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Integrated Circuits Thermal Measurement Method - Electrical Test Method (Single Semiconductor Device)

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INTEGRATED CIRCUIT THERMAL MEASUREMENT METHOD - ELECTRICAL TEST METHOD

(SINGLE SEMICONDUCTOR DEVICE)

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1. INTRODUCTION

1.1 PURPOSE

The purpose of this test method is to define a standard Electrical Test Method (ETM) that can be used to determine the thermal characteristics of single integrated circuit devices housed in some form of electronic package. This method will provide a basis for comparison of different devices housed in the same electronic package or similar devices housed in different electronic packages. By virtue of the standardizing of all pertinent terms, this method also improves the communication and exchange of information relative to the thermal characteristics of electronic packages housing a single semiconductor device.

1.2 SCOPE

The measurement method described herein is equally applicable to both <u>thermal test die</u> and <u>active integrated circuit devices</u>. Thermal test die, consisting of a heat source and temperature sensor integrated into a semiconductor chip, are commonly used for package thermal characterization efforts, especially when one package is being compared to another. Integrated circuit devices, operating in an active mode that approximates intended applications, are used when specific application-oriented specification information is required.

The measurement is limited to a single die (either test die or active die) housed in a package intended for a single die.

1.3 RATIONALE

Increased requirements for semiconductor performance, reliability, quality, and lower cost have forced the need for knowledge of the semiconductor device junction temperature. However, without a well-defined standard methodology for making thermal measurements, it has become increasingly difficult to accurately determine junction temperature under actual operating and environmental conditions. Knowing the semiconductor device thermal resistance for a specific electronic package allows both the manufacturer and user to determine the junction temperature of the device.

Accurate and correct thermal measurements are difficult to make because of the many variables that impact the final results. Electrical considerations (such as power, voltage and current levels, input and output levels, etc.), environmental considerations (mounting configuration, surroundings, mounting methodology, etc.) and selection of the junction temperature sensor will directly affect the thermal measurement. It should also be noted that the thermal characteristics of any semiconductor device are not necessarily constant with temperature or power dissipation, thus requiring thermal measurements under conditions that approximate actual operation in the applications.

1.4 REFERENCES

The following documents are recommended reading for reference and test method standard description purposes:

Mil Std 883C Method 1012.1
Thermal Characteristics of Microelectronic Devices

SEMI Test Method #G43-87
Test Method, Junction-to-Case Thermal Resistance Measurements of Molded Plastic Packages

SEMI Test Method #G38-87
Still and Forced Air Junction-to-Ambient Thermal Resistance Measurements of Integrated Circuit Packages

SEMI Test Method #G42-88
Specification, Thermal Test Board Standardization for Measuring Junction- To-Ambient Thermal Resistance of Semiconductor Packages

SEMI Test Method #G30-88
Junction-to-Case Thermal Resistance Measurements of Ceramic Packages

SEMI Test Method #G32-86
SEMI Guideline for Unencapsulated Thermal Test Chip

SEMI Test Method #G46-88
Thermal Transient Testing for Die Attachment Evaluation of Integrated Circuits

EIA JEDEC EB-20
Accepted Practices for Making Microelectronic Device Thermal Characteristics Test

NIST Special Publication 400-86
Semiconductor Measurement Technology: ***Thermal Resistance Measurements***

1.5 DEFINITIONS

Refer to ANNEX A for a list of terminology and symbols applicable to this document.

2. MEASUREMENT BASICS

The thermal resistance of a semiconductor device is generally defined as:

$$R_{\theta JX} = \frac{T_J - T_X}{P_H} \qquad (1)$$

where $R_{\theta JX}$ = thermal resistance from device junction to the specific environment (alternative symbol is θ_{JX}) [°C/W]
T_J = device junction temperature in the steady state test condition [°C]
T_X = reference temperature for the specific environment [°C]
P_H = power dissipated in the device [W]

The device junction temperature in the test condition can be determined by:

$$T_J = T_{J0} + \Delta T_J \qquad (2)$$

where T_{J0} = initial device junction temperature before heater power is applied [°C]
ΔT_J = change in junction temperature due to heater power application [°C]

The Electrical Test Method (ETM), described herein, makes use of a temperature-sensitive parameter (TSP) to sense the change in temperature of the junction operating area due to the application of electrical power to the device-under-test (DUT). In equation terms,

$$\Delta T_J = K \times \Delta TSP \qquad (3)$$

where ΔTSP = change in temperature-sensitive parameter value [mV]
K = constant defining relationship between changes in T_J and TSP [°C/mV]

For many test environments, the test conditions can be arranged such that the specific environment temperature (T_X) is also the initial temperature of the device before the device is powered and that the specific environment temperature does not change during the test. Under those conditions, the equations simplify to:

$$R_{\theta JX} = \frac{\left[\Delta T_J\right]_X}{P_H} \qquad (4)$$

The units of thermal resistance are usually °C/W. It should be noted that the relationship between junction temperature change and power dissipation is usually linear over some specific range of conditions and may vary considerably at the extremes of device operation. The method itself is independent of the environment of the device under test (DUT), thus requiring careful and detailed attention to environmental conditions in order to assure that the test produces meaningful results.

There are two approaches to ETM implementation. The first, referred to as the Static Mode, applies heating power to the DUT on a continuous basis while monitoring the junction temperature through measurement of the temperature-sensitive parameter. This mode is most suitable for use with thermal test die and some active integrated circuit devices. The second approach, referred to as the Dynamic Mode, switches first from a temperature-sensitive parameter measurement condition, then to a heating condition during which power is applied to the DUT for a specific period of time, and then back to the measurement condition. This mode is needed for most active integrated circuit devices and is also suitable for most thermal test die. In both modes, the difference between the initial and final measurement conditions is directly related to the temperature rise caused by the application of power to the DUT for a specific period of time.

2.1 TEMPERATURE-SENSITIVE PARAMETER

The most commonly used temperature-sensitive parameter (TSP) is the voltage drop across a forward-biased diode. This diode is specifically designed into thermal test die and usually exists as a parasitic device (substrate isolation diode, input protection diode, output steering diode, etc.) in most integrated circuit devices. Other common methods of sensing temperature on an IC die include using the resistance shift with temperature of a metal-film resistor or diffused resistor.

2.1.1 MEASUREMENT CURRENT CONSIDERATIONS

The Measurement Current (I_M) through the temperature sensing diode must be large enough to obtain a reliable forward voltage reading not influenced by surface leakage effects but small enough not to cause significant self heating. The value of I_M is chosen to be in a range right around the knee of the diode's I-V curve, as shown in figure 1, and is usually in the 100 μA to 5 mA range, depending on the diode size. Lower values of current can be used, but for greatest ease in implementing the measurement and to eliminate potential surface leakage effects (which can result in significant non-temperature dependent variability between diodes of the same construction and size) the current is rarely chosen below 100 μA and is usually 1 mA. The upper limit on I_M is determined by self-heating effects, which in turn are a function of the diode geometry.

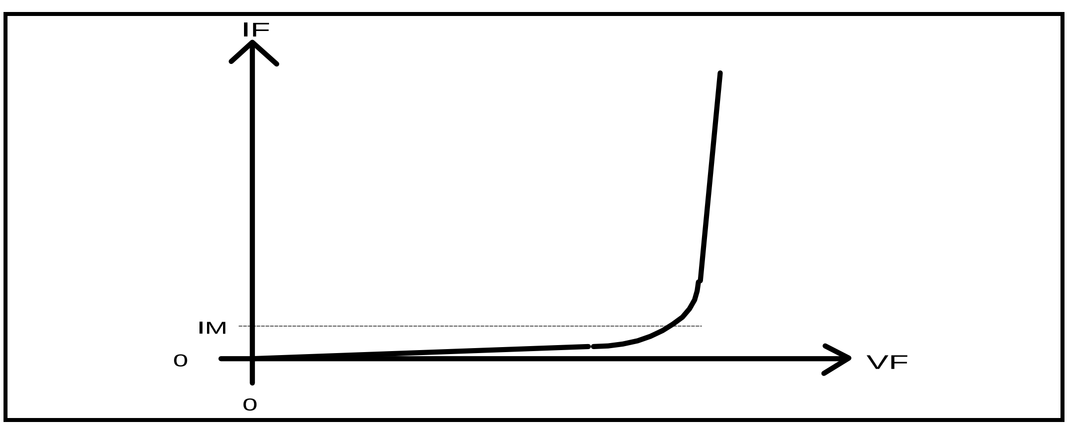

Figure 1. - I_M selection relative to typical diode I-V Curve

2.1.2 K FACTOR CALIBRATION

Once the proper value of I_M is selected, the relationship between the temperature sensing diode forward voltage and junction temperature is determined by performing a K FACTOR CALIBRATION. During this procedure, the diode is forward biased with I_M while inserted into a temperature-controlled environment. The forward voltage of the diode is recorded for two or more different equilibrium temperature conditions. Because I_M is specifically chosen not to cause significant self heating, the environment temperature and junction temperature are taken to be essentially the same.

Using the diode conduction equation, Equation 5 below, it can be shown[1,2] that for a fixed applied current (I_M in this case), the forward voltage will vary linearly with junction temperature. The saturation current (I_0) expression is given in Equation 6.

$$I = I_0\left(e^{(V/nV_T)} - 1\right) \qquad (5)$$

$$\mathbf{I_0 = MT^m e^{(-V_{G0}/nV_T)}} \qquad (6)$$

where $V_T = \left(\frac{k}{q}\right)T$

Taking the derivative of equation 5 with respect to temperature (dropping the unity term with respect to the exponential) and inserting the derivative of the logarithm of equation 6 into the first derivative, produces equation 7.

$$\frac{dV}{dT} = \frac{V}{T} - \frac{\left(V_{G0} + mnV_T\right)}{T} \qquad (7)$$

where k = Boltzmann constant
q = electronic charge
T = temperature in K

For silicon devices, n = 2 (usually in the range of 1 to 2), m = 1.5 and V_{G0} = 1.21 V. Thus, assuming an I_M value sufficient to make V equal 0.6 V at a junction temperature of 300 K, equation 7 yields:

$$\frac{dV}{dT} = 2.293\ mV/^{o}C$$

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[1] A.S. Grove, *Physics and Technology of Semiconductor Devices* , John Wiley & Sons., New York, 1967

[2] P.E. Gray & C.L. Searle, *ELECTRONIC PRINCIPLES: Physics, Models and Circuits* , John Wiley & Sons, Inc., New York, 1969

Note that the Kelvin has been replaced with degrees Celsius. On a differential basis, Kelvins and Celsius degrees are equal and the latter is more commonly used in the temperature range of interest for semiconductor devices. Further note that this K FACTOR value is based on a certain set of assumptions that are not valid for all diodes; a calibration must be performed for each specific device chip/package combination.

K FACTOR is the reciprocal of equation 7 and is usually expressed to at least three decimal places. The product of K and the difference in temperature-sensing voltage (referred to as ΔV_F) produces the device junction temperature rise:

$$\Delta T_J = K \times \Delta V_F \tag{8}$$

For most practical applications, the results of the above derivation suggest that a 'two-temperature point' K FACTOR calibration is sufficient for determining the K value. To minimize potential temperature and voltage measurement problems during the calibration, the temperature differential should be at least 50 °C to ensure a large enough voltage difference.

For die with resistive temperature detectors (RTDs) for temperature sensing, the temperature versus voltage calibration data should be fitted to a straight line or a second order polynomial to insure measurement accuracy, and this should be used for determining the temperature during the tests.

2.2 COOLING TIME CONSIDERATIONS

COOLING TIME considerations are NOT applicable to the Static Mode of testing because the monitoring of the temperature-sensitive parameter occurs on a continuous basis while the heating power is applied to the DUT.

The Dynamic Mode of the testing, in which the second measurement of the temperature-sensitive parameter is made very quickly after the removal of the heating conditions, requires that cooling of the junction between the removal of power and the completion of the second measurement be considered because of its impact on the resultant junction temperature calculation. The use of electronic switching allows the power turn-off-to-measurement completion time to be very short - in the tens of microseconds range - but the junction may cool down fast enough in this short time to render the resultant thermal resistance calculation in error by an unacceptable amount.

Figure 2 shows a COOLING CURVE generated by iterative testing of a single device within a lot with fixed heating conditions (voltage and time), fixed measurement current, and variable Measurement Delay Time (t_{MD}). The Heating Time (t_H) is chosen long enough to allow for reasonable junction heating but short enough not to allow package heating; the latter requirement ensures that environmental variations will not impact the results. The data parameter can be either a direct reading of the differential voltage (ΔV_F), the computed junction temperature rise (ΔT_J) or the computed Comparison Unit (CU). Thermal resistance ($R_{\theta JX}$ or θ_{JX}) is not usually used because these values are very low for short values of t_H. Note that, for very low values of t_{MD}, the curve shows a steep upward slope that corresponds to non-thermal switching transients due to one or more of the following reasons -- test system cannot switch fast enough to ensure an accurate voltage measurement, the device cannot switch fast enough due to excessive capacitance or other circuit problems, and significant inductance between the test system and the DUT.

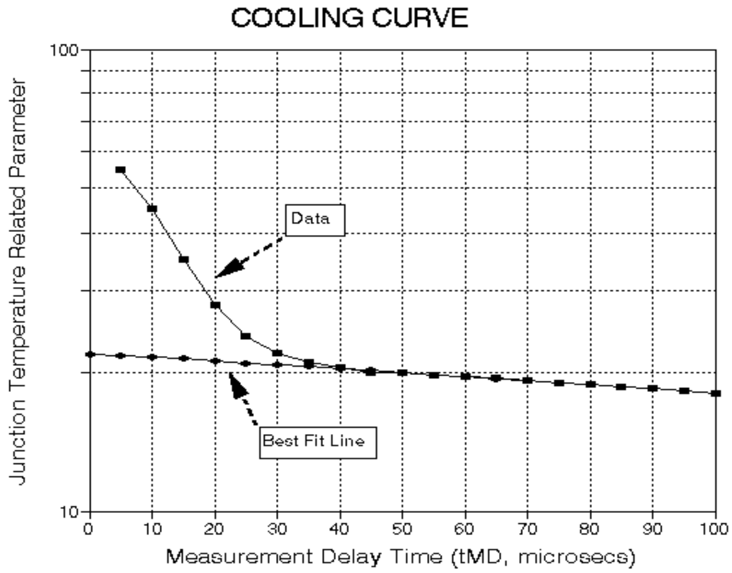

Figure 2. - Typical Cooling Curve showing actual data and best fit regression line

Usual practice when working with the Cooling Curve is to pick a point just after the break in the curve as the starting point for a best fit regression analysis for the succeeding data points. The slope of this line shows the junction cooling effects on the measured parameter as t_{MD} is increased. If this slope is very small (indicating that little cooling has occurred) then no data correction will be required. If, however, the slope is large enough to cause an unacceptable error, then the measured data will have to be corrected to take into account the cooling affects. The correction of the data for junction cooling is discussed in 3.4 and 3.5.

2.3 HEATING TIME CONSIDERATIONS

HEATING TIME considerations are applicable to both the Static and Dynamic Modes of testing.

In making thermal measurements, it is important to recognize that the heat generated at the junction requires a finite amount of time to propagate outward to the surrounding environment. Since thermal resistance is defined as a steady-state condition, it is necessary to wait the appropriate amount of time necessary for steady state to occur for the specific thermal resistance required. For example, depending on the package style, junction-to-ambient thermal resistance measurements may require thousands of seconds for steady state to occur while junction-to-case measurements may require only a few seconds. Because of this time dependence, establishing the proper t_H is critical for proper measurement of the thermal resistance under specific environmental conditions. Figure 3 shows a typical Heating Curve for a surface-mount integrated circuit package in a defined still-air environment.

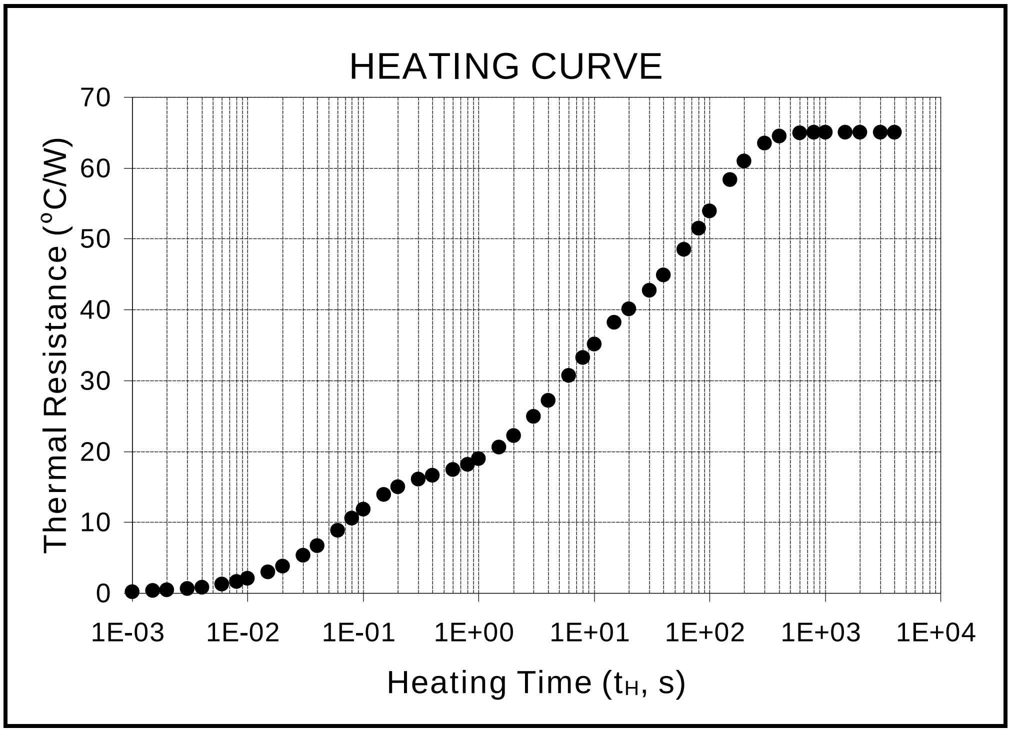

Figure 3. - Typical Heating Curve showing heating time-dependent thermal response

While most devices will produce heating curves similar to that of figure 3, it should be noted that very large packages may require considerably more time, and smaller packages somewhat less time. Further, not all package/environment variations will produce the pronounced plateau in the mid-range time frame -- this plateau is typically attributed to the heat capacitance of larger packages. As discussed in 3.6, proper heating time selection is a key part of test condition determination.

2.4 TEST WAVEFORMS

The basics of the measurement method described above are summarized with the three waveform figures below. For Static Mode, using the test connections shown in figure 8 for a Thermal Test Die, figure 4 shows the voltage across the heating element and the absolute magnitude voltage across the temperature sensing diode. (Note: the diode voltage is actually negative because the figure 8 circuit connects the diode anode to ground and the Measurement Current source pulls the diode cathode negative with respect to ground.) The temperature change is calculated from the difference between the initial voltage (V_{F0}) and the value at steady state (V_{Fss}) shown on the latter waveform. The Static Mode allows for continuous monitoring of the diode voltage without removal of the heating conditions. Heating Curves, showing junction temperature rise or thermal resistance as a function of time (see figure 3 for an example), can be generated by plotting the data collected from the start time t_0.

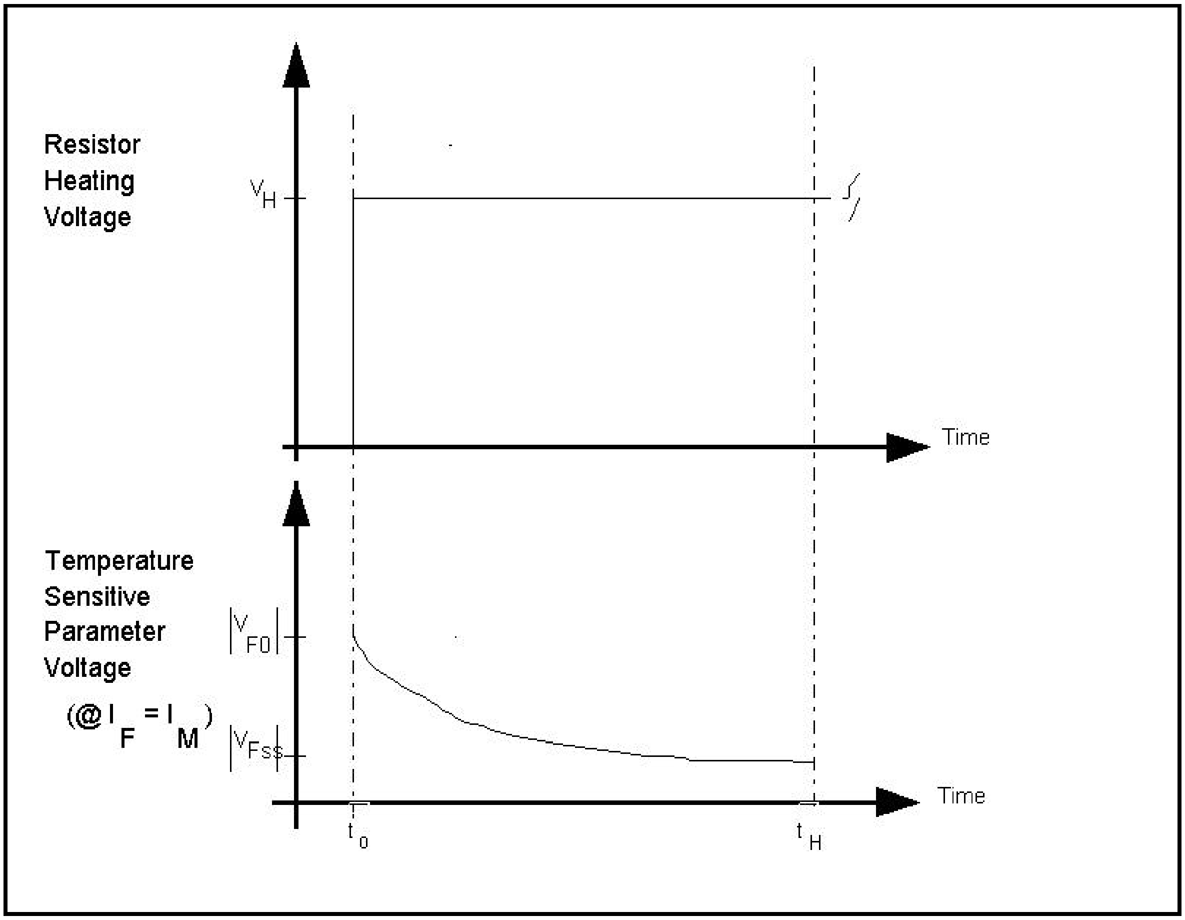

Figure 4. Static Mode Thermal Test Die test waveform (TSP voltage shown in absolute magnitude form, voltage is negative with respect to GND for fig. 8. connection circuit)

A similar waveform for the Active Die digital device Dynamic Mode test operation is shown in figure 5 (the connection configuration is shown in figure 9). This mode requires a three-step process: first, the measurement condition is applied during time t_1 and V_{F0} is measured; second, power is dissipated in the DUT during t_2 with the application of V_H and I_H is measured; third, the power is removed and the measurement condition again applied and V_{Fss} is measured. As in the prior discussion, the junction temperature change is calculated from the difference between V_{F0} and V_{Fss}. Heating Curves, as defined above, are generated from data collected from iterative tests or from cyclic testing. In the former case, a test is performed for a specific t_H data value and then subsequently repeated for each different value of t_H, allowing each time for the DUT to return to the initial test state before proceeding with the next test. This Heating Curve data collection process can be very lengthy, especially for t_H values of 1 000 seconds or more. In the latter case, the heating condition is turned off for a very brief period of time (1% or less of t_H) so that the measurement during the third step occurs at the desired data point t_H value. The heating condition is then quickly reapplied to minimize DUT cooling effects, and the test cycle proceeds to the next data point.

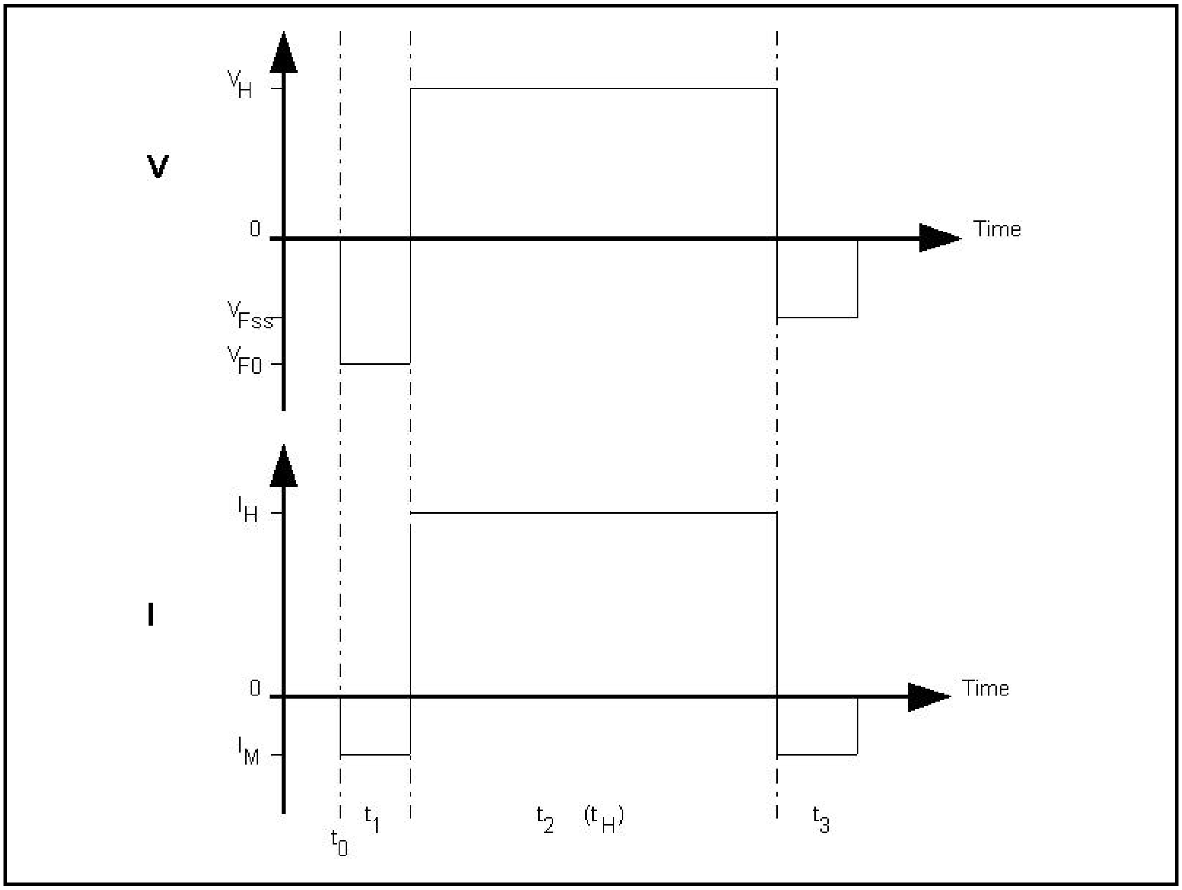

Figure 5. Dynamic Mode test waveform for typical Active Die digital device

The junction cooling effect that occurs whenever heating power is removed from the DUT is shown on an expanded time scale in figure 6. The Measurement Delay Time (t_{MD}) is the time from the start of Heating Power removal to the start of the V_{Fss} measurement. The Sample Window Time (t_{SW}) is the length of time used for making the V_{Fss} measurement, usually in the 5 to 10 µs range. If cooling proceeded long enough with the temperature of the environment remaining constant, the temperature-sensing voltage would eventually return to the V_{F0} value.

2.5 ENVIRONMENTAL CONSIDERATIONS

ENVIRONMENTAL considerations are applicable to both the Static and Dynamic Modes of testing.

Environmental considerations deal with how the device is mounted and the nature of the environment surrounding the mounted device. For example, junction-to-ambient thermal resistance ($R_{\theta JA}$ or θ_{JA}) measurements are made with the device mounted in defined manner inside a one cubic foot enclosure under still-air conditions. Similarly, some junction-to-case thermal resistance ($R_{\theta JC}$ or θ_{JC}) measurements require that the outside package surface immediately adjacent to the chip attachment be maintained at a defined isothermal temperature. These two thermal resistances represent the most commonly used reference environmental conditions for comparison of packages and devices and are reasonably well defined (see Environmental and Component Mounting documents that are part of this standard). However, these two "reference environment" conditions usually do not represent actual application of packaged devices, thus generating the need for other well-defined thermal test environments.

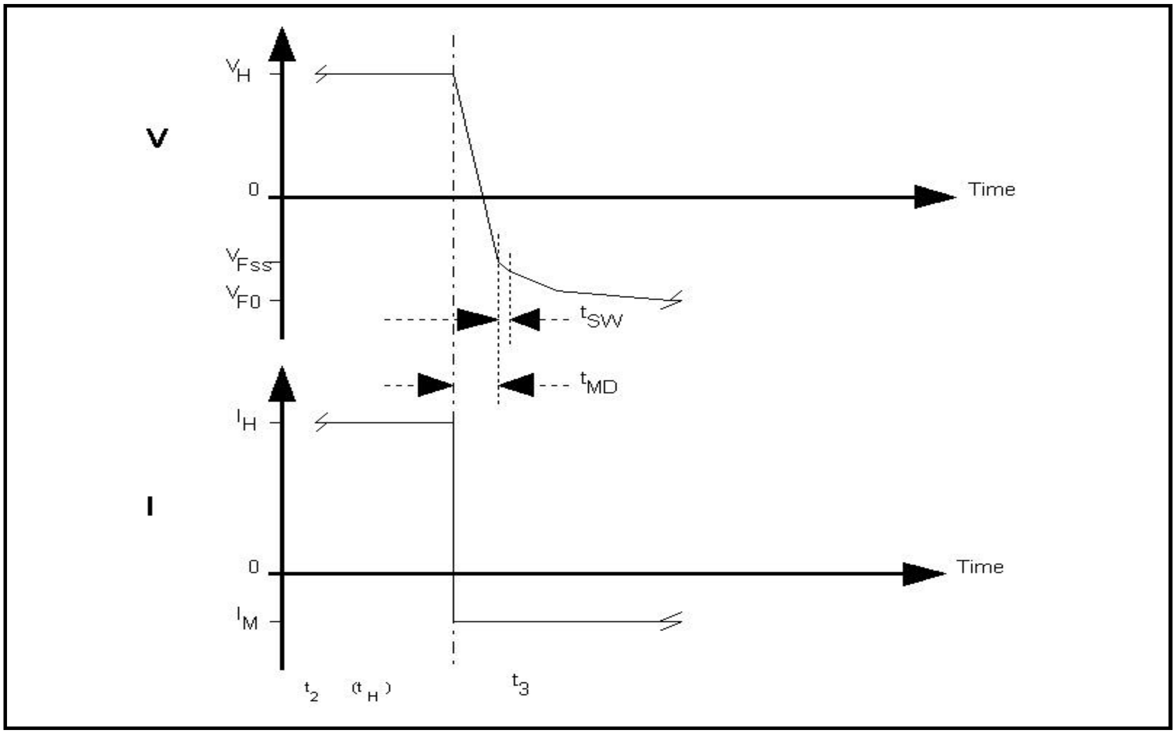

Figure 6. Expanded Dynamic Mode test waveform showing measurement times

2.6 TEST SETUP

The generic test setup shown in figure 7 is applicable to both the Static and Dynamic Modes of testing.

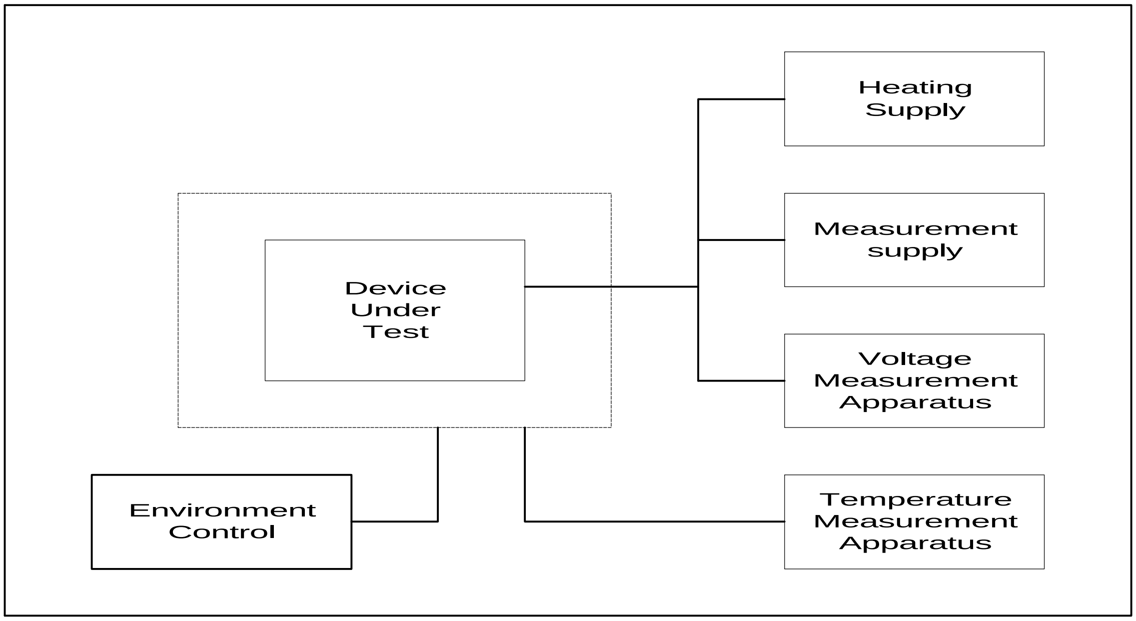

Figure 7. Generic thermal measurement test setup

The Heating Supply must be capable of applying the appropriate voltage and current to the DUT to cause sufficient Heating Power to be dissipated in the DUT during the t_H necessary for the desired specific data result. The Measurement Supply provides the necessary Measurement Current. The Voltage Measurement apparatus must have sufficient accuracy and resolution (0.5% or better and 0.5 mV or less, respectively) for measuring the TSP voltage. The Environment Control (air temperature, cold plate temperature, air velocity, etc.) must be able to maintain the thermal test environment to specified conditions during the course of the test. The Temperature Measurement apparatus monitors the thermal test environment during the course of the test; temperature is usually measured to 0.1 °C resolution with an accuracy of 1 °C or better.

3. MEASUREMENT PROCEDURE

3.1 Device Connection

Connection to the device-under-test (DUT) must take into account that the same device is used for both power dissipation (to cause the heating conditions) and voltage measurement (to sense the junction temperature). While relatively easy for Thermal Test Die (see 3.1.1 below), connection to an active die can be much more complicated (see 3.1.2 below). <u>The connection arrangements discussed below are equally applicable to both Static and Dynamic Modes of testing.</u>

3.1.1 Thermal Test Die

Thermal Test Die are specially designed to provide a uniform heating structure (i.e., a resistor or active device) for heating purposes and one or more small, strategically-placed diodes for temperature sensing. In conformance with SEMI #G32-86 and the Device Construction document that is part of the JEDEC thermal measurement standard, the total heating structure must occupy 85% or more of the total die surface. The resistor may be configured as a single unit or as two or more isolated resistors that together meet the surface coverage requirement. The latter structure is usually preferred because it provides greater flexibility in setting up the heating power supply for the desired power dissipation. If a single diode is built into the die, then it is usually placed in the center of the die. More complex Thermal Test Die may have a diode in the center with one or two others at the center of one or two sides and one located at a die corner. RTDs are an acceptable alternative to diodes for temperature sensing.

A typical Thermal Test Die measurement circuit is shown in figure 8. Usually one side of the resistor and one side of the diode are connected externally to circuit ground to simplify matters and to minimize measurement noise. Kelvin four-wire contacts are used to provide accurate forcing of the Heating Voltage. Kelvin connections may also be required for the temperature sensors if there is high series resistance (greater than 10 ohms for diode sensors) between the measurement equipment and the actual temperature sensor. Kelvin connections should always be used with RTDs.

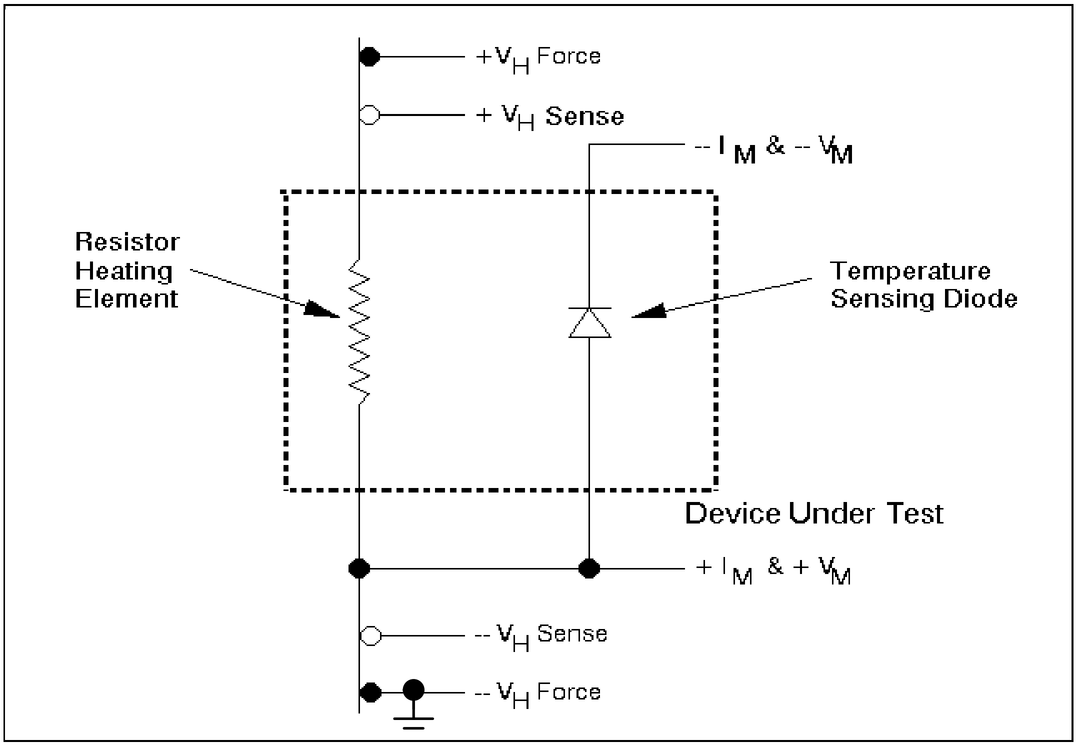

Figure 8. Typical Thermal Test Die schematic and test connection.

3.1.2 Active Die

The difficulty in using an Active Die lies in finding a way to configure the device for sufficient power dissipation in a manner that approximates actual application operating conditions without conflicting with the requirements of thermal test implementation.

Most digital devices can be made to dissipate sufficient power by connecting some combination of input and output leads either high (i.e., V_{IH} and V_{OH}, respectively; same voltage level as the supply voltage) or low (i.e., V_{IL} and V_{OL}, respectively; ground potential). Four-wire Kelvin contact is used on the power supply leads to ensure accurate forcing and measurement of the Heating Voltage. The connection circuit is shown conceptually in figure 9 for a digital device using the substrate isolation diode for temperature sensing. Some digital device die may require Reset and/or Clock pulses for proper internal setup, thus requiring additional connection circuitry. In this case, the additional circuitry must not affect the TSP measurement and, if powered by the Heating Voltage, must have its power dissipation accounted for in the data correction (see 3.5).

Analog devices, such as operational amplifiers, power amplifiers and simple voltage regulators, usually do not dissipate enough power in a quiescent state to make an accurate thermal measurement. These devices definitely require some load elements in their connection circuit to increase the internal power dissipation and to approximate an operating application condition. Figure 10 shows an operational amplifier configured for thermal testing. The substrate isolation diode is used for temperature sensing by switching the positive supply lead between the Heating Voltage supply and the Measurement Current supply. The circuit uses a steering diode to make sure the load is isolated when the most positive DUT lead is reverse-biased for access to the diode temperature sensor.

The thermal data resulting from the use of this connection circuit must be corrected to take into account the power dissipation in the load resistor (see 4.). To set the DUT's output voltage to some fixed value, the reference voltage to the positive input lead can be provided by suitable circuitry (other than tying it to V_H); if this circuitry is driven by the V_H supply, dissipation in this circuitry must also be accounted for in the data correction (see 4.). The same concepts described above can be applied to other analog devices and to mixed-signal (i.e., analog/digital combination) devices.

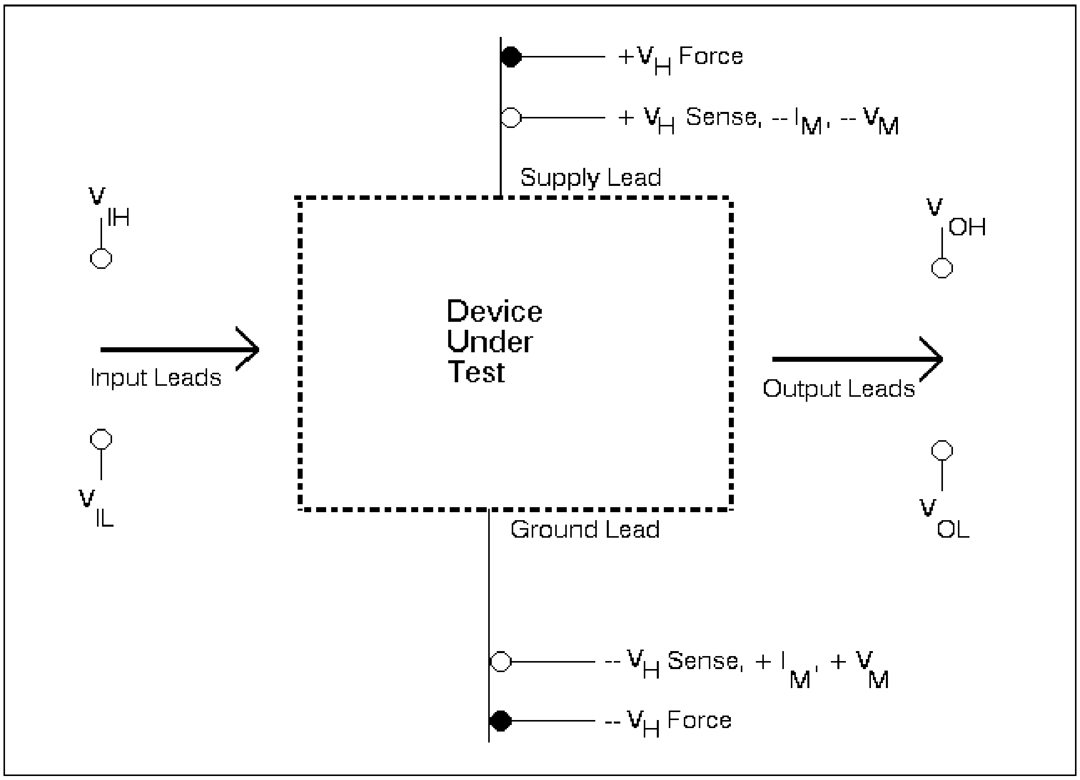

Figure 9. Conceptual connection circuit for thermal measurement of active die digital devices.

3.2 Measurement Current Determination

<u>The discussion below is equally applicable to both Static and Dynamic Modes of testing.</u>

Once the proper connection to the DUT has been determined, the next step is to select the appropriate value of Measurement Current (I_M) so that the forward-biased voltage across the diode connection established in 3.1 can be used as the temperature-sensitive parameter (TSP). As shown in figure 1, I_M is chosen around the knee of the I-V curve, typically in the range of 0.1 to 5 mA. A current in this range is chosen such that the TSP voltage a) linearly decreases with increasing junction temperature; b) does not cause significant self-heating of the TSP diode; and c) sufficiently turns on the diode so as to minimize surface leakage conduction effects. The exact value of I_M is not very critical but must be high enough to ensure that the diode is turned on. The current source used to supply I_M must be precise, as variations in current greater than 2% from the selected value will change the TSP characteristic. Measurement Current stability during the test must be better than 0.5%.

Further, especially in the case of the Dynamic Mode of testing, the current source must quickly respond to changing conditions surrounding the diode.

A more precise method for determining the optimum value of I_M consists of collecting diode voltage readings over a broad current range at two constant temperatures that encompass the temperature range of interest. The voltage data is then plotted against the log of current. The optimum value of I_M is then selected such that it resides on the linear portion of the two plotted constant-temperature curves.

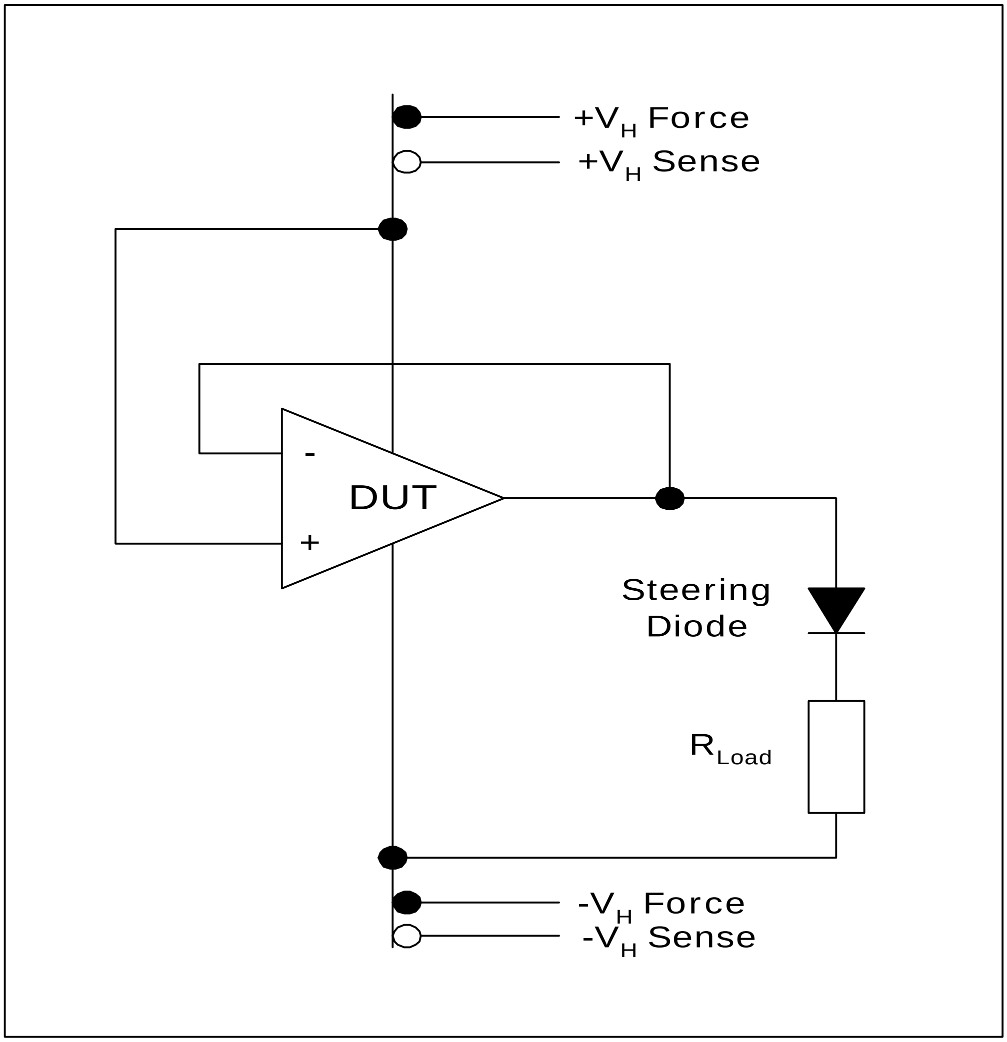

Figure 10. Conceptual connection circuit for thermal measurement of analog devices (operational amplifier) showing the use of a load resistor to increase internal DUT power dissipation.

3.3 K Factor Calibration

<u>The discussion below is equally applicable to both Static and Dynamic Modes of testing.</u>

The K Factor relates the changes in TSP voltage to changes in junction temperature (T_J). The relationship is determined by K Factor measurement (i.e., calibration). The calibration procedure consists of applying I_M to the DUT at a known fixed ambient temperature. Once the device case temperature has stabilized, indicating that temperature equilibrium has occurred, a voltage measurement is recorded to establish the first temperature point. Stability is defined as not more than 0.5 °C change during a five (5) minute interval. The ambient temperature is then raised to a new level and the process repeated. The difference between the two temperature values divided by the difference in recorded voltages produces the K Factor in units of °C/mV. This is shown graphically in figure 11 and in equation form below:

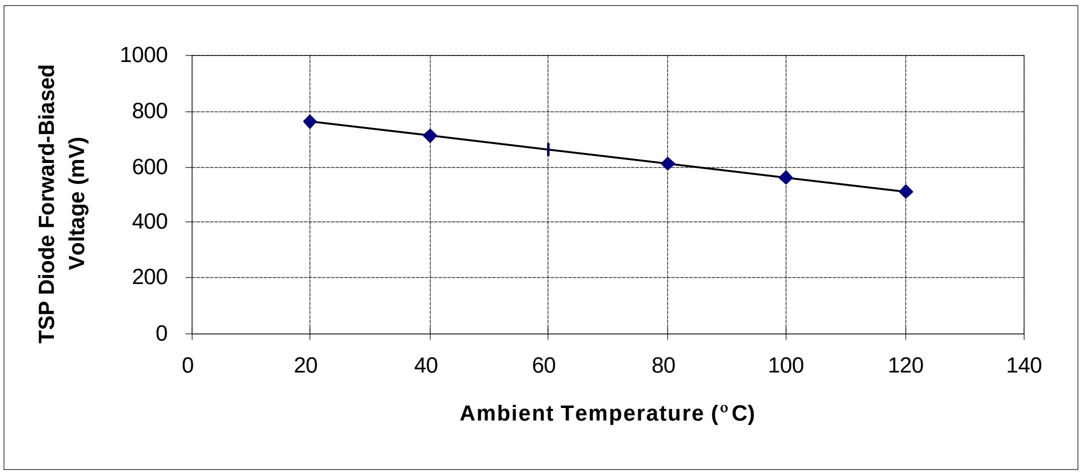

Figure 11. Typical V_F - T_A curve for temperature-sensing diode forward biased with I_M.

$$K = \left| \frac{(T_{Hi} - T_{Lo})}{(V_{Hi} - V_{Lo})} \right| \quad (9)$$

where T_{Hi} & T_{Lo} = High & Low temperatures [°C]
V_{Hi} & V_{Lo} = corresponding High & Low TSP voltages [mV]

There are several factors to consider when determining K Factor.

First, as stated previously, if the I_M value is chosen not to cause significant self-heating, the ambient temperature and junction temperature are essentially the same.

Second, since the TSP voltage offset caused by self-heating at the two different measurement points are nearly equal, taking the difference in voltage readings further reduces the effects of self heating.

Third, as long as there is good electrical contact to the diode connections, taking the difference between the two voltage readings virtually eliminates contact resistance problems without requiring Kelvin connections.

Fourth, the temperature points should be at least 50 °C apart to produce a voltage difference large enough to minimize voltage measurement problems.

Fifth, depending on the device technology and fabrication processes, some devices may exhibit a nonlinear voltage-temperature relationship. The linearity assumption must be verified before thermal testing commences.

For example, measurement at two points - one near room ambient temperature and the other near 100 °C - are sufficient for K Factor calibration. However, to detect a possible bad data point and to account for small nonlinearities in the TSP relationship, it is worthwhile to perform the calibration with smaller temperature increments of 20 to 25 °C; for example, room ambient temperature and approximately 50 °C, 75 °C and 100 °C. The resulting data then has to be analyzed to produce a best fit straight-line before an approximate K Factor value can be determined. The closeness of the straight-line fit will impact the accuracy of the thermal measurement. If a family of devices exhibits a more significant nonlinearity (greater than 1 °C deviation), then a more complicated approach involving additional data points and a polynomial fit is required (second order is generally sufficient). To simplify calibration, or if the nonlinearity in the V_F - T_J relationship is too extreme, it may be necessary to limit the Heating Power so the DUT's junction temperature never gets into the non-linear portion of the curve.

An equation for the Calibration Curve (figure 11) can be calculated such that the junction temperature can be directly determined from the TSP voltage.

The ambient temperature is usually established using either a liquid bath or a small oven. The bath setup is suitable for calibrating small numbers of hermetic devices, while the oven setup is better suited for handling a larger number of devices of either hermetic or non-hermetic construction. Because I_M is chosen not to cause any significant self-heating, the ambient temperature produced by either setup is essentially the same as the DUT junction temperature - any slight difference is virtually eliminated by using the difference between the voltages measured at the different temperature points. The temperature of the calibration environment must be measured at a surface of the device being calibrated.

A common practice, when measuring a large number of devices, is to calibrate 10 to 12 units of the same device/package-type at the same time. The average value of K ($\overline{K}$) and standard deviation (σ_K) are then calculated and the percentage ratio of the latter over the former computed. If σ_K is less than 3% of $\overline{K}$, then the $\overline{K}$ value is used for all the units within the group. However, if σ_K is greater than 3% of $\overline{K}$, then the individual values of K must be used for each respective unit.

3.4 Test Condition Determination

The discussion below is generally applicable to both Static and Dynamic Modes of testing.

3.4.1 Heating Conditions

Heating conditions are determined in one of two ways. Thermal test die units are usually tested at some pre-defined Heating Power (P_H) level for specific package thermal characterization efforts. Because thermal test die have known heating element resistance values, the Heating Voltage (V_H) required is computed as follows:

$$V_H = \sqrt{P_H \times R_H} \qquad (10)$$

where P_H = desired heating power [W]
R_H = thermal test die heating element resistance [Ω]

Because R_H may increase with temperature, it is necessary to monitor V_H and I_H and compute P_H to obtain accurate results.

Active die (i.e. not thermal test die) require a different approach to determining the heating conditions. The usual intent when testing a real device (i.e. real die mounted in a package) is to apply power to the DUT in a manner that approximates a "real life" application. Assuming that the DUT is properly connected (refer to 3.1), V_H is predetermined by the application that the device connection circuit is attempting to simulate. For example, a TTL-logic-level device normally operates with a supply voltage of 5 V. Thus, V_H is normally set to 5 V. On occasion, if the device connection circuit developed in 3.1 does not produce sufficient Heating Current (I_H), it may be necessary to either modify the connection circuit or to increase V_H to force the desired value of P_H. (Note: use caution in increasing V_H so as not to exceed the breakdown capabilities of the device.) The Heating Power is calculated as follows:

$$P_H = V_H \times I_H \qquad (11)$$

For either type of die (Thermal Test or Active), P_H must be large enough to cause the junction temperature to rise by a large amount (20 °C or more) to insure sufficient thermal measurement accuracy. Since thermal characteristics may vary with different P_H values, the actual applied power should not vary from device-to-device by more than five percent from the desired value of P_H.

3.4.2 Measurement Conditions

The discussion below is applicable to the Dynamic Modes of testing.

In addition to the proper choice of I_M for the measurement condition, the time from the removal of P_H to the start of the second TSP voltage measurement, referred to as the Measurement Delay Time (t_{MD}), must also be carefully determined. The best way to determine the proper value of t_{MD} is to collect thermal test data as a function of t_{MD} using a low value of Heating Time (t_H) in the 200 ms to 400 ms range and then plot a Cooling Curve similar to that shown in figure 2.

The proper t_{MD} value for making thermal measurements corresponds to the time just after the actual data curve and the best-fit straight line converge. However, unless the best-fit line has zero slope, using this time point for t_{MD} potentially causes an error due to junction cooling. The potential error is shown in figure 12. Point A, the best-fit straight-line Y-axis intercept value, corresponds to the "zero t_{MD}" value that would result if the second TSP measurement could be made immediately after the removal of P_H. If t_{MD} = 40 µs is the selected test condition, then the horizontal projection of this point to the Y-axis produces point B. The junction cooling error introduced by using a non-zero t_{MD} (i.e., 40 µs in this example) is represented by the ratio of the A value to the B value. If junction cooling were not a factor, then a zero-slope best-fit line would produce a ratio of one.

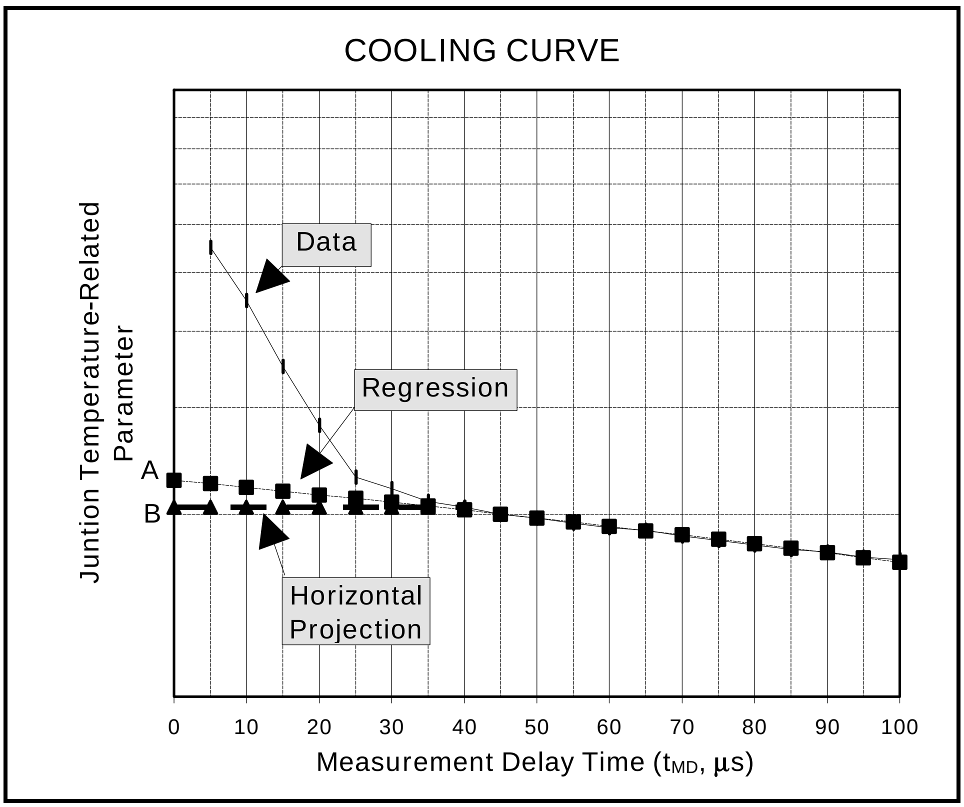

Figure 12. Cooling Curve Y-axis values for measurement error determination

3.5 Test Condition Correction

The discussion below is applicable to the Dynamic Mode of testing.

Thermal data are usually measured with accuracy in the 5% to 10% range because of difficulty in controlling the test setup and environmental conditions. One of the simpler errors that can be readily corrected is the one associated with junction cooling. Based on the discussion in 3.4, the measured value of thermal resistance ($R_{\theta JX}$ or θ_{JX}) can be corrected as follows:

$$[R_{\theta JX}]_{Actual} = [R_{\theta JX}]_{Reading} \times \left(\frac{A}{B}\right) \tag{12}$$

$$[\theta_{JX}]_{Actual} = [\theta_{JX}]_{Reading} \times \left(\frac{A}{B}\right)$$

where A = best-fit straight-line Y-axis intercept value
B = horizontal projection of chosen t_{MD} point

However, this approach to data correction requires all the thermal resistance data to be taken and then corrected afterwards - a two step process that requires extra work. The data can also be corrected as taken by modifying one of the terms in the thermal resistance equation shown below.

$$\begin{aligned}[R_{\theta JX}]_{Actual} = [\theta_{JX}]_{Actual} &= \left[\frac{\Delta V_F \times K}{V_H \times I_H}\right] \times \left(\frac{A}{B}\right) \\ &= \left[\frac{\Delta V_F}{V_H \times I_H}\right] \times \left[K \times \left(\frac{A}{B}\right)\right] \\ &= \left[\frac{\Delta V_F}{V_H \times I_H}\right] \times K'\end{aligned} \tag{13}$$

Thus, creation of K' allows the data to be corrected as taken, where K’ is the augmented K Factor described in section 3.3.

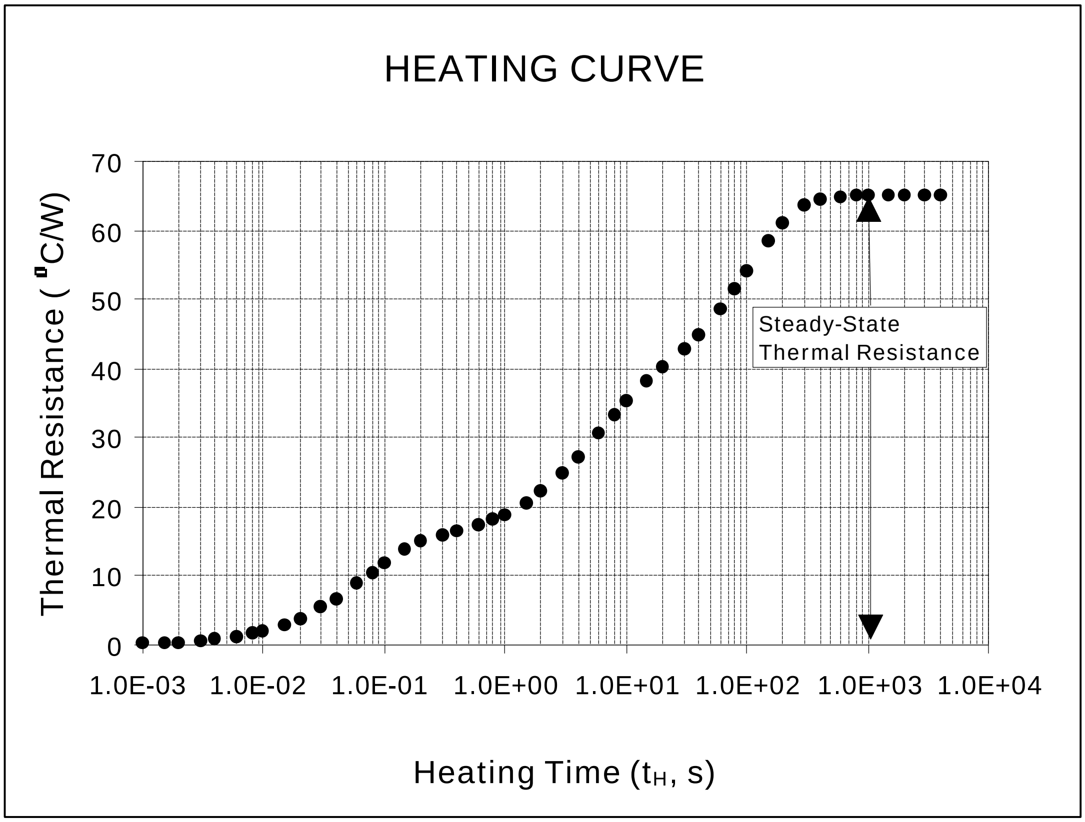

Figure 13. Example Heating Curve showing steady-state thermal resistance

3.6 Thermal Steady-State Determination

<u>The discussion below is applicable to both Static and Dynamic Modes of testing.</u>

Perhaps the most critical of all the thermal test conditions is the length of time that heat is applied to the DUT. Heat application for too short a time will produce a thermal parametric value that does not reflect the actual value for the specific environmental conditions. For example, applying the measurement to a 14-lead plastic DIP with Alloy 42 lead material in a still-air environment for 1 second, or even 500 seconds, will not produce a meaningful $R_{\theta JA}$ (θ_{Ja}) value. Similarly, under the same conditions, applying the measurement for 5 000 seconds will not improve the measurement but will require roughly three times longer than needed to make the measurement for $R_{\theta JA}$ (θ_{JA}).

The best way to determine the proper value of t_H for testing a given die/package combination under a specific set of test conditions (including environmental conditions) is to collect data for different values of t_H and then plot the data, as shown below in figure 13. For this example, it is clear from the Heating Curve that the onset of thermal steady-state (shown as θ_{JX} on the graph; X indicates an environment that must be defined) occurs at roughly 400 seconds; the curve then remains essentially flat all the way out to the end of the test. Thus, having collected the Heating Curve data for one or two units of a given die/package configuration, subsequent thermal steady-state testing of the same configuration units would require a single data point test with t_H set to roughly 1 000 seconds. The steps described in the figure 14 flow chart should be followed to ensure that the final thermal resistance value represents the steady-state condition.

If the test setup can not easily generate the Heating Curve, an alternative approach for determining when steady state has occurred is described by the flow chart in figure 14. The steady state determination process occurs in three steps. The first step occurs when the steady state condition appears to have been reached. Both the Heating Time and thermal resistance values are recorded for future comparisons. The second step occurs after the Heating Time has been increased by 10% and the new thermal resistance value is recorded. This value is then compared to the initial value and, if the specified condition below (in figure 14) is met, then the third step again increases the Heating Time by another 10%. At the end of the second increased time, the thermal resistance value is again recorded. If the specified condition below (in figure 14) is met, then steady state has occurred and the last thermal resistance value recorded is the desired value. The last time value becomes the Heating Time for steady state.

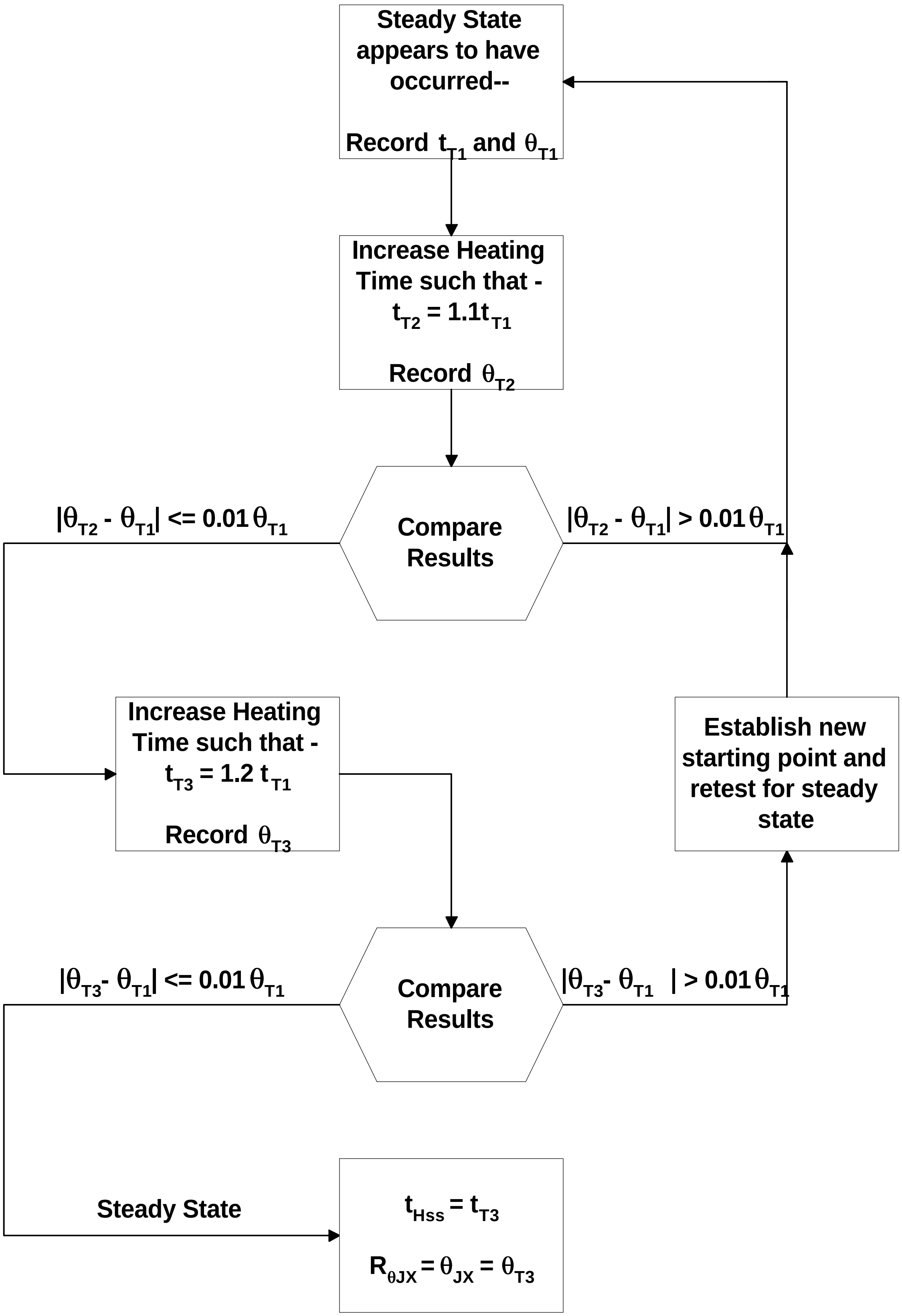

Figure 14. Flow chart of steps for determining steady-state thermal resistance

3.7 Data Validity

It is required that reported data per this document be based on five (5) or more sample units.

There are several conditions that can cause erroneous results. The following suggestions have been found effective for identifying erroneous test conditions or erroneous test results:

3.7.1 The accuracy of the junction temperature at the steady state or $R_{\theta JX}$ (θ_{JX}) condition is directly related to whether the initial temperature of the device is either unknown or whether the initial temperature of device is at T_X. It is very common for devices to be stored at a slightly different temperature than that of the test chamber or to be slightly warmed by the handling process when being placed into the test environment. Any temperature difference for the device from the expected temperature will introduce a corresponding error in the measured thermal resistance.

The most effective method to ensure that the device is at thermal equilibrium with T_X is to follow the same procedure as described in 3.6 above. The TSP is read until the device is at equilibrium with the reference temperature.

3.7.2 Changes in the environmental temperature or environmental conditions can cause erroneous results. The temperature should be monitored during the test to ensure that any changes occur slowly enough not to make the steady-state determination invalid. If the temperature changes more than specified in the environmental test specification, correction for that change must be made.

3.7.3 In some specific thermal environments, a thermocouple mounted on the DUT case is useful to validate the measurement data. For a given class of packages in a natural convection environment, the case temperatures will be slightly lower (1 to 20 °C is typical of many devices) than the junction temperature. The case temperature can then be used to identify questionable data for confirmation.

3.7.4 When using Thermal Test Die, measuring the thermal resistance of the device at two different power levels, with the same environmental conditions, is a useful technique to determine possible interactions between the heating power and the temperature-sensing technique. Any large changes in thermal resistance should be investigated.

3.7.5 It is recommended that a calibration standard (“golden unit”) be established for the purpose of measurement repeatability monitor and test setup disassembly checkout.

3.8 Test Condition Summary

Table 1 below summarizes the test condition parameters that must be selected for proper thermal measurements:

Table 1. Test Condition summary for both test modes

Parameter	Static Mode	Dynamic Mode
Heating Conditions		
Heating Power	P_H	P_H
Heating Voltage	V_H	V_H
Heating Time	t_{Hss}	t_{Hss}
Measurement Conditions		
Measurement Current	I_M	I_M
Measurement Delay Time	N/A	t_{MD}
K Factor	K	K'

4. DATA CORRECTION AND PRESENTATION

In the 3.4.1 discussion, all of the applied power to the DUT was assumed to be dissipated in the DUT. This is normally true for thermal test die DUTs but may not be true for most active die DUTs. If the device connection, as discussed in 3.1.2, requires external loading in order to get sufficient power into the DUT, then some of the apparent power applied to the DUT actually is being dissipated in the load elements. This also applies to connection circuitry that sets up the DUT input for the power and/or operational conditions. Unless corrected for, this situation will result in lower than actual thermal parameter data results.

Data correction consists of accounting for the applied power dissipated in the load (or any other power dissipating elements in the device connection circuit) as follows:

$$\left[R_{\theta JX}\right]_{\text{Actual}} = \left[R_{\theta JX}\right]_{\text{Reading}} \times \left(\frac{P_{\text{Total}}}{P_{\text{Total}} - P_{\text{Other}}}\right) \tag{14}$$

$$\left[\theta_{JX}\right]_{\text{Actual}} = \left[\theta_{JX}\right]_{\text{Reading}} \times \left(\frac{P_{\text{Total}}}{P_{\text{Total}} - P_{\text{Other}}}\right)$$

where P_{Total} = power supplied by test setup
P_{Other} = power dissipated by other elements in device connection circuit

The presentation of thermal parametric data must always be accompanied by a statement of all test conditions and environmental conditions for completeness; refer to table 2 below for information to be supplied with thermal data. The presentation of thermal data or thermal specifications is meaningless without this information.

Table 2. Thermal measurement test condition and data parameter summary.

Measurement Area	Condition Parameter(s)	Data Parameter(s)
Electrical	V_H (V) I_H (A, measured) t_{Hss} (s) I_M (mA) t_{MD} (µs) t_{SW} (µs) K (°C/mV) K' (°C/mV, if appropriate) Connection Circuit	ΔV_F (V) ΔT_J (°C) $R_{\theta JX}$ or θ_{JX} (°C/W) [X subscript defined by environment & mounting] P_H (W)
Environmental	Refer to appropriate document	Refer to appropriate document
Component Mounting	Refer to appropriate document	Refer to appropriate document
Device Construction	Refer to appropriate document	Refer to appropriate document

ANNEX A

DEFINITIONS

blackbody: a perfect radiator or emitter of infi-ared radiation.

chip attach: see DIE ATTACHMENT

cold plate: a heat absorber usually operating at some known or fixed temperature.

comparison unit: the ratio of temperature sensitive parameter change to dependent heating condition parameter; for an integrated circuit, ratio of change in temperature sensing diode forward junction voltage under measurement conditions to HEATING CURRENT - V_F/I_H. Allows for thermal comparison of one device to another when the HEATING VOLTAGE remains constant. Abbreviation is CU.

CU: see COMPARISON UNIT.

die attachment: see DIE BOND

die bond: the process or method of physically mounting a chip on a surface - package, substrate, header, etc.; also known as DIE ATTACHMENT or CHIP ATTACH.

DUT: Device-Under-Test.

emissivity: the ratio of the radiant energy emitted by a surface to that emitted by a blackbody at the same temperature.

heating current: a current supplied to device-under-test to cause the junction temperature to rise. Symbol is I_H.

heating power: the product of HEATING CURRENT and HEATING VOLTAGE; causing deviceunder-test junction temperature to rise. Symbol is P_H.

heating pulse width: the length of time electrical power is applied to the device-under-test to cause the junction temperature to rise. Symbol is t_H.

heating voltage: the voltage across the DUT during the application of HEATING CURRENT.
Symbol is V_H.

heat sink: an external object in contact with component package for purposes of removing heat from the component.

I_H: see HEATING CURRENT.

I_M: see MEASUREMENT CURRENT.

junction temperature: the temperature of the operating portion of a semiconductor device. Symbol is T_J.
K Factor: the quotient of junction temperature change to temperature sensitive parameter change in linear region of temperature sensitive parameter - temperature relationship.

K Factor calibration: the measurement and data reduction process that results in values of K factor for the semiconductor DUT.

measurement current: the current applied to the device-under-test during the measurement of the temperature sensitive parameter. Symbol is I_M.

measurement delay time: time from removal of heating conditions to the start of the measurement sample window. Symbol is t_{MD}.

peak junction temperature: the highest temperature on the semiconductor chip due to power dissipation internal to the semiconductor chip.

radiation: the transmission of heat via electromagnetic waves.

$R_{\theta JA}$: see THERMAL RESISTANCE, JUNCTION-TO-AMBIENT.

$R_{\theta JC}$: see THERMAL RESISTANCE, JUNCTION-TO-CASE.

$R_{\theta JL}$: see THERMAL RESISTANCE, JUNCTION-TO-LIQUID.

$R_{\theta JMA}$: see THERMAL RESISTANCE, JUNCTION-TO-MOVING AIR.

$R_{\theta JR}$: see THERMAL RESISTANCE, JUNCTION-TO-REFERENCE POINT.

$R_{\theta JX}$: see THERMAL RESISTANCE, JUNCTION-TO-DEFINED ENVIRONMENT.

sample window time: length of time during which the temperature sensitive parameter is measured after HEATING POWER is removed. Symbol is t_{SW}.

spatial resolution: the diameter of a spot whose size is determined from the half-power points resulting born a point infkared source.

Temperature-sensitive parameter: an electrical parameter of a semiconductor device that varies directly with junction temperature in a linear or very nearly linear fashion. Symbol is TSP.

thermal resistance: a measure of the steady-state heat flow from a point of higher temperature to a point of lower temperature, calculated by dividing the temperature difference by the power dissipated between the two points. Symbol is R_θ (alternative is θ).

thermal resistance, junction-to-ambient: the thermal resistance from the operating portion of a semiconductor device to a natural convection (still-air) environment surrounding the device. Symbol is $R_{\theta JA}$ (alternative θ_{JA}).

thermal resistance, junction-to-case: the thermal resistance from the operating portion of a semiconductor device to outside surface of the package (case) closest to the chip mounting area when that same surface is properly heat sunk so as to minimize temperature variation across that surface. Symbol is $R_{\theta JC}$ (akernative is θ_{JC}).

thermal resistance, junction-to-liquid: the thermal resistance from the operating portion of a semiconductor device to a liquid environment surrounding the device. Symbol is $R_{\theta JL}$ (alternative is θ_{JL}).

thermal resistance, junction-to-moving air: the thermal resistance horn the operating portion of a semiconductor device to a forced convection (moving-gas) environment surrounding the device; the gas is assumed to be air unless otherwise defined. Symbol is $R_{\theta JMA}$ (alternative is θ_{JMA}).

thermal resistance, junction-to-reference point: the thermal resistance from the operating portion of a semiconductor device to a defined reference point within the specified environment surrounding the device. Symbol is $R_{\theta JR}$ (alternative is θ_{JR}).

thermal resistance, junction-to-defined environment: the thermal resistance from the operating portion of a semiconductor device to a defied nonstandard environment surrounding the device. Symbol is $R_{\theta JX}$ (alternative is θ_{JX}).

thermal impedance: a measure of the transient heat flow restrictions from a point of high temperature to a point of lower temperature. Symbol is Z_{θ}.

t_H: See HEATING PULSE WIDTH.

t_{Hss}: Heating pulse width corresponding to a steady-state condition.

T_J: see JUNCTION TEMPERATURE.

$T_{J(Peak)}$: see PEAK JUNCTION TEMPERATURE.

t_{MD}: see MEASUREMENT DELAY TIME.

TSP: see TEMPERATURE-SENSITIVE PARAMETER.

t_{SW}: see SAMPLE WINDOW TIME.

ΔT_J: change in JUNCTION TEMPERATURE caused by application of P_H for t_H.

ΔV_F: change in forward voltage TSP caused by application of P_H for t_H.

$Z_{\theta JX}$: see THERMAL IMPEDANCE.

θ_{JA}: alternative symbol; see $R_{\theta JA}$

θ_{JC}: alternative symbol; see $R_{\theta JC}$

θ_{JL}: alternative symbol; see $R_{\theta JL}$

θ_{JMA}: alternative symbol; see $R_{\theta JMA}$

θ_{JR}: alternative symbol; see $R_{\theta JR}$

θ_{JX}: alternative symbol; see $R_{\theta JX}$