Technical Notes
Issue 1 January 2010

Thermal Management for LEDs

Poor thermal management can lead to early LED product failure. This Technical Note discusses thermal management techniques and good system design. (Manufacturers should serve as the primary guide for thermal management of their LEDs.)

The Information contained in this article builds on previous Technical Notes. See also: http://www.lightingafrica.org/resources/briefing-notes.html

Introduction

Light from an LED (light emitting diode) comes from the LED chip (or die) within the LED package. Light output increases with increasing drive current, but in addition to emitting visible light, the LED chip also becomes hot. This thermal energy limits the amount of power an LED can ultimately handle and must be conducted away from the LED chip and dissipated to the surrounding environment. Light output, light color, lumen maintenance, and LED lifetime are all adversely affected by excessive LED temperatures during operation.

The critical temperature of the LED is called the LED chip junction temperature (Tj). Tj is a function of:

- LED component design. Some LEDs have enhanced thermally conductive lead frames and can handle higher drive currents and power levels.
- LED forward current and voltage (this is the power dissipated in the LED). Higher drive currents result in more power dissipation and higher Tj.
- Printed circuit board (pcb) design.
- Thermal resistances of components in the system.
- Ambient temperature

Good LED product design achieves a balance between maximizing the light output from the LED (by increasing the drive current) while maintaining safe power and temperature levels in the LEDs and other system components. The designer must understand the basics of thermal heat transfer, employ proper thermal techniques in the design, measure the temperature of the LEDs, and reliably control the delivered power.

PCB (printed circuit board) Design

The PCB used to mount the LEDs is the first thermal conductor in the system, and frequently has the largest effect on heat transfer from the LEDs to the ambient environment.

Fortunately, copper is an excellent heat conductor and can serve as both an electrical connection and a thermal transfer surface. Just as thicker copper has lower electrical resistance, a thicker copper cross section will also exhibit lower thermal resistance.

Thick copper layers help with heat flow. Use 2 oz. or greater (>70 um) copper whenever possible.

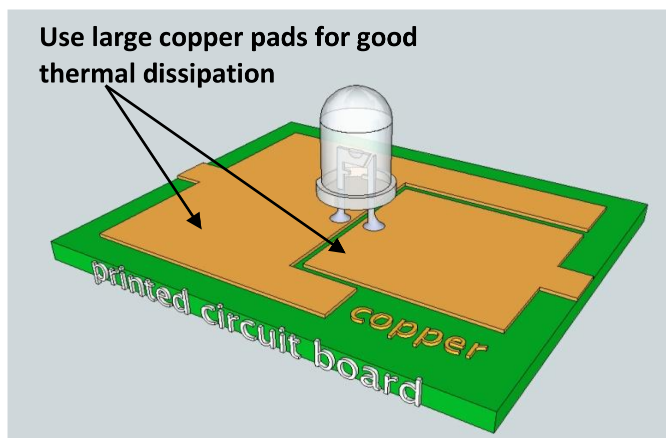

Fig. 1 Through-hole LED on a Printed Circuit Board (PCB) with copper pads for thermal dissipation

The copper pads used to solder the LED to the PCB should be as large as practical (Fig. 1). Pads should be on both sides of the PCB. The copper pad soldered to the heat sink side of the LED (usually the cathode) is the most important, but both pads can be large.

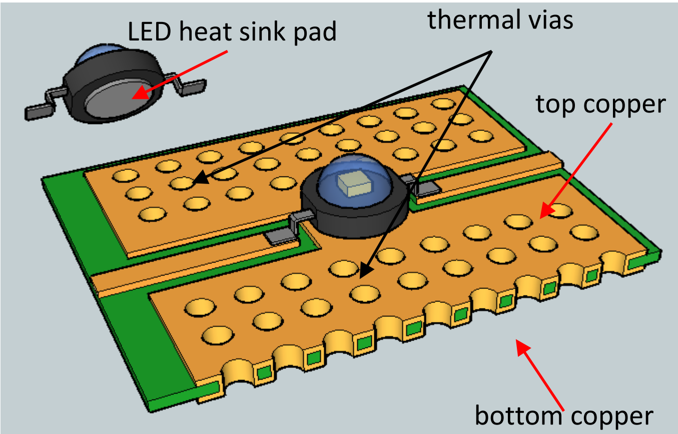

Fig. 2 Surface mount LED with thermal vias

For surface mount LEDs, use large copper pads on both sides under the heat sink of the LED. Connect pads with multiple vias (Fig. 2 above) to conduct heat from one side of the pcb to the other.

Metal Core Printed Circuit Boards (MCPCB)

Another type of circuit board is called a Metal Core Printed Circuit Board (MCPCB) that places an aluminum plate under the dielectric fiberglass layer (Fig 3). This 'core' facilitates heat flow and is often mounted onto a heat sink for use with higher power LEDs.

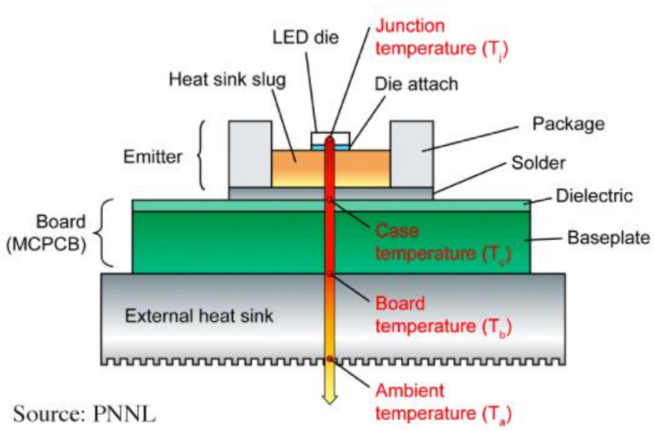

Fig. 3 Heat flow diagram of a metal core pcb

Measuring LED Temperatures

Direct contact measurements of the LED junction temperature are not possible because the LED chip is encapsulated. Instead, thermocouples are commonly used to measure the LED case temperature Tc (also known as the solder point temperature Ts or temperature measurement point TMP (Fig. 4)). Tc is specified by the LED manufacturer, and should be close to the LED chip junction. For through-hole LEDs, the thermocouple measurements will be taken on the lead that attaches directly to the LED chip.

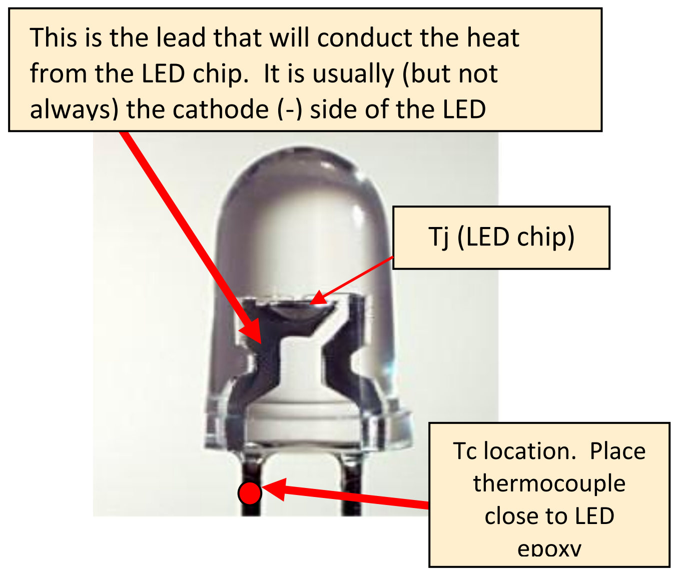

Fig. 4 Through-hole LED with Tj and Tc location

Thermal Measurement Guidelines

Good thermal measurement results are vital to proper design engineering. Care must be taken when making measurements because mistakes will yield temperature readings that are lower than the actual temperatures.

1) Check thermocouples for accuracy. Use ice water and boiling water to make sure the thermocouple measures 0 °C and 100 °C, respectively (these values apply at sea level; adjust as necessary for altitude).

2) Use thin gauge thermocouple wire (30 gauge or higher). The thermocouple mass should not be large enough to conduct significant heat away from the measurement point. This is particularly true of (5 mm) leaded thru-hole LEDs.

3) Attach the thermocouple to the LED case location with solder or a thermally conductive epoxy. Make sure that the head of the thermocouple is in good thermal contact with the metal lead. Type "T" thermocouples are composed of copper based wires and are easier to solder than other thermocouple types. Note that electrical noise can sometimes interfere with a thermocouple measurement, which may require the thermocouple bead to be electrically isolated from the LED lead. Read equipment instructions carefully and refer to thermocouple measurement guides when setting up thermal experiments.

4) Allow the LED light to warm up to a steady state temperature before taking measurements. This can be a half hour or longer depending on the luminaire

5) Take multiple measurements on different LEDs in a luminaire. Some LEDs can be run hotter than others, and it is important to measure the hottest LED in a group. LEDs in the center of an array usually, but not always, run at the highest temperatures.

Heat Flow Basics

Management of heat in LED products requires careful attention to heat transfer principles. Thermal energy (heat) flows from a hot object to a cool object when the two come in contact with each other. This is called ***thermal conduction,*** and both objects will eventually become warm (and equal in temperature) if no more heat is added to the system. If the warm objects are then allowed to come in contact with air, and the air is free to flow around them, the objects will transfer their thermal energy to the air by a process called ***convection***.

With both processes (convection and conduction), the amount of heat transferred from hot to cold is limited by the surface area of contact between the hot object and the cold object (or the cold air). This limit in heat transfer is mathematically represented by a thermal resistance.

Thermal Resistance

The flow of heat from an LED chip to the ambient environment can be modeled as a series of thermal resistances between the chip (at Tj) and the ambient environment (Ta). The sum of these resistances is the total thermal resistance for the system. The lower the thermal resistance, the more effective the design will be in conducting heat away from the LED chip junction.

One popular method for thermal resistance (R) notation is to use subscripts to describe the beginning and end points of a thermal path. For the entire path this is $\mathbf{R_{j\text{-}a}}$ and means the thermal resistance from ***junction to ambient.*** Including smaller individual steps along the way gives the general equation for the thermal resistance of the system:

$$\mathbf{R_{j\text{-}a} = R_{j\text{-}c} + R_{c\text{-}hs} + R_{hs\text{-}a}}$$

$\mathbf{R_{j\text{-}c}}$ = resistance from LED junction to LED case
$\mathbf{R_{c\text{-}hs}}$ = resistance from LED case to heat sink
$\mathbf{R_{hs\text{-}a}}$ = resistance from heat sink to ambient

Each thermal resistance step is given in degrees Celsius per watt (°C/W) and means the ***rise in temperature per watt of power dissipated***.

The LED manufacturer should list the value for $\mathbf{R_{j\text{-}c}}$ on the LED datasheet. Measurements of this LED case temperature Tc can then be used to estimate Tj. (see "Estimating LED Junction Temperature" below)

	Package type/ typical power	Typical Thermal resistance (R_{j-c})
	T-1¾ or 5mm LED 20 to 30 mA 0.07 to 0.1 watts	**Up to** **300** °C/W
	Thermally enhanced through-hole 70 mA 0.18 to 0.23 watts	**130-160** °C/W
	Surface mount SMT type "½ watt" 100 to 350 mA 0.3 to 1 watt	**40 – 130** °C/W
	Surface mount SMT power package 350 mA to 1+ Amp 1 to 10+ watt	**3 – 20** °C/W

Table 1. Typical LED thermal resistances **Note**: These are approximate values only. Actual thermal resistances vary by LED type and should be provided by the LED manufacturer.

Thermal Design "Rules of Thumb"

The goal of good thermal design is to keep the LED case temperatures, and therefore the LED junction temperatures, as low as practical. This means that each thermal transfer step should be designed to lower its thermal resistance. In general the following rules will apply to most LED systems:

1) **Space LEDs and power components as far apart as the optics will allow**. This lowers the energy density in the circuit and prevents hot spots.

2) **Make contact areas between mated parts as large as possible along the thermal path**. An increase in area will allow heat to conduct more easily between parts. ***Use heat transfer grease and thermal pads where possible to eliminate microscopic air gaps between surfaces.***

3) **Shorten the length of the thermal path and maximize conductor cross sections**. The farther heat has to travel from one side of a material to the other, the greater the resistance. When heat does need to be transported a long distance, use thick conductor cross sections. As with electrical conductors, heat flows better in short runs with large cross section conductors.

4) **Use high thermal conductivity materials**. Copper is a very good thermal conductor, followed by aluminum. ***Steel, particularly stainless steel, and plastics are poor thermal conductors*** and should be avoided in the thermal path.

5) **Design the luminaire housing to allow heat sink components contact with external ambient air.** The final step in the heat transfer path will be the transfer of heat to the ambient air. This is a critical step and often misunderstood. A large heat sink may not perform well if it is insulated or isolated from ambient airflow. Air itself is a poor thermal conductor, and heat sinks rely on the process of convection to transfer thermal energy. For heat sinks that are contained *inside* a plastic enclosure (the plastic case of the luminaire), the pocket of air surrounding the heat sink will be responsible for conducting and convecting heat out of the heat sink. If this pocket is isolated or sealed from the outside air, it may limit the transfer of heat and lead to higher LED junction temperatures.

6) Measure LED temperatures in normal operation. Careful measurements will reveal hotspots in the design. Always include actual ambient conditions in the tests, and allow the LEDs time to reach a steady state operating temperature. This can be 30 minutes or more depending on the size of heat sink components.

Estimating LED Junction Temperature

To calculate LED junction temperature, we must know the LED case temperature, the wattage (power) of the LED, and the thermal resistance **(R_{j-c}) (Example 1)**.

The power (in watts) dissipated in an LED is given by P = I x V, where I is the current in amps and V is the voltage drop of the individual LED. The voltage drop V can be measured with a multimeter when the LED is running normally. The current can be measured with a meter placed in series with the LED string, or calculated from the voltage drop on a series resistor R using Ohm's Law (V = I x R). Allow the system to reach a steady state operating temperature before taking measurements.]

For LEDs in series, the current in each LED is the same. For LEDs in parallel, the current may not be equal and some will have higher currents. In these cases. it is necessary to measure the current in each LED string simultaneously by inserting multiple current meters or having individual series resistors on each string.

Absolute maximum temperature ratings should be available from the LED manufacturer and listed on the LED specification sheet. A Tj of 125°C is a common maximum rating. While the LED can survive at this temperature, its lifetime may be very short.

LEDs that run at excessive temperatures will have *very short lifetimes* and fail to produce adequate light after a few short weeks or months of operation.

LED Lighting Product Lifetimes

Under normal operation and with proper thermal design, LEDs can operate for thousands of hours. The light output, however will decrease over time in a non-reversible process called *lumen depreciation*. Many manufacturers claim 100,000 hour lifetime ratings for their LED products. These claims are often overly optimistic and not supported by experimental data or actual product testing. The use of 100,000 hour lifetime ratings on product literature can spoil the marketplace by creating unrealistic expectations from consumers eager to try new LED technologies.

To ensure adequate lifetimes, LED temperatures should be measured under real world operating conditions and the measurement results compared to lumen depreciation data from the LED manufacturer. In addition, multiple test products should be run continuously early in the design phase. Lighting Africa recommends at least 2000 hours of test operation to rule out the possibility of early failure.

Heat Flow Basics

Conduction – transfer of heat through matter by communication of kinetic energy from particle to particle. An example is the use of a conductive metal such as copper to transfer heat.

Convection – heat transfer through the circulatory motion of a liquid or gas in contact with a hot surface. Air surrounding a hot object removes heat by conduction and convection, where gas molecules flow past the surface and remove heat energy. Good circulation is important to good heat transfer.

Radiation – energy transmitted through infrared electromagnetic waves. Visible light LEDs do not produce significant infrared radiation.

Heat sink – any thermally conductive element designed to transfer heat from a heat source (the LED) to the ambient environment. Heat sinks with fins are common and work by creating a large surface area