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

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ENGINEERING DEPARTMENT**



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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 thermal test die and active integrated circuit devices. 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:

$$R_{qJX} = \frac{T_J - T_X}{P_H} \quad (1)$$

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

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

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

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

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,

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

where ΔTSP = change in temperature-sensitive parameter value [mV]
 K = constant defining relationship between changes in T_J and TSP [$^{\circ}\text{C}/\text{mV}$]

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:

$$R_{qJX} = \frac{[\Delta T_J]_X}{P_H} \quad (4)$$

The units of thermal resistance are usually $^{\circ}\text{C}/\text{W}$. 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 μ A 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 μ A 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.

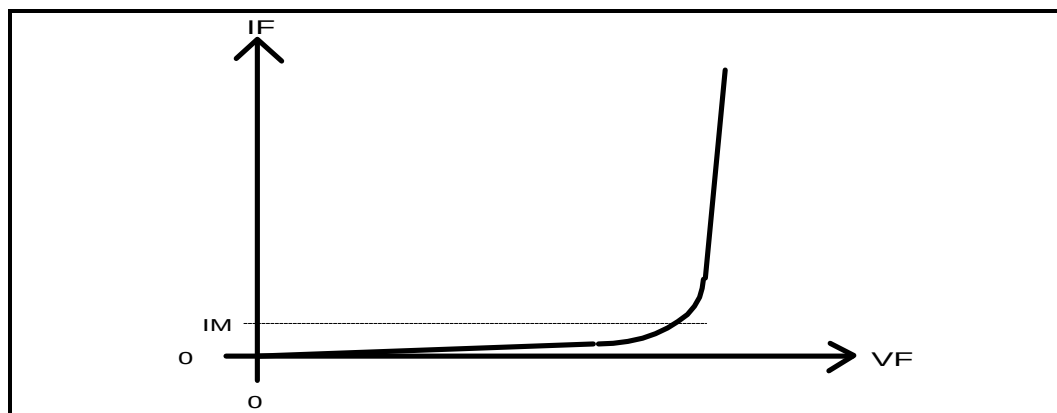


Figure 1. - I_M selection relative to typical diode I-V Curve

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.

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

$$I_0 = M T^m e^{(-V_{G0}/nV_T)} \quad (6)$$

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

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.

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

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:

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

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

²P.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:

$$\Delta T_J = K \times \Delta V_F \quad (8)$$

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.