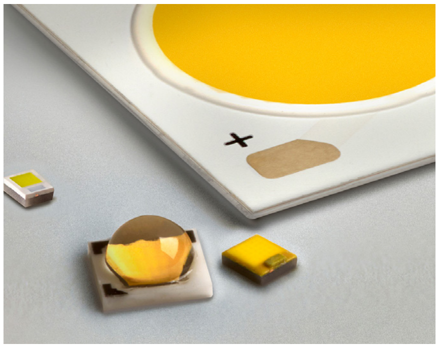
WHITE PAPER

How to Measure Thermal Resistance

of LED Emitters and LED Arrays



Purpose

To describe the process used to determine typical thermal resistance values from the LED Junction to Case and LED Junction to Ts reference point.

Introduction

Thermal performance is the most critical factor of a well-designed LED lighting system. A lighting system with proper thermal design has higher efficacy, meaning more light can be extracted using less energy, and better long term reliability. Thermal resistance, R_{th}, is defined as the ratio of the change in device temperature, ΔT, to the electrical power applied, P, and is expressed in °C/W or K/W. That is,

$$R_{th} = \frac{\Delta T}{P}.$$

The thermal resistance between LED junction and case, $R_{th\,J\text{-}C}$, is an important device parameter for understanding the thermal performance limit when an LED is in good contact with a properly dimensioned heat sink. Understanding the thermal resistance of the LED device from junction to case is essential when designing a lighting system for maximum thermal performance. Lumileds provides the $R_{th\,J\text{-}C}$ value for each LUXEON device in it's respective product datasheet.

The thermal resistance between junction and sensor pad, $R_{th\,J\text{-}S}$, is important for determining and monitoring the LED junction temperature in situ. Understanding $R_{th\,J\text{-}S}$ is important for design validation and in some applications can be used to limit the LED junction temperature. Lumileds provides the $R_{th\,J\text{-}S}$ value for each LUXEON device in its respective application brief.

It is important to note that all R_{th} values listed in LUXEON Device datasheets and application briefs are based on the electrical power going into the LED.

For the purpose of clarity, this document is separated into two parts. The first part will cover measuring $R_{th\ J-C}$ and the second part will cover measuring $R_{th\ J-S}$. Figure1 shows a diagram of the thermal path for both, junction to case and junction to solder pad.

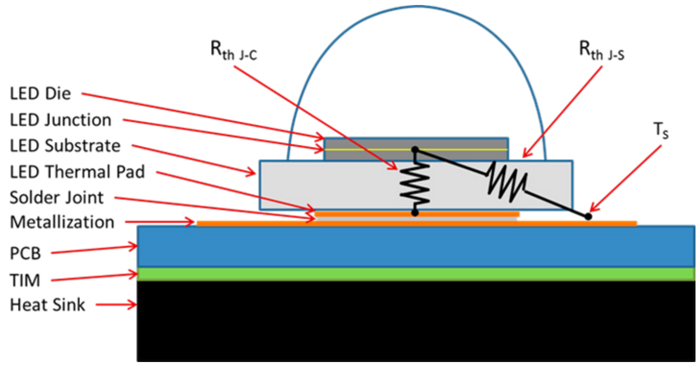


Figure 1. Graphical representation of the thermal path between junction and case and junction and solder pad.

Measuring $R_{th\ J-C}$

The junction-to-case thermal resistance, $R_{th\ J-C}$, is a measure of how well heat can be dissipated from the die to the package case from which heat is extracted by placing it in thermal contact with an external heat sink. For single emitters, the case location is defined as the back of the LED package at the center of the thermal pad (see Figure 1). For emitter arrays where the LEDs are attached to a printed circuit board (PCB) or metal core printed circuit board (MCPCB), the case is defined as the center of the Light Emitting Surface (LES) on the opposite side of the LED substrate (see Figure 2).

Lumileds uses the transient dual interface method, which is described in great detail in JDEC Standard JESD51-14 [1], to determine $R_{th\ J-C}$. This method measures the transient cooling curve for the same power device twice, with thermal interface materials of differing thermal conductivity between the device and the heat sink. As heat travels from the die towards the heat-sink, the two transient cooling curves will overlap until a point in time where the curves diverge due to the difference in thermal interface between the device and the heat-sink.

The benefits of using transient measurements of the junction temperature as opposed to the thermocouple method described in MIL Standard 833 [2] is that the transient method does not require determination of the case temperature, which is difficult to measure both accurately and repeatably between different measurement set-ups.

Lumileds currently uses the Mentor Graphics MicReD® system with T3ster® software [3] for thermal resistance junction-to-case measurements. Lumileds does not endorse MicReD® or T3ster®; however, details of this system and software are presented herein as an explanatory guide as to how thermal resistance measurements can be performed.

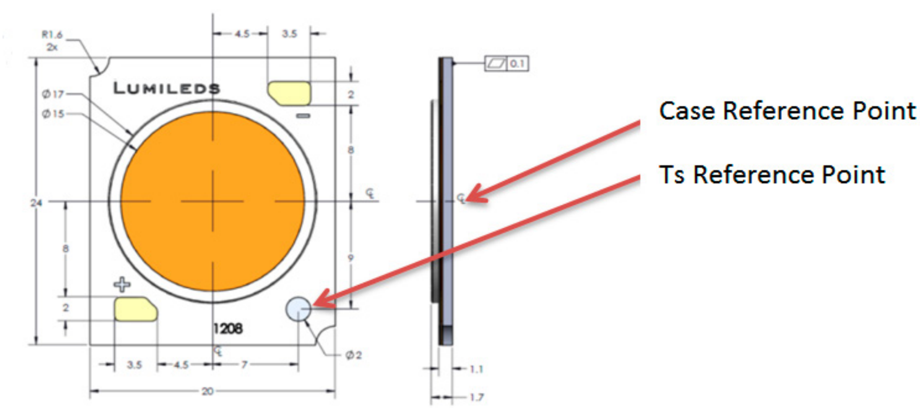


Figure 2. Example of the thermal measurement reference points for an LED array package such as a LUXEON CoB device.

Mounting DUTs

Lumileds typically determines $R_{th\ J\text{-}C}$ based on measurement data with different thermal interface materials (TIMs). The two TIMs need to be different enough to observe a divergence point in the structure functions generated by the MicReD. Typically, one TIM is very conductive (such as thermal grease) while the other TIM is insulating (such as insulating tape).

For array emitters which have contacts on top of the device (such as LUXEON CoB), the emitters are mechanically attached to a reliability board with a choice of TIM between the device and the board (see Figure 3). The reliability board consists of a heat sink and an FR4 PCB to provide the means of powering the devices. Parts are screwed down directly to the heat sink with even pressure. The first measurement is performed with insulating tape applied to the board. After this is measured in the MicReD system, the insulating tape is removed and thermal grease is applied to the parts. The parts are again screwed securely down to the board and subsequently measured for a second time in the MicReD.

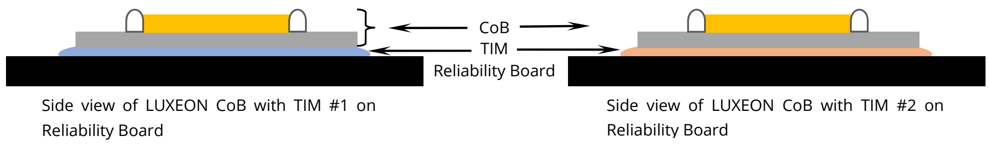


Figure 3. Cross-sectional drawing of LUXEON CoB on reliability test board with two different TIMs.

For surface mount devices which have contacts on the bottom of the device (such as LUXEON Z ES or LUXEON Flip Chip), the parts are reflowed onto ceramic substrates which are then screwed down to reliability boards using thermal grease. For 3-pad devices which have two electrical contacts and a thermal pad (such as LUXEON Z ES), the contact pads are soldered to the ceramic substrates. For the very conductive TIM measurement, the thermal pad is also soldered. For the insulating TIM measurement, only the electrical contacts are soldered (see Figure 4). For 2-pad devices (such as LUXEON Flip Chip), the devices are again attached to ceramic substrates; however, these devices are attached either with silver paste or with solder in order to achieve good electrical conductivity yet with different thermal paths (see Figure 5). The ceramic substrates are then attached to the reliability board using thermal grease.

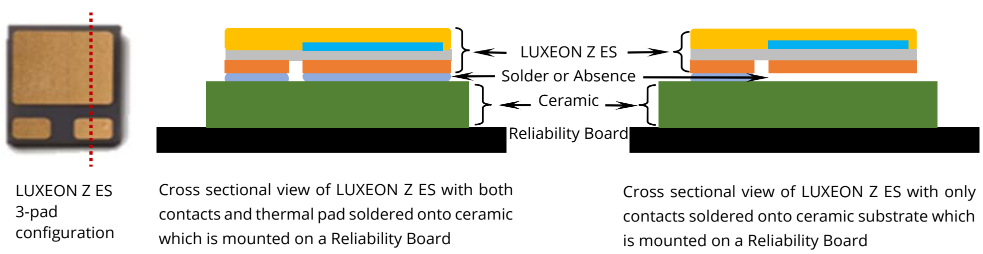


Figure 4. Cross sectional drawing through cathode of LUXEON Z ES on Reliability Board with 2 two different TIMs (note: not to scale).

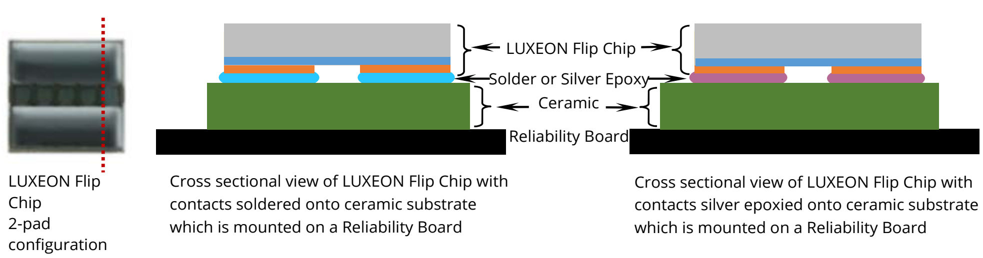


Figure 5. Cross sectional drawing of LUXEON Flip Chip on reliability board with two different TIM/electrical connections (note: not to scale).

Determining K-factor

The MicReD system is designed to measure small voltage changes in a semiconductor device during operation over time with great accuracy and speed. In order to translate this direct measurement into a thermal resistance measurement, the voltage change must first be converted to a temperature change using a calibration factor, often referred to as the "K-factor." To measure the K-factor, the reliability board is heated to a particular temperature, such as 30°C, and then the voltage to each device is measured in response to a small sense current, I_S, (small enough to not result in further device heating, typically about 1/50 of the nominal device current). The board is then heated to another temperature, say 45°C, and the measurements are repeated. This process happens for several temperatures up to 90°C and then the K-factor is calculated for each device and saved in the MicReD system. As the device should not be heated by the sense current, the temperature of the reliability board can be assumed to be equal to the junction temperature, T_j.

Testing for Thermal Resistance Junction to Case

Once the K-factor is established, the reliability board is ready for measuring the transient cooling curves. A heating current, I_H (typically the nominal current of the device) is applied to the device until the device has reached a hot steady-state. At this condition, voltage, V_H, is recorded and then I_H is switched off. Then, the same sensing current which was used for determining the K-factor is used again to measure the voltage as a function of time as the part subsequently cools to a cool steady-state condition. The measured voltage change vs. time curves are then converted into temperature change vs. time using the pre-determined K-factor by the T3ster software.

The thermal impedance curves, $Z_{th}(t)$ are then determined from the temperature change (the temperature at time, t, minus the temperature at t = 0 when the heating curve was switched off) divided by the heating power. That is,

$$Z_{th}(t) = \frac{(T_j(t) - T_j(t = 0))}{I_H V_H}.$$

These curves are recorded twice for each device using two very different TIMs. The resulting change in the contact resistance due to the different TIMs alters the total thermal resistance (often referred to as junction-to-heat-sink or junction-to-ambient thermal resistance) under steady-state conditions and therefore for a single device, the thermal impedance curves from the two measurements will follow each other from the junction to the point where the additional contact resistance occurs, after which the curves will diverge. This divergence point is recognized as the case/TIM interface and the thermal impedance at this point is approximately equal to the steady-state $R_{th\ J\text{-}C}$.

Determining $R_{th\ J\text{-}C}$

It is often difficult to determine the divergence point of thermal impedance curves and therefore further mathematical transformations of the impedance curves are required to make the difference more noticeable in order to determine the $R_{th\ J\text{-}C}$.

Thermal impedance curves or $Z_{th}(t)$ must be transformed into structure functions using a series of derivations and de-convolutions (the details of which can be found in the appendices of JEDEC Standard JESD51-14).

The T3ster software produces two types of structure function curves: cumulative and differential. The cumulative structure function is the cumulative thermal capacitance plotted against the cumulative thermal resistance from the junction of the device. The differential structure function, on the other hand, is the derivative of the cumulative thermal capacitance plotted against the cumulative thermal resistance. In a cumulative structure function curve, a difference in material properties is observed as a change in slope. On a differential structure function curve, a change in material properties is observed as a peak.

In a simple system, it may be possible to determine the thermal resistance of each material component by observing the peaks or slope-changes on the structure function curves. However, caution should be used when using peaks or slope changes to determine the thermal resistance of a more complex device, such as an LED. Again, it is recommended to follow JEDEC Standard JESD51-14 for determining thermal resistance and use the divergence point of the structure function curves of a device tested with two different TIMs to determine the junction-to-stage thermal resistance value.

In general, it is difficult to mathematically determine the junction-to-case thermal resistance of a particular device using the divergence point of two curves; therefore the structure function curves must be analyzed by a skilled scientist/engineer. Experience has shown that the divergence point can be more easily determined from differential structure functions; however, cumulative structure functions are also examined to confirm the results inferred from the differential structure functions and, in some cases, to better pinpoint the thermal resistance. The method for determining the thermal resistance junction-to-case is the same whether examining either type of structure function curves, and so for simplicity only the differential structure function analysis is shown below.

The structure functions are extracted from the T3ster software and plotted in a graphing package of choice. Care must be taken to correctly label each curve with the corresponding part and TIM for each measurement. The differential structure function curves are plotted on a log10 derivative of thermal capacitance vs. thermal resistance chart (see Figure 6a). The point on the x-axis where the curves asymptote vertically is the total thermal resistance (junction-to-heat-sink/ambient). The divergence point is better observed by narrowing the scale to "zoom-in" on the region of interest (see Figure 6b). The error can further be reduced by ensuring the lines and/or symbols used to display the graph are as thin/small as possible. Once the details of the curves are clearly visible, look for the divergence points of the individual parts and read the $R_{th\ J\text{-}C}$ value from the x-axis at that point of divergence.

For a large group of parts which may prove too time consuming to determine individual $R_{th\ J\text{-}C}$ values for each TIM pair, it may make more sense to look at the group of parts as a whole. Figure 7 shows a large group of parts measured with two TIMs. In this case, the thermal resistance for the group can be approximated by looking at the typical divergence point of the group with errors added to either side representative of the maximum and minimum $R_{th\ J\text{-}C}$ of the group's divergence. In Figure 7, the $R_{th\ J\text{-}C}$ was determined to be 0.49 ±0.05 K/W.

It is important to point out that the types of TIMs used should not affect the $R_{th\ J\text{-}C}$ determined from the divergence point of the structure functions. For example, in Figure 8, differential structure functions are plotted for a single device measured with 3 different TIMs. The total thermal resistance varies, as expected; however, the divergence point of these curves (indicating the $R_{th\ J\text{-}C}$) is unchanged no matter which TIM is chosen. Furthermore, after observing the shapes of these curves it becomes clear how difficult it would be to determine the thermal resistances of individual components corresponding to each individual peak for this complex system. Therefore, $R_{th\ J\text{-}C}$ is best determined by the divergence point of the structure functions for parts measured using two different TIMs.

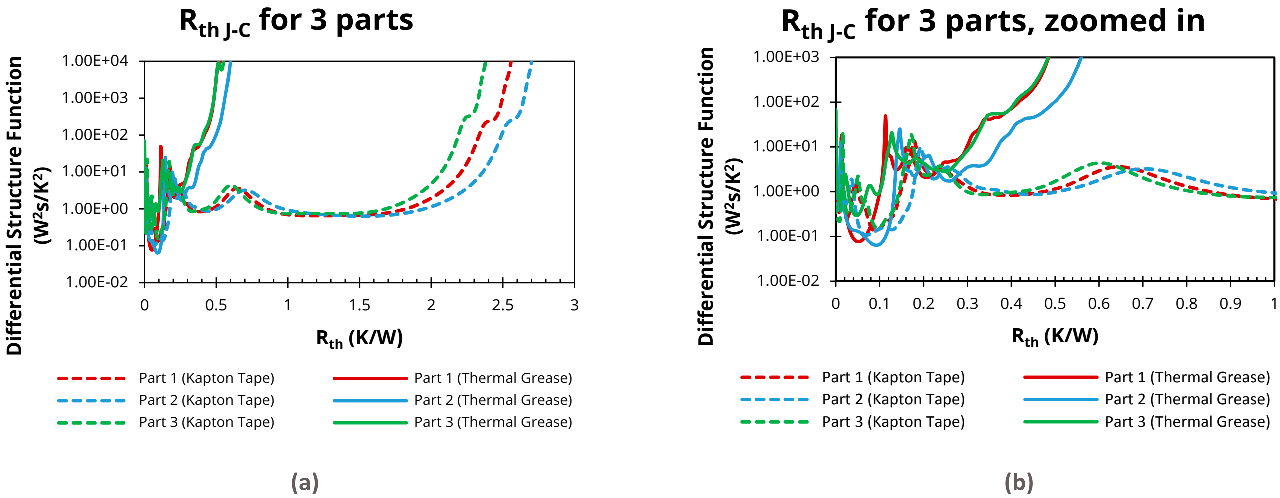


Figure 6. Example of a differential structure function graphs used to determine divergence point and $R_{th\ J\text{-}C}$.

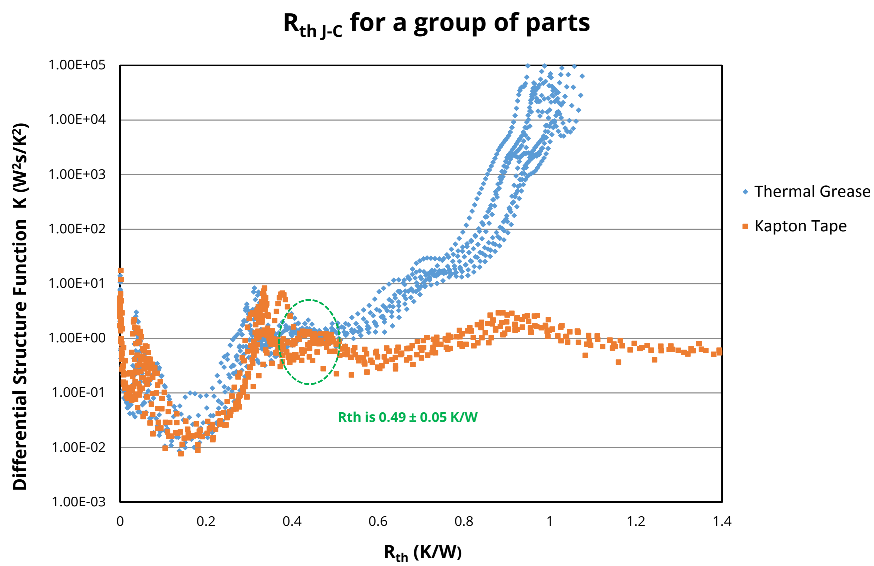


Figure 7. Determining typical divergence from multiple devices.

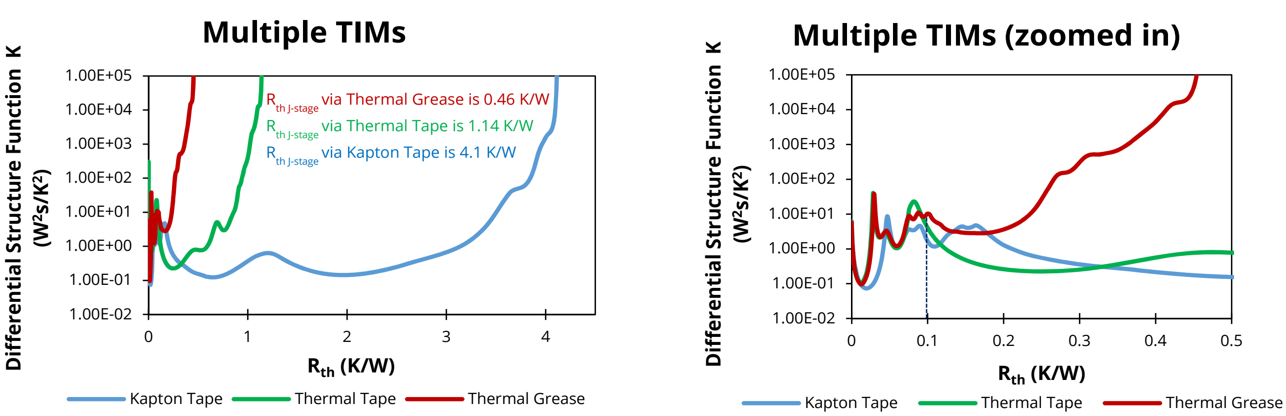


Figure 8. Sample differential structure function plot of a single device with three different thermal interface materials between case and heat sink.

Measuring $R_{th\ J\text{-}S}$

R_{th} Junction to Solder Pad ($R_{th\ J\text{-}S}$)

The method defined here to calculate and monitor device junction temperature was created because measuring the actual junction temperature of an LED is practically impossible. By knowing the thermal resistance between the device junction and an accessible reference point, the temperature at that reference point and the electrical power through the device, the device junction temperature can be calculated.

The T_s location is an accessible reference point on the device or a location on the PCB thermal pad as defined in the application brief of the respective product. This point is generally the closest point to the thermal path that allows the attachment of a thermocouple to monitor the temperature (see Figure 2 and Figure 9). With the recorded temperature at T_S, electrical power ($P = V_f I_f$) through the device and the $R_{th\ J\text{-}S}$ value from the device application brief, the LED junction temperature, T_J, can be calculated by,

$$T_J = R_{th\ J-S} V_f I_f + T_s.$$

The T_S point is often not within the direct thermal path between the LED junction and heat sink; therefore, the thermal interface material (TIM) chosen can affect the temperatures seen and accuracy of the calculated device junction temperature. It is important to use the same TIM called out in the respective product's application brief to achieve consistent measurement results.

Testing for $R_{th\ J\text{-}S}$

The application brief of each LUXEON device states the measured $R_{th\ J\text{-}S}$ value. This document also identifies the reference point (T_s) for monitoring the LED junction temperature. This point is either on the device as is the case for LUXEON CoB or LUXEON K, or is a part of the thermal pad design of the PCB to which the device is attached.

To determine the $R_{th\ J\text{-}S}$, a 40 gauge Type K thermocouple is attached at the designated point with Artic Silver Epoxy (see Figure 9). The maximum temperature is recorded during the heating cycle of the MicReD test. This value is recorded during the test runs in which the devices are attached to the reliability board with the thermal conductive TIM and not with the Kapton tape insulator. It should be noted that $R_{th\ J\text{-}S}$ values provided in the application brief are derived at specified operating conditions. This value can vary dependent upon the thermal interface material chosen.

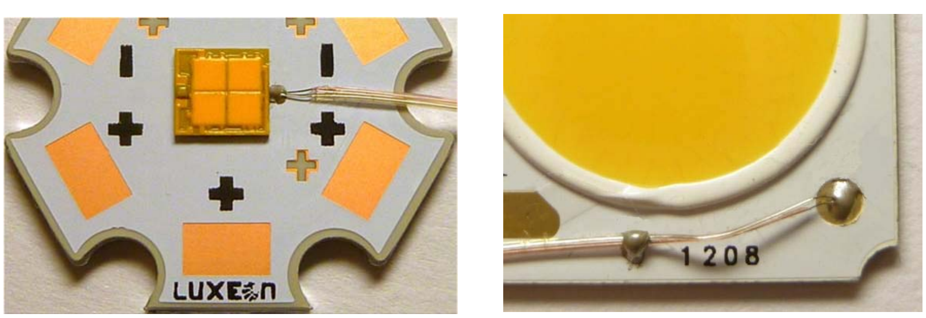


Figure 9. Example of thermocouple attachment to LUXEON MZ Starboard on the left and to a LUXEON CoB array on the right.

Determining $R_{th\ J\text{-}S}$

To calculate or determine the $R_{th\ J\text{-}S}$, three data points are necessary.

1. Electrical Power through the device in Watts
2. LED junction temperature derived from T3ster Data.
3. Temperature at the T_s point.

Thermal resistance is equal to the change in temperature divided by the power applied.

With test results from the above three data points, $R_{th\ J\text{-}S}$ is determined with this formula:

$$R_{th\ J-S} = \frac{T_J - T_S}{P}$$

Alternative Method for Determining $R_{th\ J\text{-}S}$

Lumileds may also use an automated test system that consists of a temperature controlled stage, data log thermometer for recording the T_s point temperature, a Keithley power supply to provide drive current and to monitor V_f and a desktop computer to run a scripted system control program with Agilent VEE Pro.

In this method, a short pulse K-factor is defined when device forward voltage (V_f) is measured with a short duration current pulse (< 3 ms) at 25, 35, 45, 55, 65, 75, and 85°C junction temperature to map $\Delta T/\Delta V_f$ sensitivity (see Figure 10). This is similar to establishing the K-factor as described in the $R_{th\ J\text{-}C}$ measurement process.

V_f is measured again once the device has reached a DC steady state at each of the afore mentioned temperatures. In conjunction with these measurements the temperature of the stage (ambient) and T_s point on the device is recorded along with the device current.

Junction temperature is calculated from the steady state forward voltage using the slope defined by the short pulse K-Factor. Once this calculation is complete, all the factors are known to determine device thermal resistance between LED junction to ambient and LED junction to solder pad using the formula above.

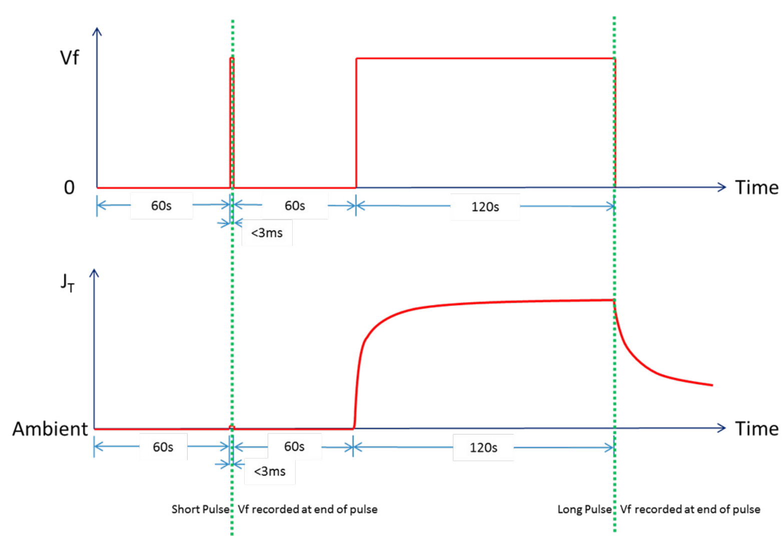


Figure 10. Input signal vs. junction temperature.

Conclusion

The thermal resistance values $R_{th\ J\text{-}C}$ and $R_{th\ J\text{-}S}$ are essential to develop and monitor the thermal performance of LED Lighting Systems.

- $R_{th\ J\text{-}C}$ defines the ability of the LED package to dissipate heat from the device junction to the case of the package.
- $R_{th\ J\text{-}C}$ is a critical factor necessary for designing a proper thermal system.
- $R_{th\ J\text{-}C}$ is a constant, unaffected by TIM or heat sink selection.
- $R_{th\ J\text{-}S}$ defines the thermal resistance between a sensor point near the direct thermal path allowing for monitoring of the LED junction temperature for the purpose of design validation or system performance monitoring.
- $R_{th\ J\text{-}S}$ is defined for a specific LED, board, and TIM configuration. Changing the board design and/or TIM will affect its value.

References

1. MIL Standard 833: MIL-STD-883E, METHOD 1012.1, Thermal Characteristics of Integrated Circuits, 4 November 1980. (http://www.thermengr.net/PDF/MilStd883M1012_IC.pdf)
2. JEDEC Standard JESD51-14: JEDEC STANDARD, JESD51-14, Transient Dual Interface Test Method for the Measurement of the Thermal Resistance Junction to Case of Semiconductor Devices with Heat Flow Through a Single Path, November 2010. (www.jedec.org/sites/default/files/docs/JESD51-14.pdf)
3. MicReD® and T3ster®: For more information on these systems, please refer to www.mentor.com/micred.

About Lumileds

Lumileds is the global leader in light engine technology. The company develops, manufactures and distributes groundbreaking LEDs and automotive lighting products that shatter the status quo and help customers gain and maintain a competitive edge.

With a rich history of industry "firsts," Lumileds is uniquely positioned to deliver lighting advancements well into the future by maintaining an unwavering focus on quality, innovation and reliability.

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