Elements of device thermal characterization

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The increased power dissipation of today's integrated circuits has made knowledge of thermal resistance important to those who manufacture and use these devices. Thermal resistance is a device (i.e. semiconductor chip mounted in a package) parameter that is used to calculate junction temperature if the device power dissipation is known or can be estimated. This parameter is a measure of heat flow from the chip junction to some defined point under specific environmental conditions. The measurement of thermal resistance is simplistic in concept but difficult in practice.

The first step in thermal resistance measurements requires careful consideration of how the junction temperature will be determined. While there are several methods available - infra-red, liquid crystal, electrical parameter, for example - only the Electrical Test Method (ETM) is truly practical for most device manufacturers and users. This method relies on the fact that a temperature sensitive electrical parameter can be found for the device that provides a direct correlation to the device junction temperature. Unlike other methods, the ETM does not require any special modification to the device and can be performed on the device in its final form by making electrical connection to its leads. The simplest and most common parameter used for temperature sensing within a device is the junction voltage across a diode forward-biased with a low value of current. This voltage will usually vary linearly with temperature over a range suitable for making thermal resistance measurements and is very repeatable.

In a typical IC, there are many diodes suitable for temperature sensing but not all of them are accessible through the device leads. Normally, the only available diodes are input protection diodes used to overcome potential ESD problems; output parasitic diodes that occur between output stages, etc., and the substrate isolation diodes that separate the various circuit elements from each other because they are back-biased during normal device operation. The latter diodes are activated whenever the device is reverse-biased with a small current; these diodes are collectively the 'diode' most commonly used to implement temperature sensing for the ETM. Although a collection of individual diodes, thinking of the collection as a single "diode" is a good approximation for most applications. Because all the diodes are associated with individual isolation wells for the elements of the IC circuit, those diodes associated with the heat producing elements on the chip will become the hottest and, hence, will have the lowest forward voltage across the device leads and provides a good estimate of the highest junction temperature internal to the chip. When deciding on the proper temperature sensor, one must keep in mind that some IC chip designs use an on-chip substrate bias generator to bias the substrate below ground level; these chips usually require either special measurement circuitry to access the substrate isolation 'diode' or the use of a different diode for temperature sensing.

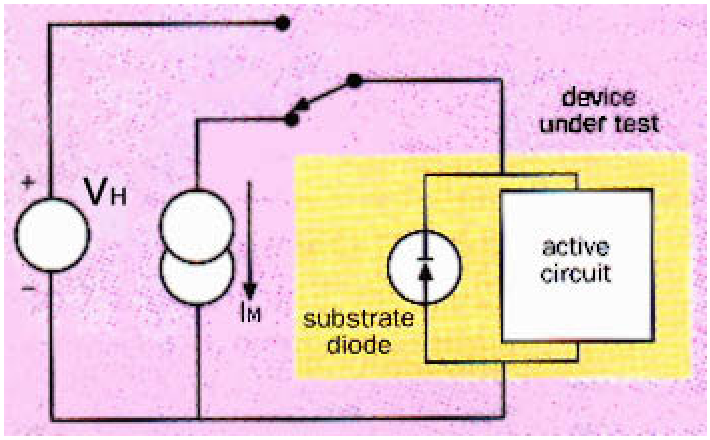

Figure 1: Simplified circuit for ETM thermal measurement. Active circuit is the chip when normally biased.

The circuitry for implementing the ETM is conceptually very simple, as shown in Figure 1. The measurement procedure consists of first obtaining the initial temperature sensing diode junction voltage by reverse biasing the device with a low current (referred to as measurement current, I_M) which forward-biases the diode. Next, power is applied to the device-under-test (DUT) with a voltage (referred to as Heating Voltage, V_H) applies in a normal manner to the DUT and the current (referred to as Heating Current, I_H) measured. Lastly, the heating conditions are removed and the initial measurement conditions reapplied to produce a new diode voltage. The waveforms for this three-step operation are shown in Figure 2.

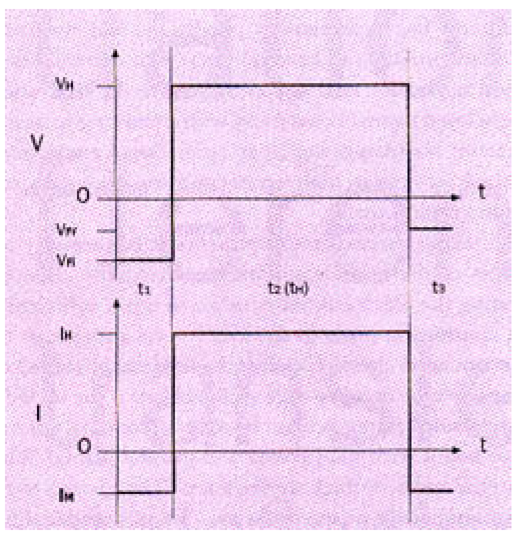

Figure 2: Conceptual waveforms for ETM circuit shown in Fig.1.

Thermal resistance is defined a s the change in temperature (junction temperature in this case) divided by the power dissipation that caused the temperature change. (Note: the term "resistance" is used for the steady state condition; "impedance" is use for the time-variant case.) From the data collection steps described above, thermal resistance (θ_{jx}) is calculated as show in Figure 3.

$$\theta_{jx} = \left[\frac{\Delta T_j}{P_H}\right] = \left[\frac{K\,(V_{Fi} - V_{Ff})}{(V_H)\,(I_H)}\right]$$

where

θ_{JX}	is the thermal resistance from device junction to some defined reference point X, in °C/W.
P_H	is the heating power, in watts
K	is relational constant between the sensing diode junction voltage and junction temperature, in °C/mV
Fi	is the initial diode junction voltage, in mV
V_{Ff}	is the final diode junction voltage, in mV
V_H	is the applied heating voltage, in volts
I_H	is the measured heating current, in amperes

Figure 3: Calculating Thermal Resistance θ_{jx}

With the basics of the ETM thermal resistance measurements described, the next important area of concern is the meaning of the "X" subscript. This is the area that causes most problems when making the measurements or reporting the results. Insufficient attention to this measurement area often results in inaccurate, non-repeatable and, in some cases, meaningless results. This area is so important that the EIA JEDEC (Electronic Industries Association Joint Electron Device Engineering Council) has a subcommittee (JC15.1) devoted to thermal characterization and modeling of electronic component packages. This subcommittee recently released two standard test method ballot proposals, one for the ETM and the other for a natural convection environment, that are awaiting formal approval before being released to industry.

From a practical point-of-view, the two 'X' conditions that define typical application extremes are the enclosed natural convection environment (still air inside a one cubic foot enclosure with a defined mounting for the DUT) and the forced conduction environment (intimate thermal contact to infinite heat sink). The former environment defines a θ_{JA} measurement conditions and the latter a θ_{JC} measurement condition. In between these two extremes lie most of the practical application environments found in the electronics industry: non-enclosed natural convection with mounting to a multi-layer printed circuit board; moving air in an enclosed environment; and non-infinite heat sinks in high temperature environments, to name a few common environments.

When making thermal measurements, it is necessary to define every aspect of the conditions that produced the collected data. Merely listing the electrical test conditions is not sufficient. How is electrical connection made to the DUT - via a socket or mounted directly to a printed circuit board? If the former, what kind of socket - a production-type or a test-type socket? How is the socket mounted - to single-sided printed circuit board with minimal trace sizes or a multi-layer board with solid power and ground planes? What is the board material and how thick are the traces? The answers to these and other environmental-type questions must be answered and fully documented to make the thermal data repeatable, comparable and meaningful.

Thermal measurements also require careful attention to the amount of time that power is applied to the device. Heat generated in the chip's various junctions takes a finite amount of time to propagate from the junction to the environment surrounding the device. A θ_{JA} measurement can take several thousand seconds before a suitable steady-state condition occurs. Similarly, θ_{JC} measurements typically require only seconds or tens of seconds to reach steady state. Improper selection of Heating Time (t_H) can produce data that does not accurately reflect desired results.

Another matter of concern is that thermal resistance can not be considered constant even if all the environmental conditions remain constant. When making thermal measurements on active devices, as compared to specially designed thermal test die which contain a resistive heater and a diode temperature sensor, the power dissipation, the location of the heat sources internal to the chip and the size of these heat sources, will vary with the applied electrical conditions. CMOS-type digital devices dissipate power primarily when making a transition form one logic state to another. Thus, the power dissipation is a function of the rate that the transitions occur (i.e. clock frequency). However, merely specifying the clock frequency used during a thermal measurement is not sufficient. The status of the device's other leads must also be specified because how inputs are configured and how output are loaded also affects the power dissipation and the where the heat is being internally generated.

One must always keep in mind that thermal measurements are more difficult to perform correctly than might be initially apparent. Close attention to detail and documentation of the detail, is necessary to provide thermal data that are accurate, repeatable, comparable, and meaningful.

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