Thermal Consideration of Flash LEDs
Application Note

Abstract
This application note focuses on how to develop an adequate thermal management for LEDs in camera flash applications.

Introduction
LEDs are very common in modern mobile devices, such as mobile phones and tablet PCs and are used for features like camera flash, torch or beacon light. Depending on the function, the LEDs either operate continuously in the milliampere range (torch) or pulsed in the ampere range (flash).

Generally speaking, the operation of LEDs is restricted by a number of different factors based on the technology and the material used. Key parameter here is the temperature at the active semiconductor layer (junction temperature), as it influences the function of the LED.

Thus, the primary objective in the application is to ensure that the maximum value recommended by the LED manufacturer is not exceeded during operation. This generally means that a suitable thermal management system is absolutely essential in the application. A key consideration during the development of a thermal management system is the thermal resistance of the overall system.

In pulse mode, however, the usual description of the thermal performance of a LED - the thermal resistance $R_{th,JA}$ (junction to ambient) used for DC operation - is not useful since the pulse width is often limited to milliseconds.

The usual approach would result here in a redundant and expensive thermal design.

Therefore for pulse operation it is more useful to consider the transient thermal behavior of the LED system setup. Its adequate design can limit the junction temperature to within the ratings of the LED device even in the presence of high dissipation peaks.

The following document provides information on critical factors and the thermal properties of LEDs during a range of operation modes as well as information on how to develop an adequate thermal management in flashlight applications.

Basics of LED Systems
LED systems are typically designed according to a basic structure and comprise one or more LEDs affixed to a PCB for control and operation purposes. Depending on the application and the related requirements and conditions, this setup is generally mounted on a heat sink (such as cooler, enclosure cover, carrier, etc.) for enhanced heat dissipation.

In the case of flash applications, it is usually necessary to drive the LED without extended heat sinks due to space restrictions. Instead, the board should be connected to shielding integrated in the device or to the cover in order to achieve a degree of heat distribution.

Figure 1 shows a diagram of the basic configuration of an LED system.
The degree to which the LED system influences operating conditions depends on a range of factors, based on the technology and the material used. The critical factors can generally be grouped into two categories/levels relative to the system – the LED itself and the remaining configuration of the application.

**Critical factors - LED**

On the LED side, the operating conditions are primarily influenced/restricted by the semiconductor and chip technology used and the design of the chip. The semiconductor technology determines the maximum permitted junction temperature ($T_{J,\text{max}}$). The chip technology and design are relevant for high current capability and decisive for the minimum and maximum forward current ($I_{F,\text{min}} / I_{F,\text{max}}$), as well as for the pulse current ($I_{F,\text{plus}}$) with which the LED can be operated.

Furthermore, package and lens material influence the maximum operating temperature ($T_{OP}$) in the application and the maximum temperature when handling the LED (assembly, mounting).

Together, the material and construction of the LED determine the thermal behavior of the LED during operation, and thus, the thermal resistance ($R_{th,\text{JS}}$) of the LED (Figure 2). The thermal resistance is usually specified in the data sheet of the respective component. For the application, the thermal resistance of an LED represents a predefined value, which cannot be modified by the customer.

**Critical factors - application**

On the application side, the operating conditions are largely influenced by the system setup, starting with LED connection, solder pad design and PCB type and through to the use/non-use of a heat sink. This influence is primarily based on the thermal properties of the individual components. The main objective is to keep the junction temperature during operation below the maximum permitted value. The component with the greatest potential influence in this instance is the PCB. The type, material and setup of the PCB determines its thermal resistance, which in turn has considerable impact on the thermal properties of the application.
In relation to this, the design of the solder pad also contributes to the thermal character of the system. The way in which the LED is connected to the PCB (solder, adhesive, clamps, contact pins, standard or low-temperature solder, etc.) also has a certain influence on the operating parameters. The thermal resistance of contact pins, for example, is considerably higher than that of a bonded or soldered joint.

The application-specific thermal resistance ($R_{th, SA}$), which comprises the values of the individual components of the system (Figure 2), generally serves as system-relevant characteristic. It generally applies that the smaller the thermal resistance $R_{th, SA}$, the better the thermal conductivity of the overall setup, and the higher the operating conditions/parameters under which the LED can be operated.

The data sheets of the LEDs show these influences in the DC derating diagram, which describes the dependence of the maximum forward current of an LED in a system on the ambient temperature.

Figure 3 shows a general representation of a DC derating with limiting/critical factors and their effect. By way of an example, the diagram shows the influence of the application-specific resistance (Setup 1, Setup 2,…) on the maximum permitted forward current and the limitations caused by the respective LED.

![Figure 3: General representation of LED and application-specific influences on the DC derating (max. permitted forward current)](image-url)
Static Operation

Assuming that constant power is dissipated in the semiconductor within the LED, the junction temperature reaches a value determined by the thermal resistance from the junction where the power is generated to the lower side of the LED package respectively the contacts or the substrate.

For this the static equivalent circuit diagram for one dimensional heat flow is shown in Figure 4. The power dissipation \( P_D \) is symbolized by a current source.

\[
\begin{align*}
T_1 - T_2 &= P_D \cdot R_{th} \\
T_j &= T_A + P_D \cdot (R_{th, JS} + R_{th, SA}) \\
\frac{T_j - T_A}{P_{D, LED}} &= R_{th, JS} = R_{th, SA}
\end{align*}
\]

Figure 4: Static Equivalent Circuit for one dimensional heat flow

In accordance with the analogy, the thermal current \( P_D = Q/t \) can now be calculated from the “thermal Ohm’s law”. For an overview of the used parameter a nomenclature is shown at the end of the paper.

\[ T_1 - T_2 = P_D \cdot R_{th,12} \]

When the amount of generated heat in the junction equals the heat transferred away, a steady state condition is reached and the junction temperature of a LED (for multichip LEDs it will be assumed that all chips have the same power dissipation level) can be calculated by the simple equation:

\[ T_j = T_S + P_D \cdot R_{th, JS} \text{ real}; \quad P_D = P_{el} - P_{opt} \]

In this case of thermal steady state behavior, a LED can be characterized with the thermal resistance value \( R_{th, JS} \text{ real} \) specified in the data sheet. For an analysis of LED systems and the development of a suitable thermal management system for DC operation, the equation must be expanded to include system-related parameters.

Dynamic Operation

Single Pulse (\( Z_n \))

While the thermal characteristics for stationary states can be described by the thermal resistance \( R_{th} \), dynamic, pulsed processes, in the region of micro- to milliseconds, additionally require that the thermal capacitance of all components has be taken into account.

This behavior can be described by terms of thermal capacitance \( C_{th} \) which is directly proportional to the relevant volume \( V \), to the density \( \rho \) of the material and to a proportionality factor of the specific heat \( c_p \). The applicable equation is:
The thermal capacitance of a body of mass \( m = \rho \times V \) corresponds to the quantity of heat needed to heat the body by 1°C. To calculate the temperature change \( \Delta T \), it is necessary to use the quantity-of-charge equation for a capacitance \( C \).

\[
\Delta T \cdot C_{th} = P_D \cdot t = Q.
\]

The power dissipation \( P \) represents the transport of thermal energy per unit of time. Consequently:

\[
\Delta T = \frac{P_D \cdot t}{C_{th}}.
\]

The equivalent circuit with the thermal capacitances added, is shown in Figure 5.

![Figure 5: Transient Equivalent Circuit for one dimensional heat flow](image)

The added thermal capacitances are shown in parallel with the thermal resistances. The product of the thermal resistance and capacitance gives the time constant \( \tau \):

\[
\tau = R_{th} \cdot C_{th}.
\]

This value determines how fast the temperature rise will occur with respect to time.

The junction temperature transients can be represented in form of a function if the dynamic thermal impedance \( Z_{th} \) is shown versus the pulse width.

\[
Z_{th} = \frac{\Delta T}{P_D} = \frac{T_{\text{max}} - T_{\text{min}}}{P_D}
\]

For any pulse length \( t_p \), a transient thermal resistance \( Z_{th}(t_p) \) is defined as the ratio between the rise of temperature at the end of the pulse and the dissipated power.

![Figure 6: Effect of a single power pulse](image)

Figure 7 shows the thermal impedance in single power pulse operation using the example of an OSLUX “LUW FQEL” LED. This function shows the regions of dominance of the various time constants.

For an infinite pulse length, the transient thermal resistance reaches a constant value. This is the steady state thermal resistance \( R_{th} \).

As described above, the dynamic thermal impedance of a LED is defined as the ratio of the temperature difference \( \Delta T = T_J - T_s \) and the power dissipation.

\[
Z_{th, \text{LED} \text{real}} = \frac{T_J - T_s}{P_D} \quad \text{(LED)}
\]

where

\[
P_D \, [W] = P_{el} - P_{opt} = \text{power dissipation}
\]

The described \( Z_{th} \) function characterizes the transient thermal behavior of a LED and is always of interest in applications where pulse operation thermal resistances are required which are below the steady state value.
For the analysis of pulsed LED systems, the application-specific parameters also need to be taken into account and the equation adapted accordingly. For the calculation of the junction temperature in the system the following formula applies:

\[ T_J = T_A + Z_{th,LED-S} \cdot P_D \]  
(LED system)

**Continued Pulse (Z\_th\_*)**

From a thermal standpoint, this operating mode represents a mixture of pulsed and continuous operation, during which a self-adjusting mean base temperature is superimposed with temperature peaks. For the characterization of the thermal behavior the so-called Z\_th\_* is used here, which describes the transient thermal resistance dependent on the repetition rate and the duty cycle.

\[ Z_{th}(t_p; D) = (1 - D) \cdot Z_{th}(t_p) + D \cdot R_{th} \]

with

\[ D = \frac{t_p}{T} \quad \text{and} \quad R_{th} = Z_{th} \quad (for \ t_p \rightarrow \infty) \]

Due to the complex interrelations and transient behavior of continued pulsed systems, one usually considers the thermal state at the end of a pulse in order to obtain an impression of the maximal change in temperature.
If $Z_{th}^*$ is multiplied by the maximum power dissipation during the pulse, an upper estimate for the junction temperature can be obtained.

To calculate the maximum junction layer temperature at this operation mode, a first approximation can be obtained by:

$$T_{junct} = T_A + Z_{th, real} \cdot P_D$$

The pulse derating diagrams generally included in the LED data sheets provide initial information on the maximum permitted current (Figure 8) for a sample application with a total thermal resistance (system $R_{th, JA \ real}$).

The current path in the diagrams generally refers to an assumed total thermal resistance and usually applies to two different ambient temperatures, as well as being dependent on pulse width and duty cycle.

Figure 8: Example for permitted pulse handling capability diagram (e.g. LUW FQEL)
Simulation of various LED systems for Flash application

Based on mobile flash applications, a closed enclosure made of plastic and dimensions of 50mm x 50mm x 10mm was defined as base and entry model for the thermal analysis. It includes the LED in pulse mode with varying degrees of system complexity. For the PCB, we used common types, such as FR4, Flex-PC and IMS, and contact pins on FR4 with a common size of 20mm x 20mm. For the LED we used an OSLUX LUW FQEL. Within the plastic enclosure, the LED system is defined as levitating. Figure 9 shows an overview of the models and additional marginal conditions.

The shown system setups were used for calculating the respective $Z_{th}$ curves (Figure 10). As expected, the system setup with IMS board displayed the lowest thermal resistance and the best behavior when subjected to pulse loading.

When compared to the two FR4 setups, it can be observed that even an expansion of the copper area of the solder pad (standard solder pad -> max. area) effects in a considerable improvement. A similar effect, if to a lesser degree, can also be seen with the different FPC systems. Starting with a pure Flex PC through to FPC on metal stiffeners and shielding, there is a clear improvement in thermal properties for pulse mode. The setup with contact pins displayed the highest $Z_{th}$ values.

During the thermal analysis, the flash systems were loaded with a typical pulse sequence and pulse quantity (10x) and the resulting temperature curve simulated for the junction layer of the LED OSLUX LUW FQEL.

**Figure 9: Overview of the various simulation models and marginal conditions**
Figure 11 shows a typical pulse sequence and compares the results of the various flash systems.

Figure 10: Overview of the Zth curves for various simulation models

Figure 11: Pulse conditions and results of transient simulations
Conclusion

The operating parameters of an LED system are influenced and limited by a wide range of direct and indirect factors. The operating parameters that enable operation of a LED at a maximum level in an application are primarily determined by its thermal properties and the specific requirements. A system-relevant, and therefore crucial parameter is the junction temperature in the semiconductor chip of the LED, as this influences the function. In practice, the junction temperature cannot be measured directly but has to be calculated indirectly via $R_{th}$ based on the solderpoint temperature or measured $Z_{th}$ progression. Because the LED with its properties is generally thermally optimized by the manufacturer, the only way to influence the operating parameters from the system side is via the system setup or its components.

For the development of a thermal management system, this means that the better the thermal properties of the setup, the greater the degree of flexibility offered by the operating parameters.

Customers should therefore question simple, wholesale statements concerning the maximum operating current of an LED, or such statements should refer directly to or provide concrete information on a specific system.

OSRAM Opto Semiconductors supports customers in their development and design process to help them find the best solution for specific applications.

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NOMENCLATURE

- $c_p$: specific heat at constant pressure
- $\rho$: density
- $V$: volume
- $m$: mass
- $\lambda$: thermal conductivity
- $T$: Temperature
- $t$: time
- $t_p$: pulse length
- $R_{th}$: thermal resistance
- $T$: time constant
- $T_A$: Ambient temperature
- $T_S$: Solderpoint Temperature
- $T_{Safety}$: Thermal Safety factor
- $C_{th}$: thermal capacity
- $Z_{th}$: transient thermal resistance
- $P$: heat generation
- $D$: duty cycle
- $f$: frequency
- $Q$: heat
- $C$: capacitance per unit length
- $G$: conductivity per unit length
- $L$: inductance per unit length
- Solder: e.g. Glue, SAC Solder, etc.
- Solder pad: recommended solder pad design (e.g. datasheet)
- PCB type: FR4, IMS, FPC, etc.
- TIM: Thermal Interface Material (e.g. Foil, Adhesive, Glue, etc.)
- Heat sink: e.g. cooler, fan, stiffener, shielding, cover, etc.
Appendix

Don't forget: LED Light for you is your place to be whenever you are looking for information or worldwide partners for your LED Lighting project.

www.ledlightforyou.com

Revision History

<table>
<thead>
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<th>Date</th>
<th>Revision History</th>
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<tr>
<td>Dec. 2014</td>
<td>Release application note</td>
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