CrayoNano®

Introduction to LED Thermal management

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Introduction

UV-C LEDs are light-emitting diodes that emit UV-C light. They have many advantages over conventional UV-C light sources, such as compact size, low power consumption, long lifetime, instant on/off and environmental friendliness.

UV-C LEDs however, also face significant challenges and requirements in thermal management. Although LEDs are more efficient than most traditional light sources, they generate a large amount of heat during operation as much of the electrical power is converted to heat. The heat generated by UV-C LEDs can increase their junction temperature, which can adversely affect their performance, reliability, and lifetime as most characteristic properties are temperature dependent. Therefore, it is essential to design, test and qualify effective thermal solutions for UV-C LED modules to ensure their optimal operation and durability.

The objective of this application note is to provide guidelines and best practices for thermal management of UV-C LEDs. The application note assumes that the reader has some basic knowledge of UV-C LEDs and their characteristics. There are examples and case studies to illustrate the concepts and methods of thermal management for UV-C LED modules.

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1. Thermal basics

Thermal management has the goal of transferring the heat generated by electrical components away from the system. There are three main mechanisms of heat transfer: conduction, convection, and radiation. Conduction is the transfer of heat through direct contact between solid materials. Convection is the transfer of heat by the movement of fluids, such as air or water. Radiation is the transfer of heat by electromagnetic waves, such as infrared or visible light. Conduction is the dominant mechanism when considering the internal heat flow of an LED assembly, whereas convection and radiation are more relevant when considering transfer of heat from the system to the ambient.

• 1.1 Thermal conduction

Thermal conduction can be described as the transfer of vibrations between neighboring particles and does not require a flow of material. Fourier's law [1] describes the heat transmitted through conduction in a one-dimensional system.

[1] $q_x = -k\frac{dT}{dx}$

Where q is the heat flux, dT/dx is the temperature difference along the path of heat transfer and k is the material-dependent thermal conductivity.

From thermodynamics: q = Q/A. Equation [1] translates to [2]:

[2] $\dot{Q} = \frac{kA\Delta T}{L} = \frac{(T_1 - T_2)}{R_{th}} \rightarrow R_{th} = \frac{(T_1 - T_2)}{\dot{Q}}$ and $R_{th} = \frac{L}{kA}$

Where Q is the heat transfer rate, L is the transfer length, and R_{th} is the thermal resistance.

• 1.2 Thermal resistance

This leads to the description of a key parameter in thermal design of electrical systems, the thermal resistance R_{th}.

Thermal resistance is a measure of how much a material, or a component resists the flow of heat. It is expressed in units of °C/W, which means how much the temperature rises for every watt of heat transferred. The lower the thermal resistance, the better the heat transfer. An important aspect of the thermal resistance in a one-dimensional system is that it can be calculated as for an electrical system: thermal resistance can be added in series or parallel, depending on the configuration of the thermal path.

Specific thermal resistance is the reciprocal of the material's thermal conductivity and is a material constant given as K*m/W that is useful for comparing materials. Absolute thermal resistance, given in kelvins per watt (K/W) or degrees Celsius per watt (°C/W), is a property of a determined quantity and shape of a material. Once a material and size have been chosen, absolute thermal resistance is the measure of that component's ability to resist heat flow.

• 1.3 Heat generation

Parts of the electrical energy that goes into the UV-C LED are dissipated through emission of light, however for the purpose of this application note it will be approximated that all the electrical power is dissipated as heat. Therefore Equation [3] expresses the total power dissipation of heat in the LED.

[3] $P_d = I_d * V_f$

• 1.4 Junction temperature

The junction temperature (T_j) is one of the most critical parameters for UV-C LEDs, as it directly affects their performance, reliability, and lifetime. A higher junction temperature can accelerate the degradation of the semiconductor material, the encapsulation material, and the solder joints as well as decrease light output during operation.

The junction temperature is the temperature inside the UV-C LED where the photons are generated, this is also where most of the heat is generated and dissipated. T_j depends on several factors, including but not limited to: power dissipation, ambient temperature, LEDs density on PCB assembly, thermal interface materials and thermal resistances of different layers. Junction temperature can be estimated by using the following equation [4]:

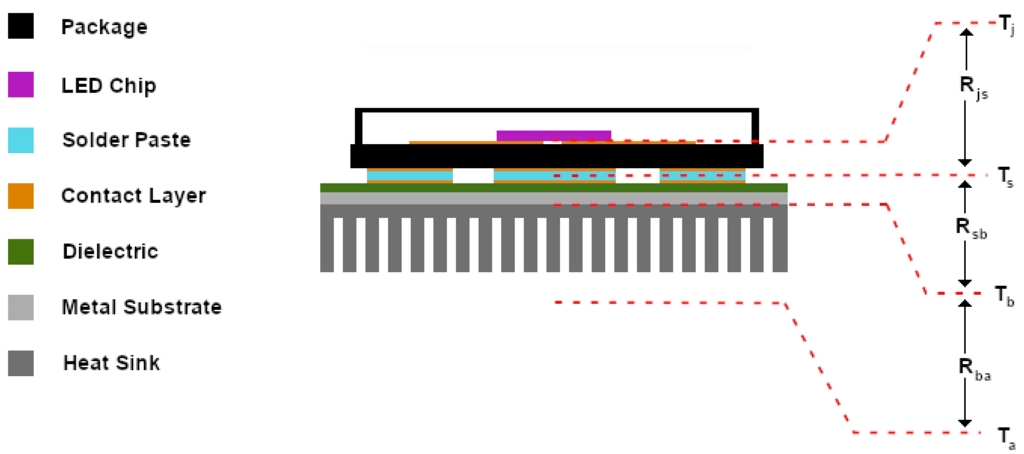
[4] $T_j = T_s + P_d R_{js}$

Where T_s is the temperature at the solder-point between the LED package and the PCB, T_j is the junction temperature and R_{js} is the thermal resistance of the LED.

2. Thermal Design

The thermal management system of an LED consists of several components, all of which must be chosen to accommodate the power class of the LED and the limitations and requirements set by each specific application. In addition to the increasing demand for more powerful, efficient, and faster disinfection from many UV-C LED applications, there is an ever-increasing demand for system optimization. As a result, the power density and in turn, the need for efficient thermal design are also increasing. Ultimately the goal of the thermal management system is to keep the junction temperature below a certain threshold set by the LED manufacturer.

The typical thermal model of a UV-C LED package consists of several layers with different thermal resistances, such as chip, solder, PCB and heat-sink, among others. The total thermal resistance from junction to ambient can be calculated by adding the thermal resistances of each layer in series. A schematic diagram of a UV-C LED package and its thermal model are shown below:



The typical heat transfer path is described below:

- The heat is generated mainly at the semiconductor chip junction, giving rise to the junction temperature T_j. R_{js} is a specified thermal resistance by the LED manufacturer between the junction a solder point.
- Heat is conducted through the LED package and solder points of the underlaying PCB resulting in the solder temperature T_s.
- Heat is conducted through the PCB to the heatsink with a thermal resistance R_{sb} resulting in the board temperature T_b .
- Heat is removed from the system though radiation and convection at the heatsink with a thermal resistance R_{ba} . T_a is the ambient temperature for a passively cooled system and the temperature of the cooling medium for an actively cooled system.

3. PCB Technologies for LED Applications

PCBs are the substrates that support and connect the electronic components of a device or a system. PCBs play an important role in LED applications, as they provide electrical, mechanical, and thermal functions for the LED packages and modules. As explained above, PCBs are part of the thermal management system and thus will affect the characteristics of the LED.

There are various types of PCB technologies that can be suitable for LED applications, depending on their design, material, and fabrication. Some of the common PCB technologies for LED applications are explained below.

3.1 Design

Some common design elements are often used to improve both horizontal and vertical heat distribution:
Horizontal:

- Enlarging the solder pads or if applicable extending the thermal pad. This effectively reduces the power density of the LED as the heat is spread over a larger area, thus lowering the vertical thermal resistance. Larger solder pads will however limit the component density.
- Increased copper thickness allows for better horizontal heat spreading.

Vertical:

- The use of thermal vias to conduct heat through less electrically conductive materials. This can be done at a relatively low cost.
- Thickness reduction of PCB will reduce the vertical thermal resistance.

3.2 PCB Materials

FR-4 is the most widely used material for PCBs. It consists of a glass fiber reinforced epoxy resin with copper foil on both sides. FR-4 PCBs are low-cost and easy to produce and have good electrical and mechanical properties. However, FR-4 PCBs have low thermal conductivity and poor heat dissipation, which can limit the power density and optical efficiency of LED applications. Typical thermal conductivity for FR4 is 0.4 W/m-K.

Metal Core PCBs are a type of PCB that use a metal, typically aluminum or copper, as the base material layer. Usually a thin dielectric layer (25-100um) covers the metal core. Among the different types of MCPCBs, aluminum is most used and is cheaper than copper, however copper MCPCBs have a higher thermal conductivity than other MCPCBs.
These boards enables thermoelectric separation which is the process of soldering the thermal pad of the LED directly to the metal base. Thermoelectric separation enables thermal conductivities close to that of the base material, ~400W/m-K for copper, however at an increased cost. Typical thermal conductivity for MCPCBs are in the range of 1-5 W/m-K, due to the limited thermal properties of the dielectric layer.

The choice of the best PCB technology for LED applications depends on several factors, such as power dissipation, optical output, cost, size, and shape. The ideal PCB technology for LED applications should be able to provide sufficient electrical connection, mechanical support, and thermal management for the LED packages and modules.

• 3.3 Solder voids

Voids are air gaps that form within the solder joints due to trapped gases from the fluxes and solder pastes during the reflow process. They can affect the thermal performance and reliability of the LED assemblies in several ways:

- Reduce the effective cross-sectional area of the solder joint, which increases the thermal resistance and reduces the heat transfer from the LED to the heat sink.
- Voids can create stress concentrations in the solder joint, which can lead to cracks and failures under thermal cycling or mechanical loading.
- Voids can interfere with the electrical conductivity of the solder joint, which can reduce the current carrying capacity and cause overheating or short circuits.
- Therefore, it is important to minimize the formation of voids in the solder joints by optimizing the solder paste selection, reflow profile, and board design.

The total area of voids in a soldered contact is usually determined using x-ray transmission techniques or similar. It is recommended that the total area of voids is below 30% of the contact surface (In close agreement with industry standards IPC-A-610 D and J-STD-001D for area array components such as BGA and CSP).

5. Examples

- Example 1: Calculate required cooling.

A CrayoLED is operated at I = 350mA with a forward voltage of V = 6V in an ambient temperature of 40C. From the datasheet $T_{j(max)}$ = 110C and R_{js} = 6K/W.

The LED is soldered to an aluminum MCPCB with thermal resistance R_{sb} = 6K/W. Assume the thermal resistance of the thermal interface material between the MCPCB and the heatsink is ~ R_{TIM} = 1C/W.
The calculations to estimate the requirements on a heat sink are as follows.

1. Equation 3 gives power dissipation as heat:
   $P_d = I * V = 2.1W$

2. Equation 2 gives the maximum allowable thermal resistance from junction to ambient:
   $R_{ja(max)} = (T_j-T_a)/Q = (110C-40C)/2.1W = 33.3C/W$

3. In a one-dimensional system the thermal resistance of the heat sink can be found by subtracting the other resistances from the total.
   $R_{ba} = R_{ja(max)} - R_{js} - R_{sb} - R_{TIM} = 33.3 - 6 - 6 - 1 = 20C/W.$

This can be achieved with a standard passively cooled finned heatsink.

Note that the calculations in these examples are intended to show various methods for estimating minimum requirements in a system. Each actual system or module is different and more complex and will require separate considerations.

5. Examples

- Example 2:

This example evaluates a thermal management system of a CrayoLED UV-C LED - CLH-N3S device.

1. From the datasheet we have $P_{d(max)}$ = 3W at 500mA, Thermal resistance R_{js} = 6K/W and $T_{j(max)}$ = 110C.
   Assume T_a = 40C and that the LED is soldered to a FR4 board with R_{sb} = 80 K/W.

2. In a one-dimensional system the thermal resistances can be added.
   $R_{th} = R_{js} + R_{sb} = 6+80 = 86K/W$

3. Equation 2 gives the heat convection through the system:
   $Q = (T_j - T_a)/R_{th} = (110-40)/86 = 0.81W$

4. The next step would be to evaluate a heat sink however it is apparent that this system does not provide sufficient heat dissipation through the PCB given that $P_{d(max)} > Q$.

This system is dominated by the thermal resistance of the FR4 board. Design improvements needs to be done in order to enable better heat transfer through the PCB. Possible improvements are to reduce R_{sb} by using thermal vias on the FR4 board and increasing the footprint by enlarging the copper solder pads on the board or changing the PCB to a MCPCB.

Note that the calculations in these examples are intended to show various methods for estimating minimum requirements in a system. Each actual system or module is different and more complex and will require separate considerations.

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