Thermal Management of Visible LEDs

Application Bulletin 228

- **Required luminous flux**
- **Desired dominant wavelength or color temperature**
- **Required MTTF**
- **Tolerable flux degradation**

Managing Junction Temperature of High-Power Visible Light Emitting Diodes (LEDs)

The purpose of this application bulletin is to answer design questions about high-power visible light emitting diodes (LEDs).

Introduction

LEDs fulfill a growing number of applications. Visible LEDs have a high luminous efficacy as compared to incandescent and fluorescent bulbs – and while incandescent and fluorescent bulbs have already reached near-maximum luminous efficacy – the efficacy of visible LEDs is forecasted to increase in the future.

Typically, LEDs have been driven at a low power with a minimum power dissipation of 150 mW -- which meant that most lighting applications required numerous low-power LEDs. The new high-power visible LEDs have power dissipations ranging from 500 milliwatts to as much as 10 watts in a single package. With improving luminous efficacy, these high-power LED components can and will replace other lighting technologies in most applications.

When using high-power visible LEDs in applications, many design considerations must be considered. These include:
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- How much luminous flux is required?
- What is the desired dominant wavelength or color temperature?
- What is the required MTTF?
- How much flux degradation is tolerable?

The temperature of the LED’s P-N junction impacts these issues. Junction temperature directly alters the performance and reliability of LEDs in the following ways:

- **Reduced output power:** At constant operating current, the luminous efficacy decreases by about 5% for every 10° C rise in junction temperature.

- **Reduced forward voltage:** At constant operating current, forward voltage decreases by about 20 mV for every 10° C rise in junction temperature.

- **Shifted dominant wavelength:** Dominant wavelengths shift by about 2 nm for every 10° C change in junction temperature.

- **Shifted Color temperature:** White LEDs are more sensitive to changes in junction temperature because the color temperature changes significantly. LEDs emit white light by combining standard blue emission with a phosphor overcoat that absorbs the blue flux and re-emits a wide range of wavelengths throughout the visible range. Re-emission efficiency is highly dependent on the wavelength of the blue flux, which shifts as junction temperature changes. If the dominant wavelength of the blue LED shifts out of the efficient range of the phosphor, more blue flux escapes the package, which increases the color temperature.

- **Reduced MTTF and accelerated degradation:** Catastrophic failure and LED degradation are mechanical and chemical processes which occur at rates described by the Arrhenius model. Their rates are inversely proportional to the exponent of the inverse of junction temperature.

The impact of junction temperature cannot be overstated. Successful thermal management is paramount to successful design.

Generating Heat

Junction temperature depends on three factors:

- Power dissipation
- Thermal resistances of the substrate and assembly
- Ambient conditions

Power dissipation determines how much heat is generated, while thermal resistances and ambient conditions dictate how efficiently heat is removed. All of the light and heat produced by an LED is generated at the P-N junction. Since the junction is very small, the heat generation rate per unit area is very large. A 1-watt 1 mm^2 LED generates 100 W/cm^2. This rate is higher than many of today’s high-power microprocessors.

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Removing Heat

To maintain a low junction temperature, all methods of removing heat from LEDs should be considered. The three means of heat transference are *conduction*, *convection* and *radiation*.

- **Thermal conduction** is the transmission of heat across matter. Thermal conductivity within and between materials is proportional to the temperature gradient and the cross-sectional area of the conductive path. Conversely, conductivity is inversely proportional to the length of the conductive path. LEDs are typically encapsulated in a light-transmissive plastic, which is a very poor thermal conductor. Nearly all heat produced is conducted through the back side of the chip. For an interface with area **A** and thickness ***l***, the rate of heat conduction has the following proportion:

$$Q_{\text{oç}}\ A \cdot \Delta T / l \ ^{(1)}$$

- **Convection** is the transfer of heat by currents in a liquid or gas. Convection rate is proportional to surface area and the temperature gradient between the surface and the fluid. LEDs do not benefit from convection at the component level, because their surface area is too small. Convective technologies include fans, heat pipes and liquid cooling. For a surface with area A_S and temperature T_S, convection has the following proportion:

$$Q\mu\ \ A_S \cdot [T_S - T_A] \ ^{(2)}$$

- **Thermal radiation** is electromagnetic radiation from an object's surface due to the object's temperature. Radiation is proportional to the object's absolute temperature raised to the fourth power and its surface area. Heatsinks with large surface area are effective at radiating heat. For a surface with area A_S and temperature T_S, convection has the following proportion:

$$Q\mu\ \ A_S \cdot [T_S - T_A]^{4\,(3)}$$

Thermal Equilibrium

Heat transference is an equilibrium condition. All three types of heat transference become more efficient as temperature gradients increase. The junction temperature will rise until the rate of heat transference out of the system is equal to the rate of heat generation at the junction.

Analogy to Electrical Circuits

Thermal systems are analogous to electrical circuits with the following relationships:

- Power dissipated **(Q)** - current
- Thermal resistance **(R8)** - electrical resistance
- Temperature difference **(ΔT)** - voltage

The Ohms law equivalent is:

$$\Delta T = Q \cdot R\theta \ ^{(4)}$$

Heat input is calculated:

$$Q = I_F \cdot V_F \ ^{(5)}$$

Where I_F is the operating current and VF is the measured forward voltage of the LED.

Thermal resistance is usually unknown and should be calculated using Equation 1 and measured **ΔT** and **Q**. For thermal interface materials (TIM), the thermal resistance of the material, $R\Theta_{TM}$, depends on its thermal conductivity, ***K***, expressed in W/m·*K*. Thermal resistance is calculated:

$$R\theta_{TIM} = k_{TIM} \cdot [l / A] \ ^{(6)}$$

Where ***l*** is the length of the thermal path and **A** is the cross-sectional area of the thermal path. To minimize thermal resistance, the cross-sectional area should be maximized and the thickness of the interface should be minimized.

Temperatures within the thermal system can usually be measured directly. Junction temperature is the exception, because the junction is inaccessible.

Fortunately, the forward voltage of an LED has distinct temperature dependence that makes the junction its own thermometer once calibrated.

Determining Junction Temperature from Forward Voltage

The forward voltages of nearly all III-V LEDs decrease by between 1 and 3 mV per 1˚ C increase in temperature.

The following test can be conducted on single components or on large assemblies with multiple LEDs. The temperature-forward voltage curve is empirically generated as follows:

1. Connect the LED to a constant current power supply and install the device in a controlled oven with the power off. Set the operating current, I_F, to the expected application condition.
2. Set the temperature to 25˚C and allow sufficient time for the oven and assembly to stabilize. Turn the power on for a short period, preferably less than 10 ms, and record the forward voltage, V_F. When possible, use sense cables to measure V_F. Since the LED is on for a very short period, it does not significantly heat itself and $T_J \sim T_A$.
3. Repeat step 2 at 50˚C, 75˚C, 100˚C, and 125˚C. ***Note that this test is destructive.***

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4. Plot T_J as a function of V_F and derive a best-fit line. The temperature dependence is not linear, but within the operating range a best-fit line is quite accurate.
5. Drive the assembly at the application I_F. The V_F will decrease until thermal equilibrium is reached. Cross the stabilized V_F with the plot generated in step 4 to derive the junction temperature.

Repeat the procedure for multiple current loads to fully characterize the system across all power dissipations.

Passive Thermal Management

Passive thermal management systems have no moving parts or consumption of additional energy. They rely primarily on conduction and radiation to remove heat from the junction. The typical method is to attach LEDs to a thermally conductive substrate, such as a metal-core IMS substrate or ceramic substrate, and then attach the substrate to a heat sink. Novel technologies such as Anotherm make it possible to attach the LEDs directly to the heatsink. Heat is conducted to the heatsink and radiated from its surface. Thermal performance is enhanced by reducing the length and thermal resistances along the path to the heatsink and by increasing the surface area of the heatsink.

Active Thermal Management

Active thermal management systems involve convection by incorporating fans, heat pipes and liquid cooling. These technologies enable significantly better thermal management and should be considered for ultra-hot applications. In most cases, they are more complex and require better design to avoid decreasing the reliability of the system. These trade-offs are manageable if extreme thermal management is required.

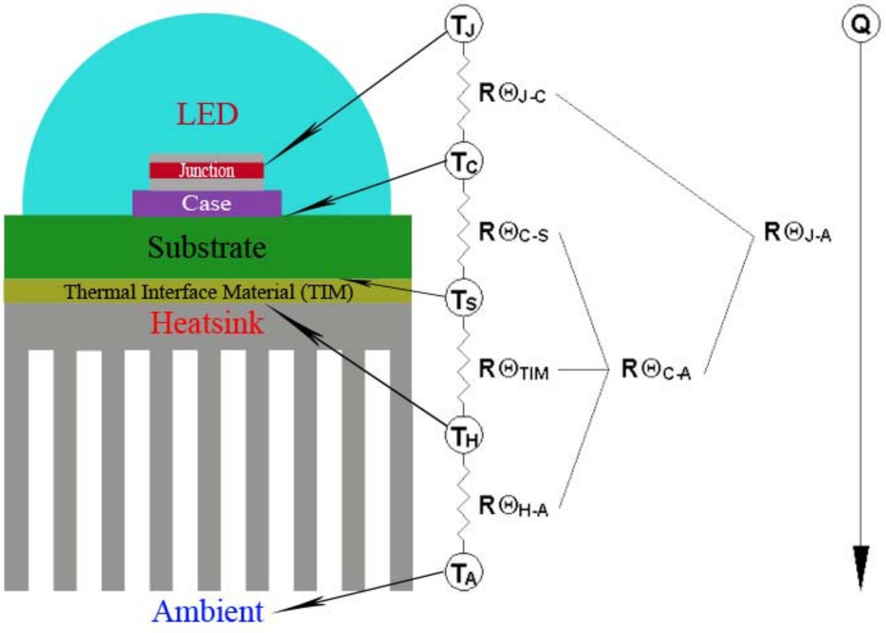

Figure 1 - Thermal Model for Single-Component Assembly

The assembly's thermal characteristics are expressed by the following equations:

$$\Delta T_{J\text{-}A} = Q \cdot R\theta_{J\text{-}A} \tag{7}$$

$$\Delta T_{J\text{-}A} = Q \cdot [R\theta_{J\text{-}C} + R\theta_{C\text{-}A}] \tag{8}$$

$$\Delta T_{J\text{-}A} = Q \cdot [R\theta_{J\text{-}C} + R\theta_{C\text{-}S} + R\theta_{TIM} + R\theta_{H\text{-}A}] \tag{9}$$

$\Delta T_{J\text{-}A}$ and **Q** must be measured and $R\theta_{J\text{-}C}$ is provided by the LED vendor. $R\theta_{C\text{-}A}$ is the combined thermal resistance of the rest of the assembly. Equation 9 can be used to calculate $\Delta T_{J\text{-}A}$ if sufficient data is supplied by the substrate, thermal interface material, and heatsink vendors; however, OPTEK recommends calculating $R\theta_{C\text{-}A}$ by rearranging Equation 8 to:

$$R\theta_{C\text{-}A} = [\Delta T_{J\text{-}A}] / Q - R\theta_{J\text{-}C} \tag{10}$$

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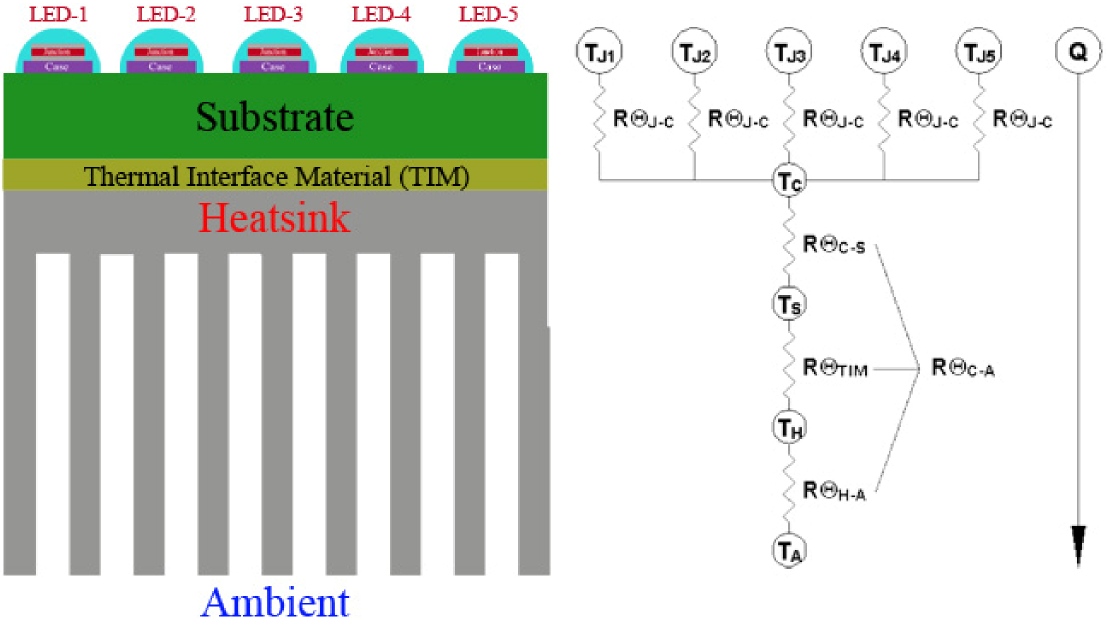

Figure 2 - Thermal Model for a Multiple-Component Assembly

The multiple-component assembly's thermal characteristics are described by equations that are similar to those for single-component assemblies:

$$\mathbf{\Delta T_{J\text{-}A\mathit{n}} = Q_{\mathit{n}} \cdot R\theta_{J\text{-}A\mathit{n}}} \tag{11}$$

$$\mathbf{\Delta T_{J\text{-}A\mathit{n}} = Q_{\mathit{n}} \cdot R\theta_{J\text{-}C\mathit{n}} + Q_{Total} \cdot R\theta_{C\text{-}A}} \tag{12}$$

$$\mathbf{\Delta T_{J\text{-}A\mathit{n}} = Q_{\mathit{n}} \cdot R\theta_{J\text{-}C\mathit{n}} + Q_{Total} \cdot [R\theta_{C\text{-}S} + R\theta_{TIM} + R\theta_{H\text{-}A}]} \tag{13}$$

$$\mathbf{R\theta_{C\text{-}A} = [\Delta T_{J\text{-}A\mathit{n}}] / Q_{\mathit{n}} - R\theta_{J\text{-}C\mathit{n}}} \tag{14}$$

For single-component assemblies, the equation for $\mathbf{R\theta_{C\text{-}A}}$ **(**equation 10) is derived from equation 8. Note that equation 14 was not derived from equation 12 in a similar manner. $\mathbf{T_C}$ is the same for all components on the multiple-component assembly, and $\mathbf{R\theta_{C\text{-}A}}$ can be derived based on one component's $\Delta T_{J\text{-}A}$, **Q**, and $\mathbf{R\theta_{J\text{-}C}}$.

For the same component and power dissipation, $\mathbf{\Delta T_{J\text{-}C}}$ will be the same whether the LED is alone or is part of an array. In an array, however, the heat input of all LEDs must be transferred through the substrate, TIM, and heatsink. $\mathbf{\Delta T_{C\text{-}A}}$ and $\mathbf{\Delta T_{J\text{-}A}}$ increase considerably over single-component assemblies.

When making a choice between **1** ***p*****-watt** component and ***p*** **1-watt** components, the *p*-watt component must have *p* times lower thermal resistance than the 1-watt component for the junction temperatures of both designs to be the same. The reality is that most package technologies for high-power LEDs have similar thermal resistances. Spreading the heat input to multiple components is recommended because less thermal management is required.

What Works?

Recommendations for reducing junction temperature without compromising luminous flux:

- Use components with better luminous efficacy to reduce $\mathbf{I_F}$ and **Q**
- Increase the number of components at the same total power dissipation to reduce $\mathbf{R\Theta_{J\text{-}C}}$
- Change to better packaged components to reduce $\mathbf{R\Theta_{J\text{-}C}}$
- Use Anotherm substrates to eliminate $\mathbf{R\Theta_{C\text{-}S}}$
- Use Anotherm heatsinks to eliminate $\mathbf{R\Theta_{C\text{-}S}}$ and $\mathbf{R\Theta_{TIM}}$
- Increase the heatsink's surface area to reduce $\mathbf{R\Theta_{H\text{-}A}}$
- Add a fan, heat pipe or liquid cooling to reduce $\mathbf{R\Theta_{H\text{-}A}}$

Practical Thermal Management Solutions

See component-specific application notes for empirical results and suggested changes.