Thermal Management Considerations for Visible LEDs in General Illumination and Signage Applications

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Historically, visible LEDs have been used as indicators with relatively low light output. LEDs used for these types of applications have typically been driven at low power with a minimum power dissipation of 150 mW or less. When visible LEDs were first specified for specialized illumination applications that required a solid-state lighting source, this low light output meant that most lighting applications required numerous low-power LEDs. With recent developments in increased efficiency and brightness for visible LEDs, however, they are now fulfilling a growing number of applications and design engineers are finding use for them in general illumination as well as signage and displays.

Visible LEDs

Visible LEDs have gained a high luminous efficacy as compared to incandescent and fluorescent bulbs. The new high-power visible LEDs have power dissipation ratings ranging from 500 mW to as much as 10 watts in a single package and this is only expected to increase in the future. With improving luminous efficacy, these high-power LED components can and will replace other lighting technologies in an increasing number of general illumination applications. Although LEDs are more efficient than incandescent and fluorescent lighting, thermal management is critical for proper operation and extended life span of the LED.

Several design considerations must be taken into account when using high-power visible LEDs in illumination applications. Those include:

- How much luminous flux is required?
- What is the desired dominant wavelength or color temperature?
- What is the required MTTF (mean time to failure)?
- How much flux degradation is tolerable?

Junction Temperature

The key to visible LED performance in any given application is maintaining the specified junction temperature. Junction temperature is critical and its importance cannot be overstated when it comes to the use of LEDs in general illumination and signage applications. Junction temperature directly alters the performance and reliability of LEDs in a number of ways:

1. Junction temperature reduces output power and forward voltage. For every 10°C rise in junction temperature, the luminous efficacy decreases by about 5 percent (at constant operating current).

2. Junction temperature also decreases forward voltage by about 20 mV for every rise of 10°C.

3. At this same rise in junction temperature, dominant wavelengths shift by about 2 nm.

4. Junction temperature also affects the performance of LEDs by shifting 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.

5. Increased junction temperature reduces MTTF and accelerates 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.

Junction temperature depends on three factors: power dissipation, thermal resistances of the substrate and assembly, and 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 of the device. 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.

Heat Transference

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.

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.

The third means of heat transference, 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. Typically, heatsinks with large surface area are effective at radiating heat.

Because heat transference is an equilibrium condition, all three types become more efficient as temperature gradients increase. Therefore, 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.

Determining Junction Temperature

Temperatures within a thermal system can usually be measured directly, however the junction of an LED is inaccessible, so the temperature cannot be calculated. Fortunately, the forward voltage of an LED has distinct temperature dependence that makes the junction its own thermometer once calibrated. This allows the junction temperature to be calculated from the forward voltage.

The forward voltages of nearly all III-V LEDs decrease by between 1 mV 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, IF, 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, VF. When possible, use sense cables to measure VF. Since the LED is on for a very short period, it does not significantly heat itself and TJ ~ TA.

3. Repeat step two at 50°C, 75°C, 100°C, and 125°C (note that at higher temperatures this test is destructive).

4. Plot TJ as a function of VF 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 IF. The VF will decrease until

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thermal equilibrium is reached. Cross the stabilized VF with the plot generated in step four to derive the junction temperature.

Repeating this process for multiple current loads allows the full characterization of the system across all power dissipations.

Signs and displays can utilize low current devices where thermal management is not a real issue, but most illumination applications require LED power ratings of 1/2 W and above. For these higher power LEDs, the junction temperature must be kept to about 85°C.

Passive Thermal Designs

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. Heat sinking on signage and illumination is a major challenge because LEDs can die if they are not properly attached.

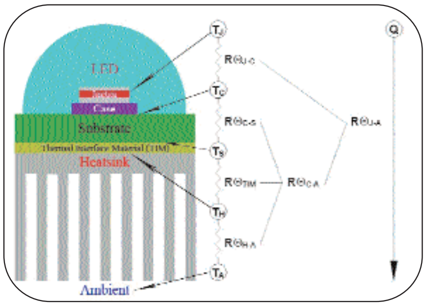

Figure 1. Thermal model for single-component assembly

Some technologies, such as Anotherm anodized aluminum substrates, make it possible to attach the LEDs directly to the heatsink. The Anotherm substrates feature an insulation system consisting of a thin layer of anodized aluminum oxide that is chemically grown on the aluminum core, producing a dielectric layer approximately 0.0014 inches thick (0.035 nm), which provides an inorganic insulation that is not affected by temperature or chemical exposure. This construction gives Anotherm technology the ability to operate in extreme temperatures, up to 175ºC, but the specified LED limits must be considered in practice.

By conducting heat to the heatsink and radiating it from the surface, thermal performance is enhanced because the length and thermal resistances along the path to the heatsink are reduced. Additionally, mounting LEDs directly to a heatsink eliminates the need for attached heatsinks, mounting hardware and the associated assembly costs, driving down the overall cost of the application.

Optek's LEDs are mounted onto thermally efficient substrates for use in indoor and outdoor signage and displays.

Some thermal management substrates, including Anotherm, can be designed for specific lighting applications. For example, the substrates can be formed in long strips to serve as the base for an LED replacement light source that takes on the form factor of a fluorescent bulb. If the device the LEDs are going to be mounted to can be used as part of the aesthetic appearance of the sign, the cost of the application is reduced even further.

Active Thermal Systems

Active thermal management systems, on the other hand, 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. Additionally, since most package technologies for high-power LEDs have similar thermal resistances, spreading the heat input to multiple components will require less thermal management.

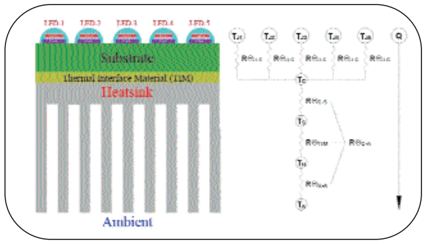

Figure 2. Thermal model for multiple-component assembly

For outdoor signage, such as portable warning signs, many remote installations utilize solar power to drive the LEDs. However, problems can arise because there is typically not enough power to run both the LEDs and the fans that keep the LEDs cool.

Another example is channel lights (LED assemblies that form visible letter displays) that use power LEDs mounted on FR4 PC board attached to the sign frame with tape. The tape acts as an insulator, hindering the thermal conductivity of the sign. This results in these types of signs being forced to run at a very low current, thus diminishing their light output.

For many companies in the illumination industry, the use of solid state lighting is relatively new. For most applications, the quickest time to market is realized with a partnership with an LED manufacturer who has experience with thermal management. When partnering with an LED manufacturer, it is important to consider whether or not they have an exclusive technical and engineering support staff, are capable of manufacturing high efficiency, properly packaged LEDs and have an on-site lab.

On-site labs provide manufacturers with the ability to compare traditional lighting solutions, such as incandescent and fluorescent sources, to solid-state lighting designs, as well as compare competitive LEDs and assemblies side-by-side. The lab's equipment will also provide spectral analysis of LEDs in both ultra-violet and visible wavelengths (200 nm to 780 nm), in order to make data-based comparisons.

Optek's visible LED laboratory, for example, includes a thermal imaging camera to provide data for optimizing thermal management designs enhancing the lifespan and light output of power LED assemblies; a scanning electron microscope with a Princeton Gamma Tech x-ray analyzer for failure analysis; a luminous flux and wavelength tester to verify color and hue; and a spectroradiometer system capable of light engines up to 0.2 meters to measure the radiometric and photometric characteristics of LED assemblies of all shapes. The spectroradiometer system also includes a goniometer, CIE 127 Publication Condition A&B tube and a 6-inch integrating sphere.

Optek Technology's on-site LED lab

The more efficient you make a device, the less you have to worry about thermal management. As the illumination and signage markets continue to grow, the use of LEDs will increase as well. By maximizing thermal efficiency, designers are able to use LEDs at their maximum brightness, taking advantage of their entire capabilities and powering their applications to the fullest extent.

Richard E. Saffa has more than 20 years experience in the optoelectronics, commercial, industrial, military and SSL markets. He began his career in optoelectronics at TRW and has held several management positions before joining Optek in 2005 as VP of the Visible LED Business Unit.

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