Thermal Management of UV LEDs: From Junction Temperature to System Reliability

Introduction

Light-emitting diodes have proven their benefits and have been adopted at a large scale in many general lighting applications. Although there are many advantages to using LEDs over traditional lighting sources, thermal properties of LEDs must be appropriately understood and managed to achieve optimized usage. Without a suitably designed thermal management solution, LED systems may encounter issues such as shortened lifetime and rapid degradation in output levels. Visible LEDs generally have efficiencies ranging from 30-40%, resulting in 60-70% of the remaining energy to be generated as heat. In the case of ultraviolet LEDs, the impact of heat generation is exacerbated due to lower conversion efficiencies. The efficiency of most commercially available UVC LEDs is <10%, which creates a critical need for sufficient cooling before UVC LEDs can be integrated effectively.

While this paper will highlight the principal concepts of heat generation in LEDs and how the performance of LEDs can be affected by heat, we want to emphasize what Christian Belady rightly mentioned in this article [1]:

> “The ultimate goal of system thermal design is not the prediction of component temperatures, but rather the reduction of thermally associated risk to the product.”

Taking the end-product into consideration, the target of an LED product designer is not to measure or determine temperatures but to ensure that the product can withstand the target lifetime and operate at a certain efficiency, while keeping the thermal budgets low and within

BOM costs for production quantities. Thermal designs may be compared and evaluated using the LED junction temperature as a performance indicator, as the junction temperature directly affects the optical output and overall lifetime of an LED. Lowering the junction temperature hence becomes a critical design task to ensure system performance and reliability. Furthermore, tradeoffs on cost as well as the mechanical dimensions require consideration and a thorough understanding of user requirements and the end product.

Keeping this in mind, it is important to understand the underlying mechanism of heat generation in an LED and the different stages at which positive interventions can be made during product development to control junction temperatures.

Heat Generation in LEDs

The primary thermal emission source in the LED package is the heat generation at the junction due to nonradiative recombination processes [2]. Shockley-Read-Hall (SRH) recombination dominates at low carrier-densities while Auger recombination dominates at high carrier densities. The SRH processes occur due to defects and impurities in the crystal and the energy released after recombination is released as phonons (heat) instead of photons (light). In Auger processes, electrons collide with other electrons and emit heat rather than emitting light. Auger recombination also causes efficiency droop at high current densities. The droop effect is different from efficiency reduction caused by LED heating due to higher drive current which can be optimized via adequate thermal design.

The series electrical resistance of the diode along with that of interconnects causes Joule (I^2R) heating. Junction temperature at high-driving currents is affected by the resistance as shown in Equation 1:

$$T_J = T_C + R_{th} \cdot (I_F \cdot V_F - P_o) \quad [1]$$

where T_C is the case temperature, R_{th} is the junction-to-case thermal resistance, T_J is the junction temperature, I_F is the drive current, V_F is the forward voltage and P_o is the optical power.

Thermal resistance, if lowered, can hence directly contribute to the reduction of junction temperature. This value is typically provided on product datasheets in the form of a junction-to-case resistance value and allows for comparative evaluation of similar products. In addition to this, photon re-absorption in the material can also contribute to the overall heat generation in the LED.

Heat Extraction through the LED System

To understand and evaluate the effect of thermal management on UV LEDs, it is vital to understand the LED supply chain and the various levels at which intervention can aid in reducing thermal effects. From a well-designed quantum well to a thermally efficient LED package, accompanied with passive or active thermal management components at the module and at the end-product level, the overall system efficiency and lifetime can be improved. Figure 1 shows the simplified LED supply chain [2].

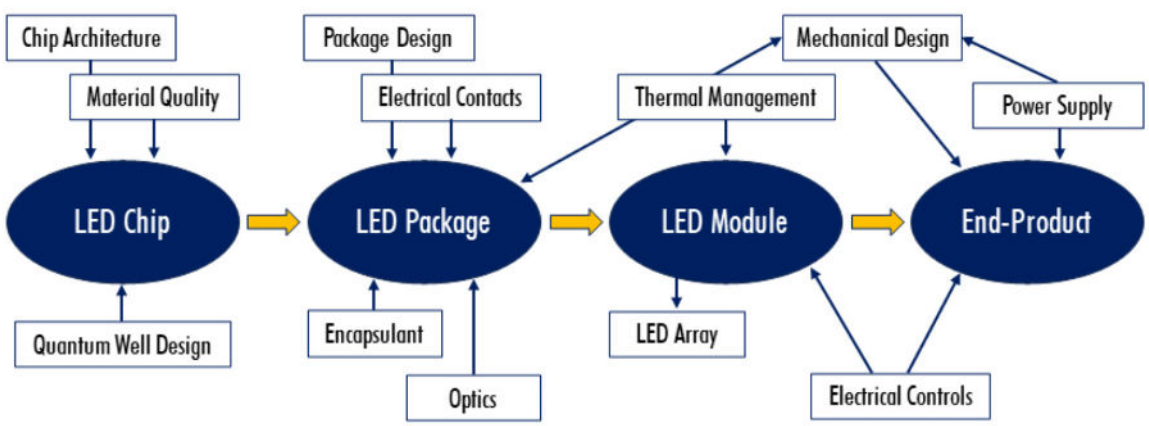

Figure 1. LED supply chain (Adapted and redrawn from [2]

The first contributor to higher temperatures is the LED chip which generates heat due to the non-radiative recombination processes. This heat is conducted through the back of the LED chip to the printed circuit board on which the chip is mounted. In order to improve thermal dissipation, a large surface area, electrically isolated, ***thermal pad*** may be integrated into the LED and mate with the thermal pad on the PCB. This intervention in packaging can enable high lifetimes and optical output. While most of the heat may be directed through the thermal pad, electrical connections can also carry a small amount of heat. Figure 2 shows an example of a package using an additional thermal pad, creating a direct thermal path from the LED to the PCB pillar.

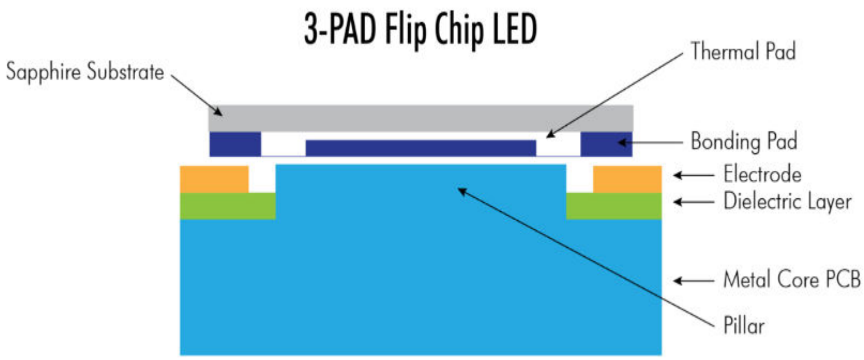

Figure 2: One of the ways to extract heat from the LED chip is by addition of a thermal pad (T-pad)

The composition of the printed circuit board, the size and materials of the thermal vias and the surface metallization also need to be considered. For UV LED chips, it is important to choose a metal-core printed circuit board with appropriate material selections to improve heat dissipation. Metal Core PCBs (MCPCBs) are engineered to merge a circuit board with a heat sink for better heat dissipation and consist of three main layers: a copper foil on the top, a dielectric insulator, and an aluminum or copper base. A typical FR4 PCB has a thermal conductivity of around 0.25W/m·K, while the thermal conductivity of aluminum-based PCB material is >1W/m·K and the thermal conductivity of a copper-based PCB material is >3W/m·K.

While additional heat management methods may not be needed for low-power visible LEDs as most of the heat can be extracted through the board, UV LEDs driven at high drive currents require a larger surface area to extract heat.

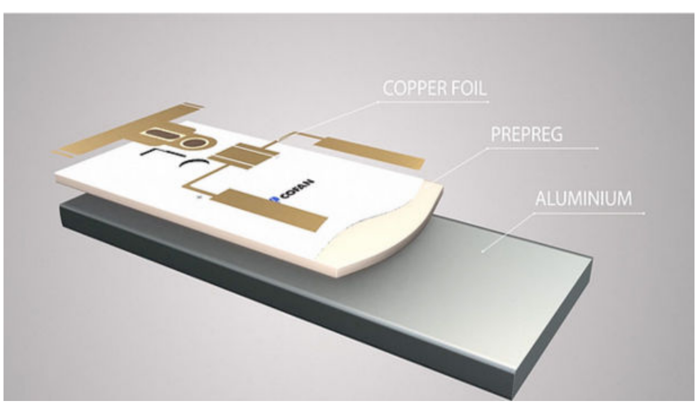

Figure 3: Example of a structure of a metal-core PCB (MCPCB) with an aluminum base which acts as a heatsink. Aluminum is chosen often due to its high thermal conductivity and lower costs as compared to copper. [3]

Effect of Heat on LEDs

Heat affects many aspects of the LED including its lifetime and radiant flux output. Below are some of the parameters that should be taken into consideration:

- **Material quality:** Increase in junction temperatures can lead to temporary or permanent degradation in the different layers of the LED and hence affect reliability and lifetime.
- **Light output:** LED light output decreases with a temperature rise in the LEDs, since the quantum efficiency decreases at higher temperatures, which contributes to more nonradiative recombination events in LEDs.
- **Efficiency:** Efficiency decreases specifically at higher drive currents as the joule-heating effects would increase.
- **Reliability and lifetime:** LED Lifetimes can significantly reduce at higher junction temperatures.

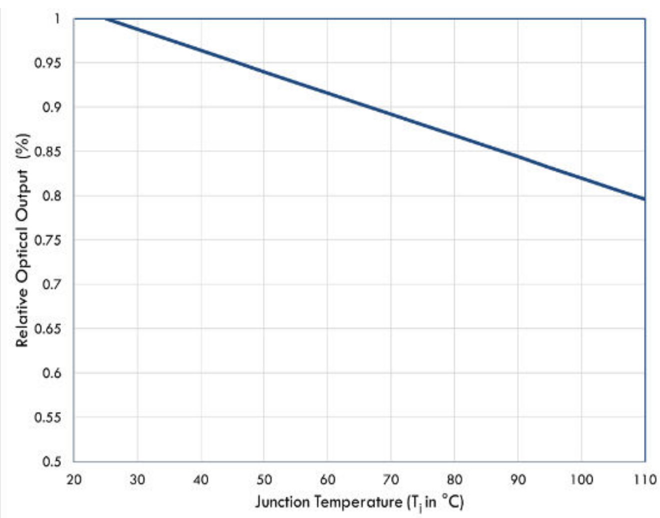

Figure 4: Decrease in light-output with increase in junctional temperature

- **Spectral variation:** Color and peak wavelength shifts are possible due to changes in temperature. In visible LEDs, the spectral shift is seen towards longer wavelengths.

Heat management interventions can be made at package, module and system level to improve LED lifetimes and reliability. Product designers have the challenging job of finding suitable thermal management methods which are suitable in terms of mechanical requirements and cost trade-offs.

References:

[1] https://www.electronics-cooling.com/2003/05/effective-thermal-design-for-electronic-systems/

[2] Lasance CJM, Poppe A (2014) Thermal Management for LED Applications (Springer New York).

[3] https://www.cofan-pcb.com/mcpcb

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[5] Weblink: https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/led/heatSinkingMaterials.asp

[6] https://www.cofan-usa.com/products/vapor-chambers