V_F}{I_H \times V_H} \right] = \left[\frac{K' \times \Delta V_F}{I_H \times V_H} \right] \qquad K' = \left(\frac{a}{b}\right) \times K$$

where - θ_{JX} is the thermal resistance for the defined test condition and environment

ΔV_F is the change in the TSP change (in this case diode forward voltage)

I_H is the applied heating current

V_H is the applied heating voltage

K is the K Factor

a/b is the junction cooling correction factor

K' is the modified K Factor to account for junction cooling

The correction factor should always be near 1.0 or higher because of the negative slope of the straight portion of the cooling curve. The magnitude of the correction factor depends on the thermal test system, the DUT, the test fixture and the inductance in the wires connecting the fixture to the system. Very small devices, such as laser diodes or microwave diodes with junction areas very small compared to the chip size, often have large values of correction factor.

When testing a batch of devices that are all the same physically and electrically, cooling curves and correction factors from a small sample of devices can typically be used to determine K' for the entire batch. When the cooling curve and correction factor varies significantly from device-to-device, it is necessary to determine and apply the correction factor for each device on a device by device basis.

Some thermal test systems, such as the TEA TTS-1000 series and TTS-4200 systems have an option for manual and automatic determination and application of the correction factor for each device tested.

5. Charge Dump

The measurement procedure described above works very well when the DUT is able to quickly switch from one current level to another. However, some devices have long minority carrier lifetimes that slow down the DUT switching speed. In this case it is often necessary to get rid of the charge stored in the DUT before attempting to make the V_{Ff} measurement. This is accomplished by reverse biasing the DUT for a short period of time; this operation is referred to as Charge Dump. The waveform of Figure 5 is modified, as shown in Figure 9, to reflect the inclusion of Charge Dump in the measurement procedure.

The best way to determine if Charge Dump is required is to perform a Cooling Curve test with and without Charge Dump enabled. The selection that produces the best curve is usually the one best suited for the device under test. If there is no difference between the two curves, then the diode has a very short minority carrier lifetime and Charge Dump is not necessary.

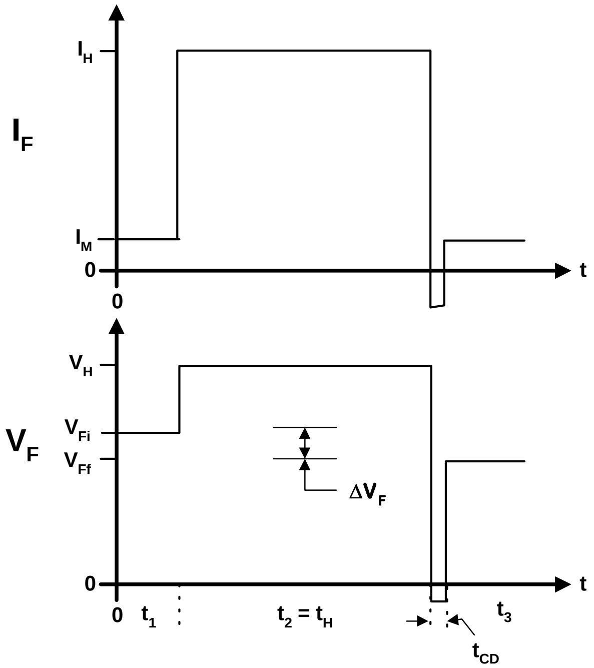


Figure 9 Charge Dump waveforms

6. Heating Power

As shown in Figure 6, the voltage across the DUT decreases as the device heats up. So the question arises as to how the heating power used in the thermal resistance equation is determined. Although the more precise value is the average power dissipated over the t_H period, usual practice is to use the voltage measured just prior (typically 10 to 15µs) to the removal of I_H. The resultant heating power value is a good approximation and deviates from the average power by a minimal amount, especially if the t_H is greater than one second for most devices.

The issue of actual P_H value is more critical when the DUT emits power during t_H. Examples of devices that emit power when activated are light emitting devices (such as LEDs and Laser Diodes) and various RF-generating devices (such as IMPATTS and Gunn devcies). If power emission from the DUT is significant, then a calculation of thermal resistance that does not take this into account will be in error.

$$\theta_{JX} = \left[\frac{\Delta T_J}{P_H} \right] = \left[\frac{\Delta T_J}{P_{Applied} - P_{Emitted}} \right]$$

Some commercially available thermal test systems (such as the TEA TTS-1000 series units) can automatically perform this correction for emitted power during the testing process. Data from thermal test systems that do not have this capability can be corrected as follows:

$$\theta_{JX}\big|_{Actual} = \theta_{JX}\big|_{Measured} \times \left[\frac{P_{Applied}}{P_{Applied} - P_{Emitted}} \right]$$

7. Environmental Conditions and Other Considerations

The measurement basics described above did not mention the DUT environment during the test. It is a combination of t_H and environment that dictates the type of measurement being made.

For example, a junction-to-case thermal resistance (θ_{JC}) measurement requires that the DUT case be held at a constant temperature and that t_H be long enough to insure that the heat generated at the DUT junction by the applied heating power (P_H) has had adequate time to propagate to the case outer surface. Typical values of t_H for most chip/package combinations are in the 0.1 to 10 second range; very small or very large packages may require less or more time, respectively. Allowing t_H to go on beyond the time for the heat to reach the package (or case) outer surface does not yield any further information for making a θ_{JC} measurement.

Similarly, at the other end of the t_H spectrum, a junction-to-ambient thermal resistance (θ_{JA}) measurement requires that the DUT case be enclosed in a standard insulated volume (one cubic foot) and that t_H be long enough to insure that the heat generated at the DUT junction by the applied heating power (P_H) has had adequate time to reach a steady-state condition within the volume. Typical values of t_H for most chip/package combinations are in the 1,000 to 3,000 second range; very small or very large packages may require less or more time, respectively. Using a t_H value less that for a steady-state condition will not produce the right thermal resistance results. Allowing t_H to go on beyond a steady state does not yield any further information for making a θ_{JA} measurement.

The composite Heating Curve in Figure 10 combines the results from several environmental conditions – natural convection (θ_{JA}), forced convection (θ_{JMA}) and heat sink or cold plate (θ_{JC}). A Heating Curve is a plot of a junction temperature related parameter versus the amount of time heat is being dissipated at the diode junction. All the data shown was made on the substrate isolation diode in a large, multi-lead

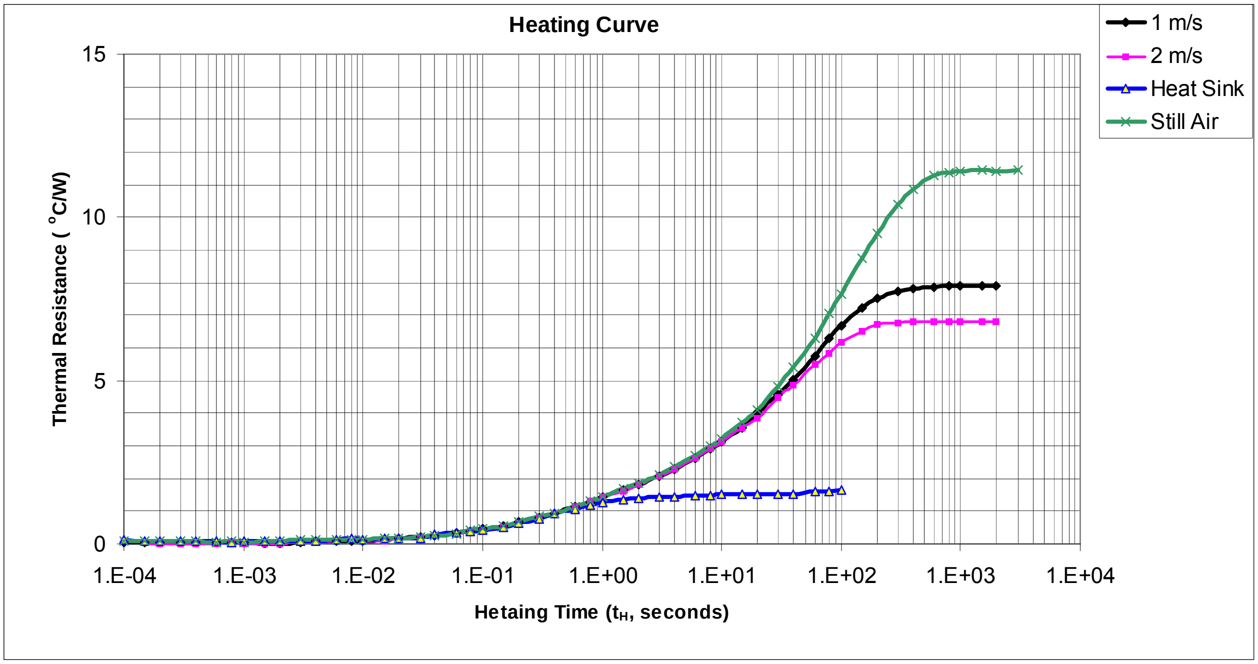


Figure 10 Composite Heating Curves

integrated circuit package. Note how the thermal test environment and t_H combination produces the different curves. The point at which each curve reaches a plateau produces the corresponding thermal resistance value.

The issue of thermal resistance measurement accuracy and repeatability always arises when discussing thermal data. The measurements can be very accurate, better than ±1%, and repeatable if the Heating Time is chosen to be less than that required for the heat to propagate to the package surfaces. However, once the heat has propagated beyond the package interface surfaces, the accuracy and the repeatability of the measurement are mostly dependent on the thermal environment.. In the latter case, accuracies of ±5% to ±10% are common.

About the Author

Bernie Siegal, founder and president of Thermal Engineering Associates, Inc. (TEA), has been actively involved in semiconductor thermal measurements for over 40 years. He has been the principal author of several Mil Std., SEMI and JEDEC standards and is currently an active participant of the EIA JEDEC JC15.1 subcommittee dealing with IC package thermal issues. He has developed thermal test systems for most commercially available semiconductor devices. He has authored over 40 technical articles, conducted numerous seminars and holds patents in various technical fields. Bernie is a co-founder of SEMI-THERM, Life Fellow of the IEEE, former chairman of the JEDEC JC15.1 thermal standards committee and is past chair of the Santa Clara Valley chapter of IEEE CPMT.

8. Symbols & Terms

Note: Temperature may be expressed in Kelvin (K) or centigrade (°C) units.

Symbol	Units	Description
ΔTSP		The change in the Temperature Sensitive Parameter; units dependent on parameter used
θ_{JA}	K/W	Junction-to-Ambient Thermal Resistance
θ_{JB}	K/W	Junction-to-Board Thermal Resistance
Ψ_{JB}	K/W	A thermal metric derived from the difference in junction temperature (T_J) and board temperature (T_B) divided by total heating power (P_H); applicable to arrayed-connection packages. The thermal environment must be specified.
θ_{JC}	K/W	Junction-to-Case Thermal Resistance
θ_{JCbot}	K/W	Junction-to-Case Thermal Resistance with heat flow through package bottom
θ_{JCtop}	K/W	Junction-to-Case Thermal Resistance with heat flow through package top
θ_{JF}	K/W	Junction-to-Fluid Thermal Resistance
θ_{JL}	K/W	Junction-to-Lead Thermal Resistance
Ψ_{JL}	K/W	A thermal metric derived from the difference in junction temperature (T_J) and lead temperature (T_L) divided by total heating power (P_H); applicable mostly to leaded device packages. The thermal environment must be specified.
θ_{JMA}	K/W	Junction-to-Moving Air Thermal Resistance
θ_{JR}	K/W	Junction-to-Reference Thermal Resistance
Ψ_{JT}	K/W	A thermal metric derived from the difference in junction temperature (T_J) and package top temperature (T_P) divided by total heating power (P_H). The thermal environment must be specified.
θ_{JX}	K/W	Junction-to-defined point (X) Thermal Resistance
ΔV_F	mV	The change in temperature sensing voltage due to the applied HEATING POWER to the device.
I_H	A	Heating Current
I_M	mA	Measurement Current
K	K/mV K/Ω	K Factor for diode sensor K Factor for resistive sensor
P_H	W	Heating Power
$R_{\theta JA}$	K/W	Junction-to-Ambient Thermal Resistance
$R_{\theta JC}$	K/W	Junction-to-Case Thermal Resistance
$R_{\theta JL}$	K/W	Junction-to-Lead Thermal Resistance
$R_{\theta JMA}$	K/W	Junction-to-Moving Air Thermal Resistance
$R_{\theta JR}$	K/W	Junction-to-Reference Thermal Resistance
$R_{\theta JX}$	K/W	Junction-to-defined point (X) Thermal Resistance
T_A	K	Ambient Temperature

Symbol	Units	Description
T_B	K	Board Temperature, measured on the board at the package long-side center
T_F	K	Fluid Temperature in immediate area of the package
t_H	s	Heating Time
t_{Hss}	s	Steady State Heating Time
T_J	K	Junction Temperature
ΔT_J	K	Junction Temperature Change
$T_{J(Peak)}$	K	Peak Junction Temperature; if multiple peaks, then term refers to the highest peak
T_L	K	Lead Temperature
t_{MD}	µs	Measurement Delay Time
T_T	K	The device package temperature; usually top-dead-center on the greatest exposed package surface
t_{SW}	µs	Sample Window Time
V_H	V	Heating Voltage
$Z_{\theta JX}$	K/W	Junction-to-defined point (X) Thermal Impedance