DIODES INCORPORATED | DISCRETE ANALOG LOGIC

Understanding Semiconductor Thermal Resistance Data

Siva Uppuluri, Applications Engineer

April, 2016

Semiconductor devices are not perfect - all diodes and transistors are characterized by power losses due to switching and conduction. Switching losses occur during the interval between the on- and off-states of a junction, when there is both a voltage across the device terminals and a current flowing through it. Conduction losses are due to the device's internal resistance that, no matter how low it is, will result in a power loss when a current is flowing. Even in the off-state, losses due to transistor leakage currents can be significant in devices such as microprocessors that have to use small geometry processes in order to pack millions of transistors into a single integrated circuit.

Whatever the cause, losses in semiconductor devices generate heat that has to be dissipated if the junction temperature is to be kept within acceptable limits for correct device operation. The packaging of semiconductor devices further complicates the means by which heat can be dissipated so it is important to understand the various processes involved and the way in which thermal information is provided in device datasheets.

This article will look at the mechanisms by which heat is normally dissipated, aiming to understand in what way these apply to semiconductor devices and in turn how the semiconductor manufacturers specify the thermal performance of their products. The inaccuracies that can arise from using the thermal information provided in the datasheet will be highlighted along with an alternate method of determining the key junction temperature of a device.

Mechanisms for Heat Dissipation

There are three basic mechanisms by which heat is dissipated from an electronic device: conduction, convection and radiation. For a packaged semiconductor device the majority of the heat will be transferred by conduction: from the heat source at the device's core through the semiconductor substrate, the lead frame to which the chip is attached, and through the molding material that encapsulates the device to its external surface. At this point heat may be further transferred by conduction through any solid material the device is in contact with, e.g. a printed circuit board or an external heatsink.

Convection is defined as the transfer of heat via a fluid, which may be a liquid or gas, as in the surrounding air. This is the mechanism that then largely accounts for the remaining heat dissipation to the surrounding ambient environment. Radiant heat transfer is rarely a significant mechanism for heat transfer in electronics and is complex to calculate because it not only depends on temperature difference but also by the distance between objects and factors such as the color and texture of surfaces.

Although effective heat transfer from source to ambient is the aim, it is more usual to determine heat dissipation by considering the inverse of heat flow, namely the thermal resistance between those points. Typically this figure will be made up from the thermal resistances between the end-points and one or more intermediate points, depending on the heat transfer mechanisms and the materials involved.

Semiconductor manufacturers provide thermal resistance values for packaged devices as a design aid to help determine their power handling capability. Normally given as a junction-to-ambient thermal

© Diodes Incorporated 2016

resistance, this figure is intended to allow calculation of the amount of power that can be safely dissipated inside a device without raising its junction temperature (Tj) above its specified maximum. For example, for a device operating in an ambient temperature (Ta) of 25°C that has a junction-to-ambient thermal resistance, Rth (JA), of 150°C /W with a specified maximum junction temperature, Tj, of 150°C, the maximum power (Pmax) can be calculated using the following formula:

Pmax = (Tj (max) – Ta)/Rth (JA) = (150-25)/150 = 0.83W

Note: This assumes the device is mounted under the same conditions for which Rth(JA) is defined in the datasheet.

Conversely from this formula, Tj can be calculated by knowing the power being dissipated inside the device and the Rth (JA) and Ta values.

Sometimes manufacturers will provide alternative or additional thermal resistance values, which can be used in a similar way to calculate the operating junction temperature. These might include the junction-to-case (top of the package) value, Rth (JC), and the junction-to-lead value (junction to the soldering point of the lead frame), Rth(JL) – see figure 1.

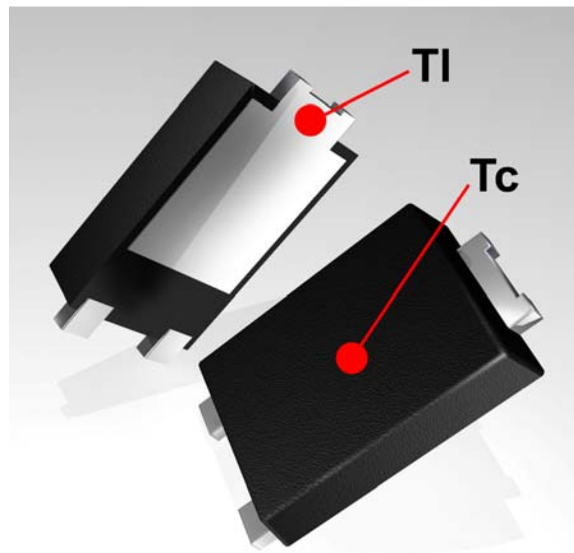

Figure 1. A PowerDI5® package showing the temperature measurement points for Tc (case temperature) and Tl (lead temperature)

Trying to measure the thermal resistance of a specific heat flow path like junction-to-case or junction-to-lead is complicated by the fact that the power dissipated at the semiconductor junction leaves the package through a number of parallel heat flow paths. Each of these has a specific thermal resistance whose value depends on the dimensions and the thermal conductivity of that path. Consequently a meaningful thermal resistance figure depends on 1) how accurately temperatures at the junction and case (or lead) can be measured and also 2) determining the fraction of the total heat generated at the semiconductor junction that is flowing between the junction and the measurement point (i.e., either the top of the case or the lead).

PowerDI is a registered trademark of Diodes Incorporated.

© Diodes Incorporated 2016

In practice, obtaining accurate temperatures at the required measurement points is difficult, even using non-contact infrared instruments. Instead, one of the following JEDEC (JESD51-12) standard methods may be used to determine thermal resistance values for Rth (JC) or Rth (JL).

Method 1: Rth(JX_ϴ)

This method aims to determine the thermal resistance of a heat flow path between the junction and a specific point of interest, 'X', which could be the top of the package, a soldering point, etc. Method 1 assumes that all the power dissipated at the junction is forced through the point of interest using an effective heat sinking arrangement at point 'X'. Then with an accurate measurement of temperature at that point (Tx) the true thermal resistance can be calculated as:

Rth(JX_ϴ) = (Tj –Tx) / P

Where P is the dissipated power (heat) that flows from the junction to the point 'X'. Ideally, during this measurement, close to 100% of the power should flow from the junction to the point 'X'. This figure depends only on the physical properties of the heat flow path and is independent of the amount of power dissipated or the size of board the device is mounted on.

The junction-to-lead thermal resistance values provided by Diodes Incorporated in its datasheets are measured using Method 1. The value is independent of board size and so helps compare the thermal performance of the lead frames of various packages.

Method 2: Rth(JX_ψ)

This method provides a thermal characterization parameter, which should not to be confused with thermal resistance. It is calculated using an equation similar to that used in method 1:

Rth(JX_ψ) = (Tj –Tx) / P

With this method, because no additional heat sinking arrangement is used to divert most of the generated heat through the path of interest, the total dissipated power value is used in the calculation instead of the fraction that is flowing between Junction and point 'X'. This results in a lower absolute value for Rth(JX_ψ).

The junction-to-case thermal resistance values provided by Diodes Incorporated in its datasheets are measured using Method 2, which is why subsequently in this article Rth(JC) will, more correctly, be referred to as ψth(JC).

Determining the junction temperature (Tj):

Accurately determining the junction temperature (Tj) of a device using Rth(JA), Rth(JL) or ψth(JC) depends on being able to measure ambient, lead or case temperatures under ideal datasheet conditions. In reality, a device will often be mounted on a circuit board crowded with other devices and components; also the amount of copper connected to the lead frame tab may not match the datasheet's conditions, limiting the usefulness of these parameters as discussed below:

Charts 1 to 3, measured on a PowerDI package (as shown in figure 1), show the relationship between junction temperature and ψth(JC), Rth(JL) and Rth(JA) respectively, under the different heatsink

© Diodes Incorporated 2016

conditions of: 1) a 2inch * 2 inch aluminum board and 2) a Minimum Recommended Pad (MRP) layout.

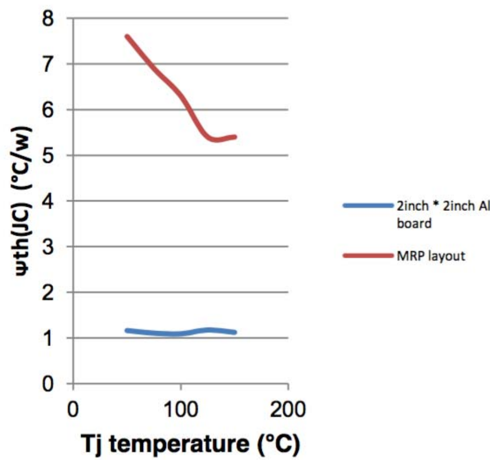

Chart 1. Ψth(JC) vs. Tj

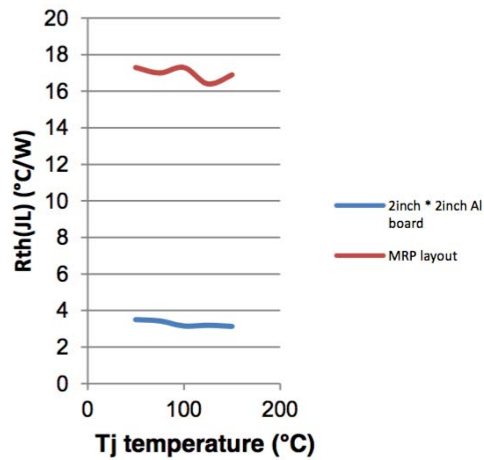

Chart 2. Rth(JL) vs. Tj

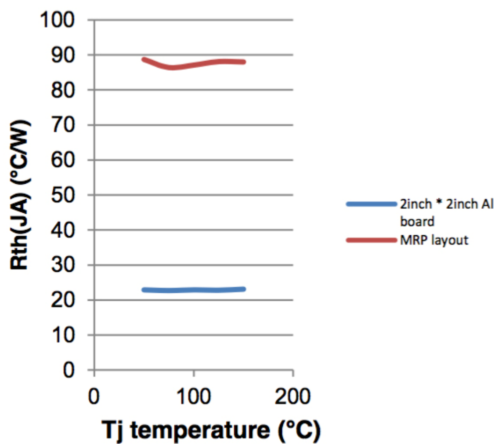

Chart 3. Rth(JA) vs. Tj

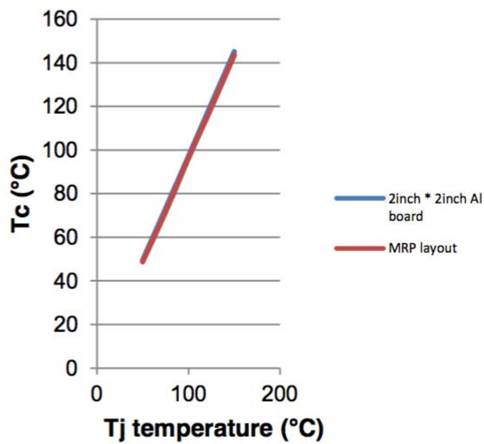

Chart 4. Tc vs. Tj

Rth(JA) … As shown in Chart 3 the variation of Rth(JA) with junction temperature is minimal but the impact due to different heatsinks is more significant. Consequently when using datasheet Rth(JA) values care must be taken to make sure that device mounting conditions in actual applications are close to those stated in the datasheet. The differences in heatsink arrangements (volume and conductivity of the heatsink connected to the lead frame tab of the device) can cause significant errors when estimating the junction temperature using Rth(JA).

Rth(JL) … This value is measured according to JEDEC (JESD51-12) Method 1 and can only be used 1) if the heat flow in every other path is made insignificant and 2) the lead temperature is measured accurately. In order to measure the datasheet Rth(JL) value using this method, it is necessary to attach a massive heatsink to the lead frame tab to ensure that most of the heat from the junction flows out of the lead frame tab into the heatsink. In a practice this is rarely the case as there will be other parallel heat flow paths that decrease the accuracy of Rth(JL). Chart 2 shows the dependency of Rth(JL) on heat sinking when practical-sized heatsinks are used. Consequently the datasheet Rth(JL) value can really only provide a comparison of the thermal conducting capabilities of different

© Diodes Incorporated 2016

manufacturers' package lead frames. For calculating junction temperature in real applications, Rth(JL) is unlikely to provide an accurate answer and more often gives the 'best case' result associated with maximum heat sinking.

Ψth(JC) … This value is measured according to JEDEC (JESD51-12) Method 2 and uses 1) the temperature difference between the junction and the measurement point on the case (which is often the center of the package) and 2) the total power dissipated in the device, but not the power flowing between the junction and the measurement point on the case. For this reason, this value should not be treated as a true thermal resistance but only a thermal parameter and therefore should only be used for comparison between various packages. Chart 1 show that this value not only depends on the size of the heatsink but also the operating junction temperature. The value decreases with increasing junction temperature due to the convection of the air around the device. Even though the measurement is done under still air conditions, the hot surface of the device will still cause air to circulate resulting in a convection effect. With Ψth(JC) often being a smaller value compared to Rth(JA) and Rth(JL), the convection effect results in a greater proportional change in its value, making it appear more significant. Consequently this value should not be used unconditionally in trying to determine the junction temperature in real applications. The lower absolute value of Ψth(JC) however does mean that the error in calculating the junction temperature will also be low.

Chart 4 proposes an alternative approach that can be used as a tool for more accurately determining a device's junction temperature in real-life application scenarios. This approach eliminates the effect of different heatsinks from the equation. However care must be taken while measuring the case temperature so 1) a non-contact thermal measurement instrument is recommended and 2) the point of measurement on the case should be as close as possible to the center of its surface.

Conclusion

The results presented above show that determining the junction temperature of a semiconductor device using the various thermal resistance parameters (junction to case, lead or ambient) typically found in a manufacturer's datasheet are highly dependent on the heatsink arrangement. Instead, chart 4 shows a much closer correlation between junction temperature and case temperature that is far less dependent on the size or effectiveness of any heatsink. Hence a graph similar to chart 4 is the most accurate tool for determining a device's junction temperature, provided the case temperature can be measured the same way on a real application circuit board.

IMPORTANT NOTICE

Diodes Incorporated and its subsidiaries reserve the right to make modifications, enhancements, improvements, corrections or other changes without further notice to any product herein. Diodes Incorporated does not assume any liability arising out of the application or use of any product described herein; neither does it convey any license under its patent rights, nor the rights of others. The user of products in such applications shall assume all risks of such use and will agree to hold Diodes Incorporated and all the companies whose products are represented on our website, harmless against all damages. Diodes Incorporated does not warrant or accept any liability whatsoever in respect of any parts purchased through unauthorized sales channels.

LIFE SUPPORT

Diodes Incorporated products are specifically not authorized for use as critical components in life support devices or systems without the express written approval of the Chief Executive Officer of Diodes Incorporated. As used herein:

A. Life support devices or systems are devices or systems which:
   1. are intended to implant into the body, or
   2. support or sustain life and whose failure to perform when properly used in accordance with instructions for use provided in the labeling can be reasonably expected to result in significant injury to the user.

B. A critical component is any component in a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or to affect its safety or effectiveness.

© Diodes Incorporated 2016