Application Note

Measuring the Thermal Impedance of LDOs in Situ

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ABSTRACT

This document describes a procedure for computing an integrated circuit's junction-to-ambient thermal impedance using its thermal shutdown temperature.

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1 Introduction

The junction-to-ambient thermal impedance ($R_{\theta JA}$) of a device is an industry-standard metric of thermal performance. It defines the linear relationship between how much power a device dissipates and how much it heats up as a result. For a given ambient operating temperature, the thermal impedance can be used to determine a device's junction temperature as a function of its power dissipation. For this reason, it is an important parameter to know when designing a robust system.

Unfortunately, knowing a device's thermal impedance is not as simple as looking it up in a data sheet. Although semiconductor manufacturers typically provide a thermal impedance value, this value comes from measurements taken on industry standard test boards. Because a device's thermal performance depends strongly on the properties of the circuit board on which it is installed, these data sheet specifications of thermal impedance cannot be assumed valid across all board designs. The best way to determine the thermal impedance of a device installed on an application board is to measure it.

This application report focuses evaluating the thermal performance of low-dropout linear regulators (LDO), but the procedure described is applicable to any device in which the power dissipation can be controlled. LDOs were chosen as an example because of the ease of the power calculation, and because their dissipative nature requires thermal properties to be considered in every design.

2 Procedure

This section presents a simple method for determining the junction-to-ambient thermal impedance of an LDO regulator installed on a circuit board. Note that this method requires that the LDO have a thermal shutdown feature. Because this feature is not always present, this is critical to check the data sheet of the device in question before proceeding. This method also requires some way of regulating the ambient temperature (T_A) and the power dissipated in the device (P_D).

The junction temperature (T_J) of a device is given by the equation:

$$T_J = T_A + R_{\theta JA} \times P_D \tag{1}$$

To determine $R_{\theta JA}$ using this equation, all other parameters (T_A, P_D, and T_J) must be known. The ambient temperature can easily be measured by a thermometer, and the power dissipated in an LDO can be calculated easily. However, this is not possible to directly measure the junction temperature.

Because the junction temperature cannot be measured, this must be removed from the equation. This can be done by making clever use of the device's thermal shutdown temperature (T_{SD}). By choosing two sets of operating conditions that result in thermal shutdown, a device's thermal impedance can be determined. In this case, the operating conditions that are varied are power dissipation and ambient temperature.

First, choose a convenient level of power dissipation. For an LDO, this is given by

$$P_D = (V_{in} - V_{out}) \times I_{out} + V_{in} \times I_q \tag{2}$$

Note that the quiescent current (I_q, also called the ground current) of an LDO is typically small enough to be neglected in power calculations. The power dissipated then can be varied easily with input voltage, output voltage, or output current.

Next, increment the ambient temperature until thermal shutdown is reached. This typically means that the internal pass element is turned off, causing the LDO's output voltage to approach 0 V. In this state, the LDO no longer dissipates power, and its junction temperature can decrease enough to turn back on. Because of the potential of cycling back and forth between on and off states, this is best to detect thermal shutdown by monitoring the output voltage versus time on an oscilloscope. Also, keep in mind that temperature generally changes slowly; allow plenty of time after the ambient set point is incremented for thermal equilibrium to be reached. After thermal shutdown is reached, allow the device to cool and make sure that this is still operating properly.

Choose another power dissipation level and repeat the preceding procedure to determine the new ambient temperature level required for device shutdown. Once two sets of operating conditions are known, the following method can now be used to compute the thermal impedance:

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$$\text{First measurement: } T_J' = T_A' + R_{\theta JA} \times P_D'$$
$$\text{Second measurement: } T_J'' = T_A'' + R_{\theta JA} \times P_D'' \tag{3}$$

Because thermal shutdown was reached under both conditions,

$$T_J' = T_J'' = T_{SD} \tag{4}$$

Therefore,

$$T_A' + R_{\theta JA} \times P_D' = T_A'' + R_{\theta JA} \times P_D'' \tag{5}$$

This equation can be rewritten to define the thermal impedance:

$$R_{\theta JA} = \frac{T_A' - T_A''}{P_D'' - P_D'} \tag{6}$$

When following this procedure, keep in mind a few additional things:

- Calculations often can be simplified by choosing an initial power dissipation of 0 W. This allows the device's shutdown temperature to be measured as well.
- The device must reach thermal equilibrium at the initial starting temperature before proceeding to heat to T_A' or T_A''. For smaller PCBs such as Texas Instruments EVMs, a 30-minute dwell time at initial temperature and load is recommended. For larger boards or systems, longer dwell times can be required.
- Increase the ambient temperature at a rate well below the thermal time constant of the board being tested. For example, Texas Instruments ramps our EVMs internally at approximately 1°C/minute. Record the shutdown temperature with a resolution of at least 0.1°C to facilitate accurate calculations.
- Device features such as current limiting can cause the actual power dissipation to be less than desired, so this is a good idea to double-check the power dissipation by measuring input voltage, output voltage, and output current.
- Thermal impedance also varies greatly with the airflow over the device. For a conservative measurement, make sure that the airflow during testing is less than the expected airflow during normal operation.

3 Conclusion

Because a device's thermal behavior depends on the properties of the application board, data sheet specifications of thermal impedance are insufficient to predict thermal behavior in all designs. Fortunately, a simple way of measuring the thermal impedance of a device installed on an application board is possible. Following the method described in this document allows engineers to accurately determine the device's junction temperature under various operating conditions.

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4 Revision History

Changes from Revision * (July 2010) to Revision A (May 2025)	Page
• Updated the numbering format for tables, figures, and cross-references throughout the document	1
• Updated *Procedure* topic to provide clarity on measurement procedure	2

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