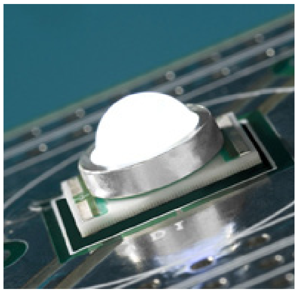
CREE

THERMAL MANAGEMENT

CLD-AP05 REV 2

Cree® XLamp® XR Family LEDs



This application note describes the types of failures common to high-power LEDs, details Cree's pre-release qualification testing for XLamp XR Family LEDs and includes the results of white point stability testing. For information on long-term lumen maintenance testing and projections, please see the XLamp Long-Term Lumen Maintenance application note.

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INTRODUCTION

The majority of LED failure mechanisms are temperature-dependent. Elevated junction temperatures cause light output reduction and accelerated chip degradation. The maximum junction temperature for each product line is specified in the product data sheet. Junction temperature is primarily affected by three parameters:

- Ambient temperature of the LED's immediate surroundings
- Thermal path between the LED junction and ambient conditions
- Power dissipated by the LED

When designing lighting systems using high-power LEDs, the following general guidelines should be followed:

- The most important consideration for successful thermal design is to minimize the amount of heat that needs to be removed. It is important to separate the LED drive circuitry from the LED board so that the heat generated by the driver will not contribute to the LED junction temperature.
- The next most effective strategy is to minimize the ambient temperature inside the fixture. This goal is achieved by paying attention to several design parameters such as a conservative packaging design that does not allow the upper limit on overall system power density to be reached. Maintaining clear and clean airflow paths for natural convection cooling is vital as well.
- Enhancing thermal conductivity between the heat sinks and the LED is very preferable for thermal management. Even though the heat removal from the heat sink is via convection, the path from the LED to the heat sink depends upon conduction.
- Finally, the orientation of the LED PCB/heat sink should be considered carefully. It is important to position the board/heat sink so that the plane is vertical. If the board plane is horizontal, it will block the formation of air convection currents and substantially reduce the cooling capability of the system.

THERMAL MANAGEMENT TECHNOLOGY

Thermal resistance

The thermal resistance between two points is defined as the ratio of the difference in temperature to the power dissipated. For calculations in this document the units used are °C/W. In the case of LEDs, the resistance of two important thermal paths affects the junction temperature:

- From the LED junction to the thermal contact at the bottom of the package. This thermal resistance is governed by the package design. It is referred to as the thermal resistance between junction and solder point ($R_{th\ j\text{-}sp}$)
- From the thermal contact to ambient conditions. This thermal resistance is defined by the path between the solder point and ambient. It is referred to as the thermal resistance between solder point and ambient ($R_{th\ sp\text{-}a}$)

The overall thermal resistance between the LED junction and ambient ($R_{th\ j\text{-}a}$) can be modeled as the sum of the series resistances $R_{th\ j\text{-}sp}$ and $R_{th\ sp\text{-}a}$.

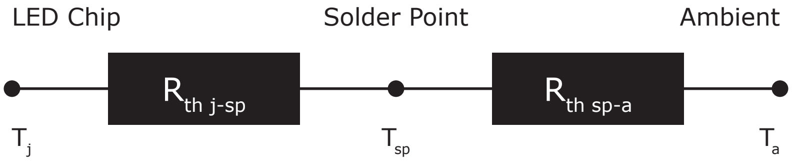

Figure 1: Thermal Resistance Model

Power dissipated

The total power dissipated by the LED (Pd) is the product of the forward voltage (V_f) and the forward current (I_f) of the LED.

Junction temperature

The temperature of the LED junction (T_j) is the sum of the ambient temperature (T_a) and the product of the thermal resistance from junction to ambient and the power dissipated.

$$T_j = T_a + (R_{th\ j\text{-}a} \times P_d)$$

CALCULATIONS

In the most cases, power LEDs will be mounted on metal-core printed circuit boards (MCPCB), which will be attached to a heat sink. Heat flows from the LED junction through the MCPCB to the heat sink by way of conduction. The heat sink diffuses heat to the ambient surroundings by convection. In most LED applications, the contact thermal resistance between LED and MCPCB and/or heat sink is small with respect to the thermal resistance between the junction and thermal pad and thermal pad to ambient.

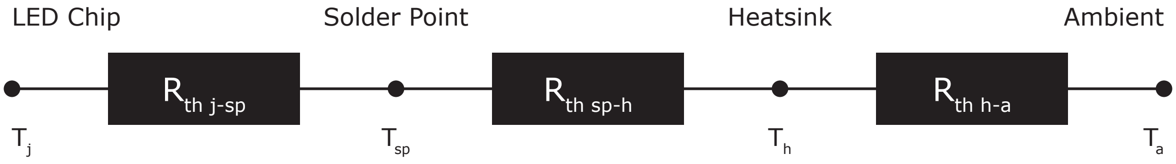

Figure 2: Thermal Resistance Model Including Heat Sink

When a heat sink is used, the total thermal resistance is the series resistances from the junction to the solder point ($R_{th\ j\text{-}sp}$), from the solder point to the heat sink ($R_{th\ sp\text{-}h}$) and from the heat sink to ambient ($R_{th\ h\text{-}a}$).

$$R_{th\ j\text{-}a} = R_{th\ j\text{-}sp} + R_{th\ sp\text{-}h} + R_{th\ h\text{-}a}$$

Note that the direct heat loss from the LED package to ambient is small enough to be neglected for calculations.

The overall design goal in determining the size and nature of the required heat sink is to calculate the maximum heat sink thermal resistance (Rth h-a) that will maintain the junction temperature below the maximum value at worst-case operation conditions.

Example 1: Heat Sink Thermal Resistance

In this example, six white 7090 XLamp LEDs are used in an application that sees a maximum ambient temperature (T_a) of 55°C. Assuming a typical forward voltage (V_f) of 3.25 V at 350 mA and that the power supply is outside of the fixture, the total power dissipated is:

$$P_{total} = 6 \times 0.350\ A \times 3.25\ V = 6.825\ W$$

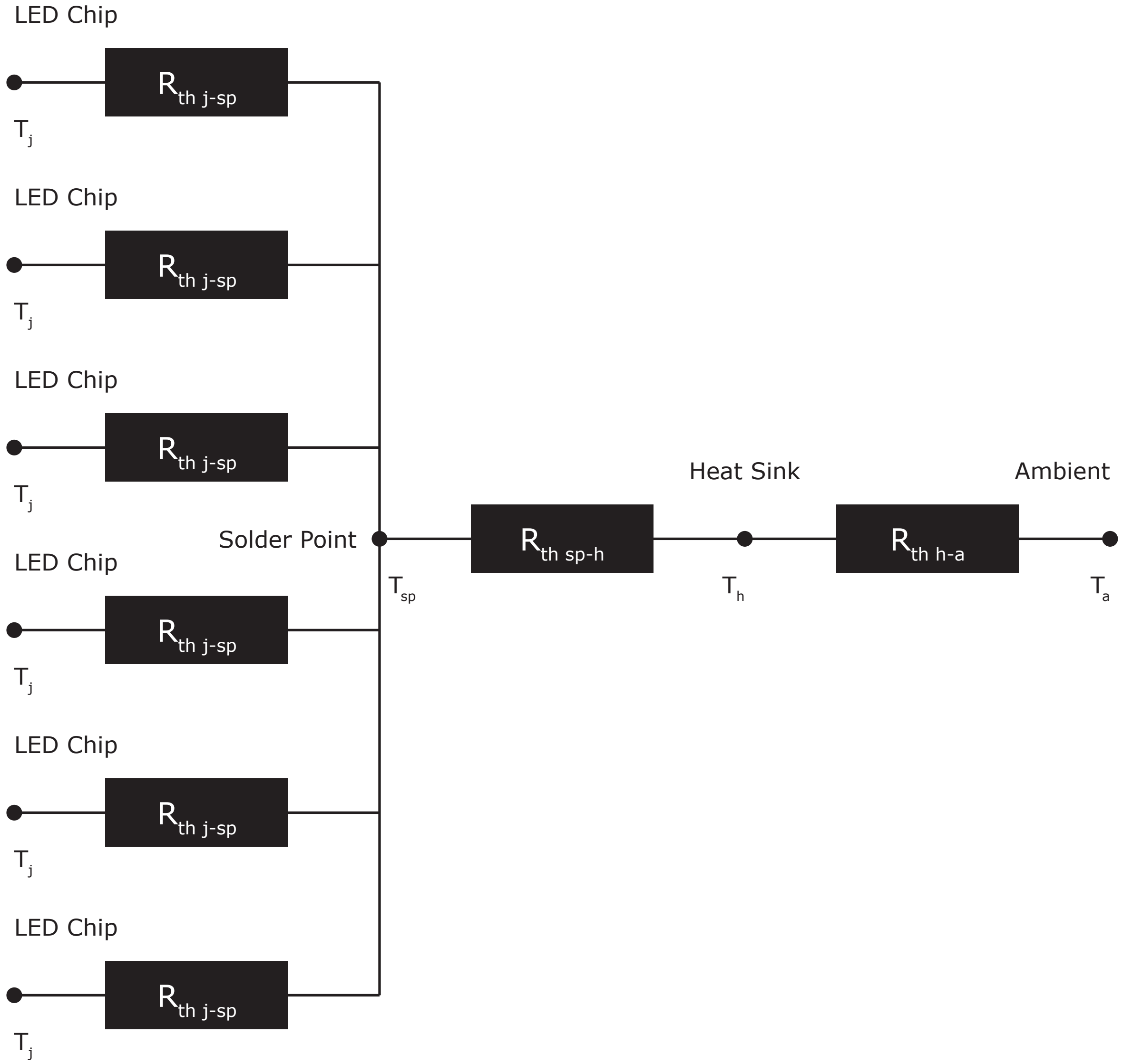

Figure 3: Thermal Resistance Model for Six (6) XLamp LEDs

The thermal resistance from junction to solder point ($R_{th\ j\text{-}sp}$) is listed in the data sheet as 8°C/W. The maximum LED junction temperature (Tj) provided in the data sheet is 145°C. Therefore:

$$T_j = T_a + P_{total} (R_{th\ j\text{-}sp}/6 + R_{th\ sp\text{-}h} + R_{th\ h\text{-}a})$$

The thermal resistance between the LED solder point and heat sink, $R_{th\ sp\text{-}h}$, depends on the surface finish, flatness, applied mounting pressure, contact area, and the type of interface material and its thickness. With good design, it can be minimized to less than 1°C/W.

The maximum thermal resistance from the heatsink to ambient ($R_{th\ h\text{-}a}$) can be calculated. Using the previous equation and solving for $R_{th\ h\text{-}a}$:

$$R_{th\ h\text{-}a} = (145°C - 55°C – 8°C/W \times 6.825\ W/6 – 1°C/W \times 6.825\ W)/6.825\ W = 10.85°C/W$$

In order to keep the junction temperature below 145°C in worst-case conditions, a heat sink with thermal resistance from heat sink to air ($R_{th\ h\text{-}a}$) less than 10.85°C/W must be chosen. A heat sink with the required characteristics may be selected using figures published by heat sink manufacturers or through modeling and testing.

Example 2: Test and Calculate Thermal Resistance

Cree does not recommend operating XLamp LEDs without a heat sink. This example demonstrates the procedure for calculating the thermal resistance and maximum operating temperature of one XLamp 7090 on a 1-inch^2 MCPCB.

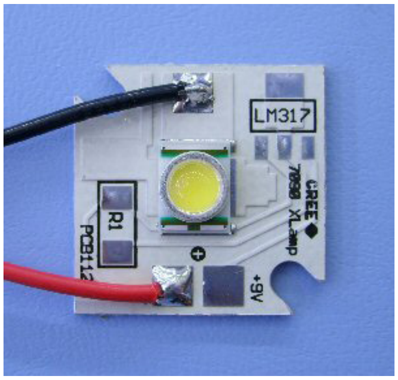

Figure 4: XLamp 7090 White on MCPCB

Since there is no additional heat sink in this example, the MCPCB serves as the heat sink and thermal interface to ambient. In order to calculate the thermal resistance from junction to ambient, the temperature on the back of the LED must be measured. In this case, the LED is reflow soldered on MCPCB. The board temperature can be measured by applying a thermocouple directly to the back of the MCPCB. In most applications, it is impossible to attach a thermocouple to the solder point of the LED. The test point should be the point that is as close as possible to the back of the LED or the hottest point on the back of the MCPCB.

Figure 5 shows the MCPCB temperature at different forward currents. The room temperature was controlled to 23°C. Due to the low thermal conductance of the MCPCB to air, temperatures quickly reach a steady-state.

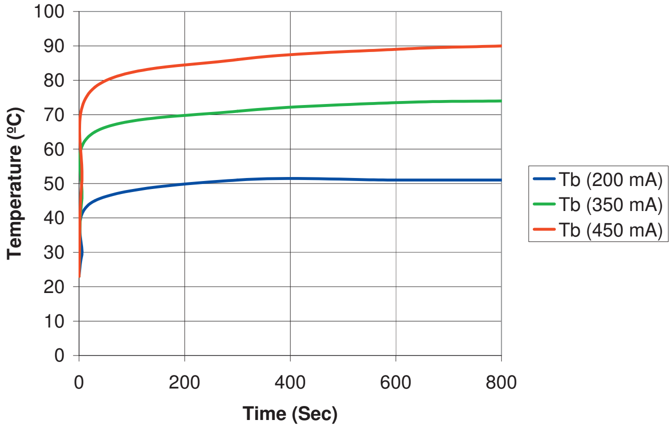

Figure 5: MCPCB Temperature

The board temperature (T_b) can be measured at different forward currents. Using a junction-to-solder-pad resistance of 8°C/W and assuming a thermal resistance from solder point to MCPCB of 1°C/W (this will be on the high end based on the mounting method), the junction temperature at different currents can be calculated by:

$$T_j = T_a + P_{total} \times R_{th\ j\text{-}a}$$

Where,

$$R_{th\ j\text{-}a} = R_{th\ j\text{-}b} + R_{th\ b\text{-}a}$$

$$R_{th\ j\text{-}b} = R_{th\ j\text{-}sp} + R_{th\ sp\text{-}b} = 8°C/W + 1°C/W = 9°C/W$$

$$R_{th\ b\text{-}a} = (T_b - T_a) / P_{total}$$

$$P_{total} = If \times V_f$$

$$T_a = 23°C$$

Table 1 shows the test and calculated results.

I_f (mA)	V_f (V)	T_b (°C)	$R_{th\ b\text{-}a}$ (°C/W)	$R_{th\ j\text{-}a}$ (°C/W)	T_j (°C)
200	2.95	51	47	56	56
350	3.11	74	47	56	84
450	3.21	90	46	55	102

Table 1: Junction-Temperature Calculations

From the test results we can conclude that with a 1-inch^2 MCPCB as a heat sink, the XLamp 7090 can be safely operated at room temperature when driven at 350 mA. The maximum allowable ambient temperature is 84°C. However, at room-temperature conditions, the LED junction will quickly reach a temperature of 84°C. For better results, the designer should use a secondary heat sink.

HEAT SINK DESIGN AND SELECTION

In order to design and select the heat sink, it is useful to know how heat sinks work. Transmission of heat from a heat source (e.g. the junction of a LED) via the heat sink into the surrounding medium takes place in four successive steps:

1. Transfer from heat source to the heat sink
2. Conduction from within the heat sink to its surface
3. Transfer from surface into the surrounding medium by convection
4. Radiation depending on the nature of the heat sink's surface

The efficiency and capability of a heat sink are a function of the heat transfer modes utilized. Heat sinks provide a path for heat from the LED to flow through conduction. The heat "trapped" in the heatsink must be dissipated in order for the power from the source to continually flow. If the heat remains trapped in the sink, the temperature will rise and eventually overheat the source. Heat sinks can dissipate power in three ways: conduction (heat transfer from one solid to another), convection (heat transfer from a solid to a moving fluid, for most LED applications the fluid will be air), or radiation (heat transfer from two bodies of different surface temperatures through electromagnetic waves).

There are three common varieties of heat sinks: flat plates, die-cast finned heatsinks, and extruded finned heat sinks. The material normally used for heat sink construction is aluminum, although copper may be used with an advantage for flat-sheet heat sinks.

Heat sink thermal radiation is a function of surface finish, especially when the heat sink is at higher temperatures. A painted surface will have a greater emissivity than a bright, unpainted one. The effect is most remarkable with flat-plate heat sinks, where about one-third of the heat is dissipated by radiation. The color of the paint used is relatively unimportant. The thermal resistance of a flat-plate heatsink painted gloss white will be only about 3% higher than that of the same heat sink painted matte black. With finned heat sinks, painting is less effective since heat radiated from most fins will fall on adjacent fins, but it is still worthwhile. Both anodizing and etching will decrease the thermal resistance.

A number of important factors need to be considered when selecting a heat sink:

- Surface area: Thermal transfer takes place at the surface of the heat sink. Therefore, heat sinks should be designed to have a large surface area. This goal can be reached by using a large number of fine fins or by increasing the size of the heat sink itself.

- Aerodynamics: Heat sinks must be designed in a way that air can flow through easily and quickly. Heat sinks with a large number of fine fins with short distances between the fins may not allow good air flow. A compromise between high surface area (many fins with small gaps between them) and good aerodynamics must be found.

- Thermal transfer within the heat sink: Large cooling fins are ineffective if the heat can't reach them. The heat sink must be designed to allow adequate thermal transfer from the heat source to the fins. Thicker fins have better thermal conductivity; so again, a compromise between large surface area (many thin fins) and good thermal transfer (thicker fins) must be found. The material used has a major influence on thermal transfer within the heat sink.

- Flatness of the contact area: The portion of the heat sink that is in contact with the LED or MCPCB must be perfectly flat. A flat contact area allows the use of a thinner layer of thermal compound, which will reduce the thermal resistance between the heat sink and LED source.

HEAT SINK DESIGN AND SELECTION (CONTINUED)

- Mounting method: For good thermal transfer, the pressure between the heat sink and the heat source must be high. Heat sink clips must be designed to provide high pressure, while still being reasonably easy to install. Heat-sink mountings with screws or springs are often better than regular clips. Thermo-conductive glue or sticky tape should only be used in situations where mounting with clips or screws is not possible.

For more information regarding to heat sink design and selection, please contact your heat sink manufacturer and explore these links for further information:

http://www.electronics-cooling.com/

http://www.r-theta.com/

http://www.aavidthermalloy.com

http://www.electronics-cooling.com/html/consultants.html

http://www.coolingzone.com/

The formulas and diagrams given in this application note should be considered as a guide for thermal management of XLamp LEDs. The thermal resistance of a heat sink depends on numerous parameters that cannot be predetermined. These parameters include but are not limited to the position of the LED on the heat sink, the extent to which air can flow unhindered, the screening effect of nearby components, and heating from other components in the fixture. It is always advisable to check important temperatures in the finished fixture under the worst possible operating conditions and calculate the LED junction temperature. The probe points should be as close as possible to the back of the LED.