AN1570

Basic Semiconductor Thermal Measurement

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INTRODUCTION

This paper will provide the reader with a basic understanding of power semiconductor thermal parameters, how they are measured, and how they are used. With this knowledge, the reader will be able to better describe power semiconductors and answer many common questions relating to their power handling capability.

This paper will cover the following key topics.

- Understanding basic semiconductor thermal parameters.
- Semiconductor thermal test equipment.
- Thermal parameter test procedures.
- Using thermal parameters to solve often asked thermal questions.

UNDERSTANDING BASIC SEMICONDUCTOR THERMAL PARAMETERS

Heat flows from a higher to a lower temperature region. The quantity that resists or impedes this flow of heat energy is called thermal resistance or thermal impedance.

When the quantity of heat being generated by a device is equal to the quantity of heat being removed from it, a steady state condition is achieved.

To describe the thermal capability of a device, several key parameters and terms are used. They describe the steady state thermal capability of a power semiconductor device.

Key Parameters, Terms, and Definitions

T_J = *junction* temperature
T_C = *case* temperature
T_A = *ambient* temperature
TSP = **T**emperature **S**ensitive **P**arameter
T_R = *reference* temperature (i.e., *case* or *ambient*)
$R_{\theta JR}$ = junction–to–*reference* thermal resistance
$R_{\theta JC}$ = junction–to–*case* thermal resistance
$R_{\theta JA}$ = junction–to–*ambient* thermal resistance
$R_{\theta JR(t)}$ = junction–to–*reference* transient thermal resistance
P_D = power dissipation

The thermal behavior of a device can be described, for practical purposes, by an electrical equivalent circuit. This circuit consists of a resistor–capacitor network as shown in Figure 1.

Resistors R1, R2, and R3 are all analogous to individual thermal resistance, or quantities that impede heat flow.

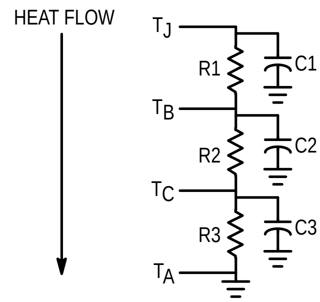

Figure 1. Thermal Electrical Equivalent Circuit

Heat generated in a device's junction flows from a higher temperature region through each resistor–capacitor pair to a lower temperature region.

Resistor R1 is the thermal resistance from the device's junction to its die–bond. Resistor R2 is the thermal resistance from the die–bond to the device's case. Resistor R3 is the thermal resistance from the device's case to ambient. The thermal resistance from the junction to some reference point is equal to the sum of the individual resistors between the two points. For instance, the thermal resistance $R_{\theta JC}$ from junction–to–case is equal to the sum of resistors R1 and R2. The thermal resistance $R_{\theta JA}$ from junction–to–ambient, therefore, is equal to the sum of resistors R1, R2 and R3.

The capacitors shown help model the transient thermal response of the circuit. When heat is instantaneously applied and or generated, there is a charging effect that takes place. This response follows an RC time constant determined by the resistor–capacitor thermal network. Thermal resistance, at a given time, is called transient thermal resistance, $R_{\theta JR(t)}$.

To further understand transient thermal response, refer to Motorola Application Note AN569, "Transient Thermal Resistance — General Data And Its Use." [4] A detailed discussion of this will not be included here.

Using the key parameters and terms shown earlier, only a few equations are necessary to solve often asked thermal questions.

$$R_{\theta JR} = (T_J - T_R) / \text{power} \quad (1)$$

$$P_D = (\text{max. device temperature} - T_R) / R_{\theta JR} \quad (2)$$

$$T_J = P_D * R_{\theta JR} + T_R \quad (3)$$

SEMICONDUCTOR THERMAL TEST EQUIPMENT

The procedure used determines the test equipment needed for measurement. Below you will find the equipment used for both a manual and an automated approach to thermal measurement.

Manual technique:

Power supply	*(supplies power to the device under test)*
Thermocouple	*(measures T_R)*
Multimeter	*(measures current and voltage)*
Heat exchanger	*(needed to mount device to and remove heat)*
Chiller	*(needed to remove heat from device)*
Test fixture	*(provides power and sampling pulse train)*

Automated systems available:

Analysis Tech	*(Phase 6, 7, 8, and 9)*
Sage	*(Star 150)*
TESEC	*(DV240)*

The automated systems shown above each provide different levels of automation. Analysis Tech has the most complete automation and TESEC the least. One nice feature of the Analysis Tech system is that it will output the 3 resistor–capacitor values for the electrical equivalent circuit. These values are very useful for modeling the thermal effects in computer simulation software such as SPICE. The level of automation you need depends both on your thermal measurement goals and available budget.

The main advantages of an automated approach are:

- Ease of use
- Less operator dependence on measurement
- Consistency
- Accuracy
- System network capability for data transfer

THERMAL PARAMETER TEST PROCEDURE

The basic procedure for measuring thermal parameters is as follows:

1) Calibrate the TSP (Temperature Sensitive Parameter).
2) Apply continuous power and TSP sampling pulses.
3) Measure T_J, T_R, and applied test power.
4) Calculate thermal resistance, $R_{\theta J(R)}$, and Maximum Power, P_D.

Calibrating the TSP, Temperature Sensitive Parameter

Since it is basically impossible to put a physical thermometer onto a device's junction to measure its temperature while under power, we must find another approach. Fortunately, we can use the device's forward junction voltage to tell us its temperature. The forward voltage drop of a diode's pn junction has a very linear relationship with temperature. We can use this relationship to tell us what the junction temperature is under any power condition.

To determine the actual voltage temperature relationship of a TSP for a given device, simply calibrate the TSP at a constant sense current over temperature as shown in Figure 2. The TSP sense current used should be small so as to not cause additional heating during calibration.

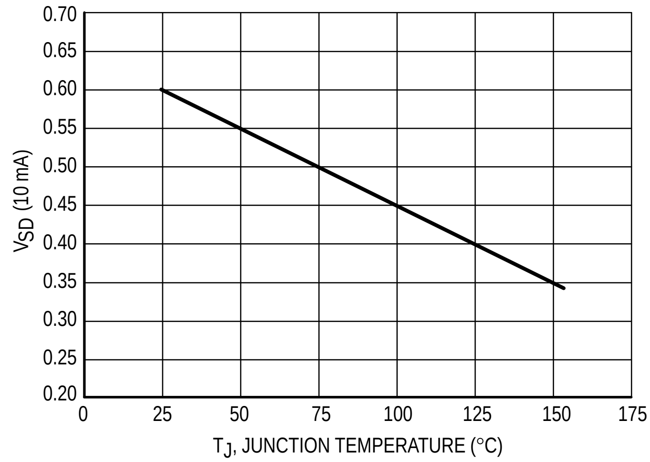

Figure 2. Typical Temperature Calibration Curve for a TMOS™ Body Diode

The forward voltage drop of a MOSFET body diode decreases linearly over temperature at rate of about 2 mili volts per degree Celsius when measured at a sense current of 10 mA.

Other device electrical parameters have similar linear relationships to temperature as well. The following are several other temperature sensitive parameters used in the industry to determine a device's junction temperature.

Common TSP	Device Type
V_{th}, $V_{DS(on)}$, $R_{DS(on)}$	MOSFET
V_{th}, $V_{CE(s)}$	IGBT
V_{BE}, $V_{CE(s)}$	Bipolar
V_F	Diode

Make sure to develop the actual electrical to thermal correlation of the TSP and check it for linearity prior to its use. The linearity of this parameter is critical for accurate thermal measurement.

Applying Continuous Power and TSP Sampling Pulses

With a properly chosen and calibrated TSP, we can now provide test signals to the device and make thermal measurements.

We begin by applying a continuous power of known current and voltage to the device. A continuous train of sampling pulses monitors the TSP, and thus the junction temperature. The TSP sampling pulse must provide a sense current equal to that used during calibration. While monitoring the TSP, adjust the applied power so as to insure a sufficient rise in T_J. Adjusting the applied power to achieve a T_J rise of about 100° above the reference temperature will generate enough temperature delta to insure good measurement resolution.

The TSP sample time must be very short so as to not allow for any appreciable cooling of the junction prior to re–applying power. The power and sample pulse train shown in Figure 3 has a duty cycle of 99.9% which for all practical purposes is considered continuous power.

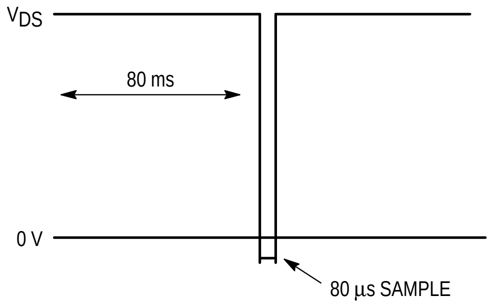

Figure 3. Example of a Power and Sample Pulse Train During $R_{\theta JC}$ Measurement of a TMOS Device

A continuous pulse train consisting of an 80 ms power pulse followed by an 80 µs diode sample is used to apply both power to the device as well as a sample pulse for TSP measurement.

Obviously, with this much power being applied to the device under test, the device's case will get very hot. To keep the device cool while under test, we need to mount it to a heat sink of some sort. A heat exchanger with chilled water flowing through it provides a good heat sink. In this way, we can keep the device's case temperature down (i.e., near 25°C) and maintain good measurement resolution (i.e., large temperature delta between the junction and reference location).

Measuring T_J, T_R, and Applied Power

After T_J has stabilized, we must record its value along with the reference temperature, T_R, and applied power. To calculate the devices maximum power rating, P_D, and thermal resistance, $R_{\theta JR}$, we need to have these measurements.

The devices junction temperature, T_J, is taken from the TSP electrical measurement. With the correlation between the TSP electrical measurement and temperature already established, determining T_J is pretty much straightforward.

A thermocouple placed at the reference location measures the reference temperature, T_R. Most power semiconductor manufacturer's use the devices' case, however, the lead, ambient, or all three can be used as reference locations.

Key elements to insure accurate reference temperature measurement are:

- Good thermocouple to reference contact
- Consistent thermocouple placement location

The reference thermocouple needs to make a good thermal contact to its reference location. This applies to reference locations other than ambient. Without a good thermal contact, measurement error will occur. To improve this contact, use both thermal grease and device clamping pressure.

Use thermal grease to insure good thermal conductivity and to eliminate air gaps. Applying thermal grease between the device and the heat sink used to keep the case temperature near 25°C will help in two ways. First, it will help keep the case temperature down during measurement by improving the thermal contact to the heat sink. Second, it will also improve the thermocouple to case contact as well. As stated earlier, the case is usually used as the reference location for thermal measurements. Thermal grease helps to maintain good thermal contact and insure measurement accuracy.

Applying about 85 to 90 PSI between the thermocouple and the reference location (i.e., device's case) also improves the thermal contact as shown in Figure 4. The application of pressure to the device seems to smooth out thermal grease thickness variations and eliminate air gaps at the contact interface.

Taking these precautions into consideration will help insure a good thermal contact to the reference location surface (i.e., device case).

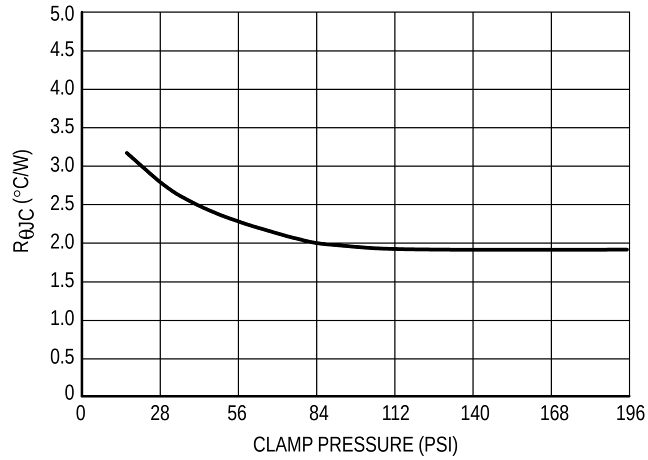

Figure 4. $R_{\theta JC}$ versus Clamp Pressure

The value of measured thermal resistance drops and becomes consistent at about 85–90 PSI insuring good thermal contact between the thermal couple and the devices case. [1]

The reference thermocouple needs to be placed at the same location for every device. Any change in the placement of this thermocouple will result in error or at the very least inconsistencies between measurements. A different thermal resistance exists between the junction and the location of each thermocouple placement. Usually for the best readings, the reference thermocouple should be placed at the hottest location on the package (i.e. for TO–220 devices, at the center of the die on the back side of the devices metal case). In any event, to be accurate and consistent, always place the reference thermocouple in the same location for each device measured.

Calculating Thermal Resistance, $R_{\theta J(R)}$, and Maximum Power, P_D

We can use equations (1) and (2) presented earlier, along with our measurements, to calculate the devices thermal resistance and maximum power capability.

Assuming we measured the following: T_J = 100°C, applied test power = 50 W, T_C = 25°C, and maximum device temperature rating = 150°C, we use equation (1) to calculate $R_{\theta JC}$.

$$R_{\theta JC} = (100 - 25)/50$$
$$= 1.5°C/W \text{ (measured value)}$$

Most manufacturer's will guardband the measured $R_{\theta JR}$ reading to establish their device limits. This helps take into consideration all of the variables involved which cause inconsistencies in readings. A guardband of 25% for thermal measurements is considered good practice.

Multiplying the measured thermal resistance from above by 1.25 to guardband it by 25%, we get the following specified $R_{\theta JC}$.

$R_{\theta JC}$ = 1.5 * 1.25
= 1.9°C/W (manufacturer's guaranteed limit)

As shown in Figure 5, the thermal resistance from junction to case is largely dependent on the die size of the device. This implies that silicon has a much larger thermal resistance, or opposition to heat flow, than that of the copper header to which it is bonded to.

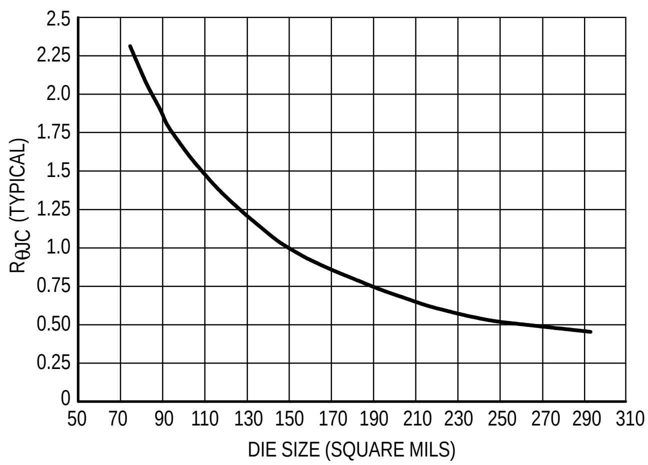

Figure 5. $R_{\theta JC}$ versus Die Size for TMOS™ Devices in TO–220, D^2PAK, DPAK & TO–247 Packages

To determine a devices power handling capability, P_D, we use the specified $R_{\theta JC}$ taken from above along with equation (2).

P_D = (150 – 25)/1.9
= 66 W (manufacturer's guaranteed limit)

USING THERMAL PARAMETERS TO SOLVE OFTEN ASKED THERMAL QUESTIONS

One can use measured or specified thermal parameters to solve many common questions asked about power semiconductor devices. The two examples shown below use thermal parameters to solve frequently asked questions.

Example #1

Calculate the device's junction temperature: Using equation (3) with a known $R_{\theta JC}$ of 1.25°C/W, case temperature of 85°, and applied power of 35 W.

T_J = 35 * 1.25 + 85
= 128.8°C

Example #2

Calculate the power handling capability: Using equation (2) with a known $R_{\theta JC}$ of 1.0°C/W, a starting case temperature of 75°C and a maximum rated T_J of 150°C.

P_D = (150 – 75)/1.0
= 75 W

SUMMARY

This paper presents a description of basic semiconductor thermal measurement as well as the use of thermal data in real world examples. Included are terms, definitions, equations and test equipment required. This provides the reader with information useful in answering many common questions regarding the basic thermal capabilities of power semiconductor devices.

REFERENCES

[1] Billings, Dave. 1992, "Thermal Performance of the TO–218 Fullpak MJF10012 under Force Loading," Motorola Semiconductor Products Sector.
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