LED THERMAL MANAGEMENT

Dimitar Georgiev Todorov, Lazar Georgiev Kapisazov

Department of Electronics, Technical University of Sofia, 8, Kliment Ohridski St., Sofia-1000, Bulgaria, phone:+359/29653281, e-mail: dgt@vmei.acad.bg, lazar_gk@abv.bg

Light Emitting Diodes (LEDs) have been around for years, primarily concentrated as the lighting source for a variety of applications. Besides their electrical properties the optical parameters of LEDs also depend on junction temperature. The junction temperature of the power LEDs affects the device's luminous flux, the color of the device, and its forward voltage. The key in that case is maintaining the specified junction temperature. For this reason thermal characterization and thermal management play important role in case of power LEDs, necessitating both physical measurements and simulation tools.

Keywords: LED, Junction temperature, Thermal management

1. INTRODUCTION

The global lighting community expresses no doubt that high-power light-emitting diodes (LEDs) will play a major role in general lighting applications in the near future. Since its first demonstration in 1994, white LED technology has rapidly evolved and has now reached a stage that it can compete with traditional light sources in some niche lighting applications [1]. However, thermal management is one of the major issues to be improved for implementing LEDs into lighting fixtures because heat affects the performance and reliability of those fixtures and LEDs. When it comes to the thermal management of an LED, thermal resistance is an important device performance parameter, indicating the obstruction of the heat flow from the p-n junction to the ambient during operation. Manufacturers of high-power LEDs have been exploring and using components with high thermal conductivity within the LED package to lower the thermal resistance from the p-n junction to the LED board, so that the junction will be at a lower temperature during operation. Therefore, measuring junction temperature is one way to evaluate the performance of an LED. To the first order, junction temperature is a good predictor of LED life. It has been a common practice in the industry to use the following one-dimensional heat transfer equation for conducted heat to estimate junction temperature, T_j:

$$T_j = T_b + R\Theta_{jb}(P) \quad (1)$$

where T_b is the board temperature, $R\Theta_{jb}$ is the junction to board thermal resistance coefficient, and P is the total power dissipated at the junction of LED. When using the above equation, it is assumed that $R\Theta_{jb}$ is a constant, independent of how the LED is driven or where it is used. However for high-power LEDs, $R\Theta_{jb}$ is not a constant and changes with power dissipation, ambient temperature, and the amount of external heat sink provided to the LED. $R\Theta_{jb}$ for high-power LEDs is not a constant and is affected by factors such as power, ambient temperature, and applied pressure at different interfaces.

2. JUNCTION TEMPERATURE

The light output of different colored LEDs responds differently to temperature changes, with amber and red the most sensitive, and blue the least Fig. 1. These unique temperature response rates can result in noticeable color shifts in RGB-based white light systems if operating Tj differs from the design parameters. LED manufacturers test and sort (or "bin") their products for luminous flux and color based on a 25 millisecond power pulse, at a fixed Tj of 25°C (77°F). Under constant current operation at room temperatures and with engineered heat mitigation mechanisms, Tj is typically 60°C or greater. Therefore white LEDs will provide at least 10% less light than the manufacturer's rating, and the reduction in light output for products with inadequate thermal design can be significantly higher [2].

COLOR	K (nm/°C)
Amber	.09
Red	.03
Blue	.04
Green	.04
Cyan	.04

Table1 Dominant λ vs. Temperature [4]

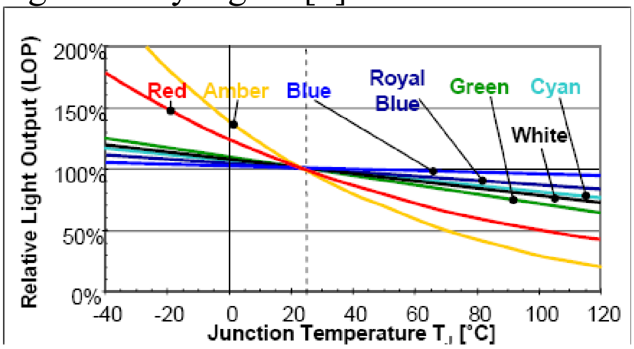

Fig. 1 Light output vs. temperature changes [4]

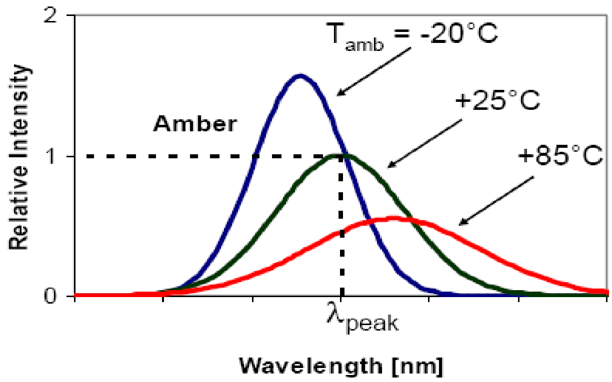

Fig. 2 Wavelengths shift due rise temperature [4]

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 [3]:

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 20mV for every rise of 10°C.

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

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 (2):

(2) $$\Delta\lambda_D/\Delta T\ (nm/°C) \approx K,$$

where $\Delta\lambda_D = \lambda_{D2} - \lambda_{D1}$, $\Delta T = T_2 - T_1$, λ_{D2} – wavelength at temperature T_2, λ_{D1} - wavelength at temperature T_1.

5. Increased junction temperature reduces MTTF (mean time to failure) 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.

A series of things affect the junction temperature of an LED: drive current, LED forward voltage, the method of driving an LED, thermal path (thermal resistance) from the LED junction to ambient, wattage output of the LED(s) per dissipating surface area, orientation of an LED fixture and the spatial LED configuration, and ambient temperature. 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.

In general, the higher the drive current, the greater the heat generated at the die. A light output of the same LED die on different circuit board materials at a maintained die temperature of 50°C. Heat must be moved away in order to maintain expected light output, life, and color. The amount of heat that can be removed depends upon the ambient temperature and the design of the thermal path from the die to the surroundings.

As shown in equation (3), the thermal resistance $R\Theta_{jb}$, from the junction to board of a high-power LED can be estimated by measuring the junction temperature T_j, and the board temperature T_b for a given power dissipation P_d:

(3) $$R\Theta_{jb} = (T_j - T_b)/P_d, \qquad P_d = I_f \times V_f$$

where I_f is a forward current and V_f – forward voltage on LED.

If we consider only the power that is not turned into radiant energy, then equation (3) becomes:

(4) $$R\Theta_{jb} = (T_j - T_b) / (P_d - P_o),$$

where P_o is the radiant optical power emitted by the LED.

For systems involving conduction between multiple surfaces and materials, a simplified model of the thermal path is a series-thermal resistance circuit, as shown in Fig. 3. The overall thermal resistance ($R\Theta_{JA}$) of an application can be expressed as the sum of the individual resistances of the thermal path from junction to ambient (Equation 5). The corresponding components of each resistance in the heat path are shown in Fig. 4. The physical components of eachresistance lie between the respective temperature nodes [5].

(5) $$R\Theta_{JA} = R\Theta_{J\text{-}S} + R\Theta_{S\text{-}B} + R\Theta_{B\text{-}A}$$

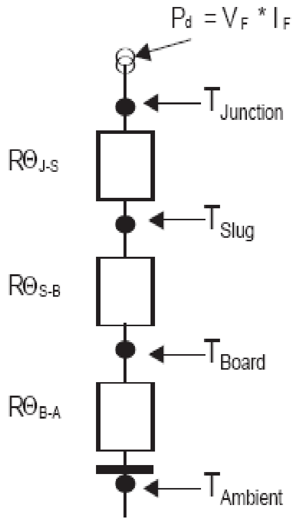

Fig. 3 Resistance Series Configuration

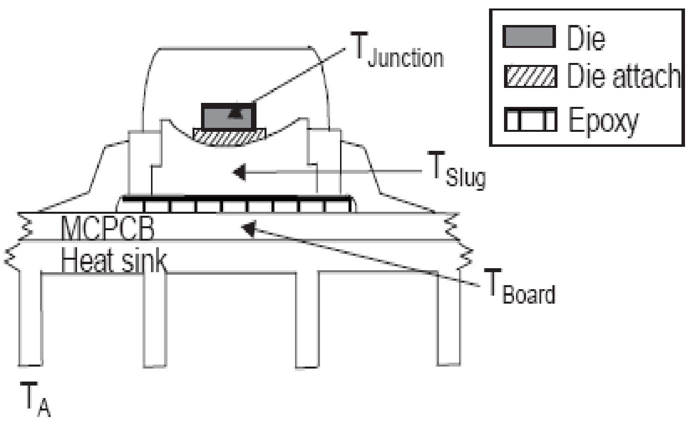

Fig. 4 Junction to ambient heat-flow path

where $R\Theta_{J\text{-}S(Junction\text{-}Slug)}$ = RΘ of the die attach combined with die and slug material in contact with the die attach; $R\Theta_{S\text{-}B(Slug\text{-}Board)}$ = RΘ of the epoxy combined with slug and board materials in contact with the epoxy; $R\Theta_{B\text{-}A(Board\text{-}Ambient)}$ = the combined RΘ of the surface contact or adhesive between the heat sink and the board and the heat sink into ambient air. To maintain a low junction temperature, all methods of removing heat from LEDs should be considered. In the case of LED systems there are two important thermal paths whose resistance affects the junction temperature:

1. The thermal resistance between the LED junction and the solder point ($R_{th\ j\text{-}sp}$);
2. The thermal resistance between the solder point and ambient ($R_{th\ sp\text{-}a}$).

where $R_{th\ j\text{-}sp}$ is thermal resistance between junction and the solder point, and $R_{th\ sp\text{-}a}$ – thermal resistance between the solder point and ambient. The overall thermal resistance between the LED junction and ambient ($R_{th\ j\text{-}a}$) can be calculated as the sum of the series resistances $R_{th\ j\text{-}sp}$ and $R_{th\ sp\text{-}a}$ as shown in Fig. 5. Over the last 15 years the development of high power LEDs have required new materials and package formats to be used in order to help reduce overall LED thermal resistances.

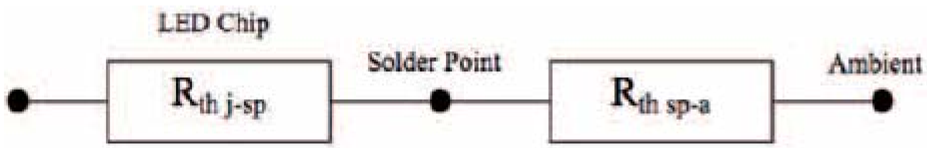

Fig. 5 Overall thermal resistance

A typical LED fixture will comprise of an LED emitter placed upon a metal-core printed circuit board (MCPCB) attached to a form of heat sink as shown in Fig. 4. The LED die thermally conducts heat through the heat sink slug within the LED emitter which is soldered onto a MCPCB that is mechanically connected to an external heat sink which can be a dedicated device integrated into the luminaire or the case of the luminaire itself. The heat sink then diffuses heat to the ambient surroundings through convection. It is important to note that at every interface within the thermal path shown in Fig. 4 there is a resistance to heat transfer which needs to be minimised as far as possible. Therefore, many LED fixture designs employ a thermally conductive paste or thin film (made typically from silicone oil filled with aluminium oxide, zinc oxide, boron nitride or nanodiamond thermal grease) between the MCPCB and an external heat sink to reduce air gaps which are not very good thermal conductors and to significantly improve heat transfer.

3. THERMAL MANAGEMENT SOLUTIONS

For specifying of power LEDs at their maximum power levels "The Bergquist company" with vast experience in the thermal field, present solid customer-focused solutions [6]: Thermal Clad^R Insulated Metal Substrates (IMS), Thermally Conductive Adhesives, Thermal Interface Compounds and Thermally Conductive Gap Filling Materials (Fig. 6). Other decision is Synjets an Nuventix [7] with their SynJet^{TM} module (Fig. 7).

The SynJet^{TM} module creates turbulent, pulsated air-jets that can be directed precisely to locations where thermal management and spot cooling are needed for challenges requiring high-reliability cooling and flexible form-factor implementations. The SynJet module expels high momentum pulses of air. The Fig. 8.1 shows the velocity vectors of the SynJet flow as the jet is ejected. Figure 8.1a shows the pulse of air emerging from the nozzle. In Figure 8.1b the pulse has moved away from the nozzle. Note the large velocity vectors associated with the vortices accompanying the SynJet formation. In Figure 8.1c the pulse has moved further away, and the entrained air can be seen behind it in the form of the large velocity vectors all pointing in the direction of the pulse. In Figure 8.1d the tail of the pulse is seen. Finally in Figure 8.1e the pulse has almost fully left the frame, and the air can be seen recharging the nozzle in preparation for the next pulse. The qualities of SynJet modules are: increased thermal efficiency, low audible noise (< 22dBA at 1 meter), low power consumption (to 1.5W) and high reliability cooling outpaces even a high reliability fan.

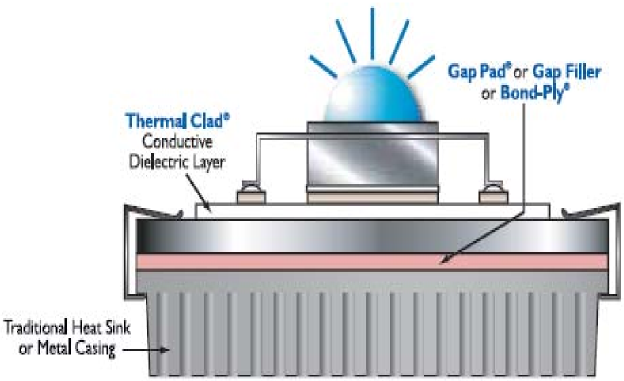

Fig. 6 Thermally Conductive Gap Filling Materials

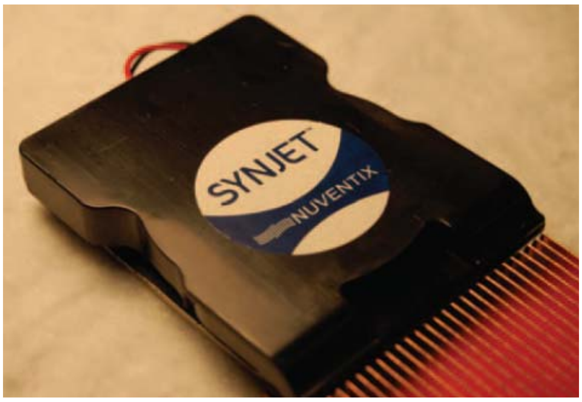

Fig. 7 SynJet module

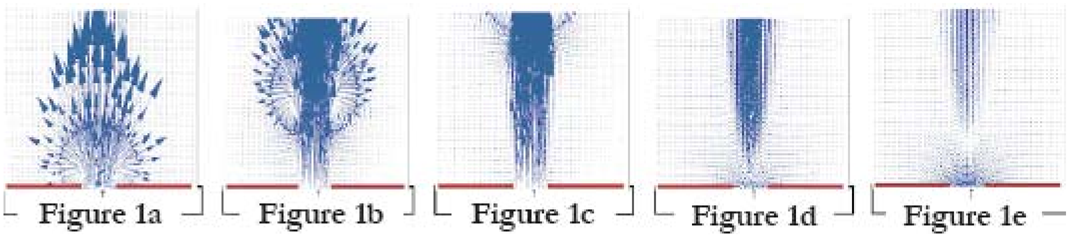

Fig. 8.1 Velocity vectors of the SynJet air flow

4. CONCLUSION

1. Thermal management is one of the key areas that need serious attention when designing power LED fixture.

2. Effective thermal management will prolong the LED lifespan and also reduce the IV drop due to the increasing LED junction temperature.

3. One way to effective thermal management is to use high thermal conductivity materials and methods to transfer the heat away from the LED junction as efficiently and quickly as possible.

4. The number of mating surfaces and interfacial thermal resistance between any mating surfaces must to be reduce by using a thermal interface compound and high bonding pressures.

4. REFERENCES

[1] Jayasinghe, L., T.Dong, and N. Narendran, *Is the thermal resistance coefficient of high-power LEDs constant?* Seventh international conference on solid state lighting, 2007

[2] *www.netl.doe.gov/ssl*

[3] *www.ledjournal.com*

[4] *www.luminary.kr*

[5] *www.luxeon.com*

[6] *www.bergquistcompany.com*

[7] *www.nuventix.com*