Thermal management of LED light sources

Application Note

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Thermal management of LED light sources

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all SMT LEDs

Abstract

This application note provides an introduction to the basic principles of heat transfer and their influence on LED applications. It deals with the respective thermal management of the individual system components. Relevant properties are described and discussed.

Further information:

Please also refer to the application notes “The thermal measurement point of LEDs” and “Temperature measurement with thermocouples”

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1 Introduction

Light-emitting diodes (LEDs) are widely used in lighting technology today. They are the light sources of the future, and already represent the latest state of technology for many applications.

Thanks to the direct conversion of electrical current to light (optical radiation) in the semiconductor, LEDs are highly efficient — more efficient than most traditional light sources. However, even in the case of LEDs, nearly most of the electrical power is converted to heat rather than light. To put it simply, the higher the current, the more heat is created in the component.

This heat loss must be conducted away from the LEDs, since the used semiconductor material is subject to a maximum temperature limit and because its characteristic properties such as light output, forward voltage, wavelength, and service life are temperature dependent.

In particular in the case of innovative, miniaturized high-performance LEDs, the dissipation of heat is of major importance in order to keep the junction temperatures down — and is regarded as the biggest challenge.

Only adequate thermal management across all system levels can allow for the full exploitation of the LED performance and efficiency during operation.

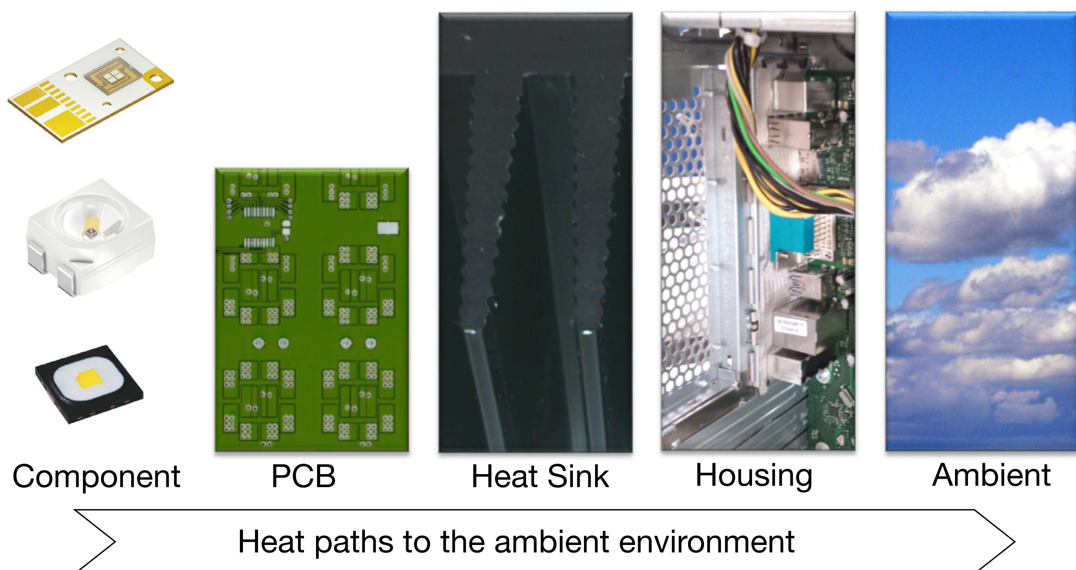
This application note provides a general introduction on the basic principles of heat transfer and its influence on LED applications using thermal management at different system levels. Relevant characteristics are described and discussed in this context.

2 Basic principles of heat transfer

In the case of most LED systems and other forms of electronics with a certain amount of heat loss, the aim is generally to transfer this heat into the ambient air to a lesser or greater extent in order to prevent the overheating of components.

The system heat transfer path is the same in practically all cases, starting from the heat source (semiconductor junction layer) via the PCB, heat sink, and package, and into the ambient air.

Figure 1: General heat path through an LED system



Here, the term "heat" designates a form of energy which can be transmitted through various mechanisms from one medium to another in the form of a heat flow.

Table 1: Heat and the flow of heat

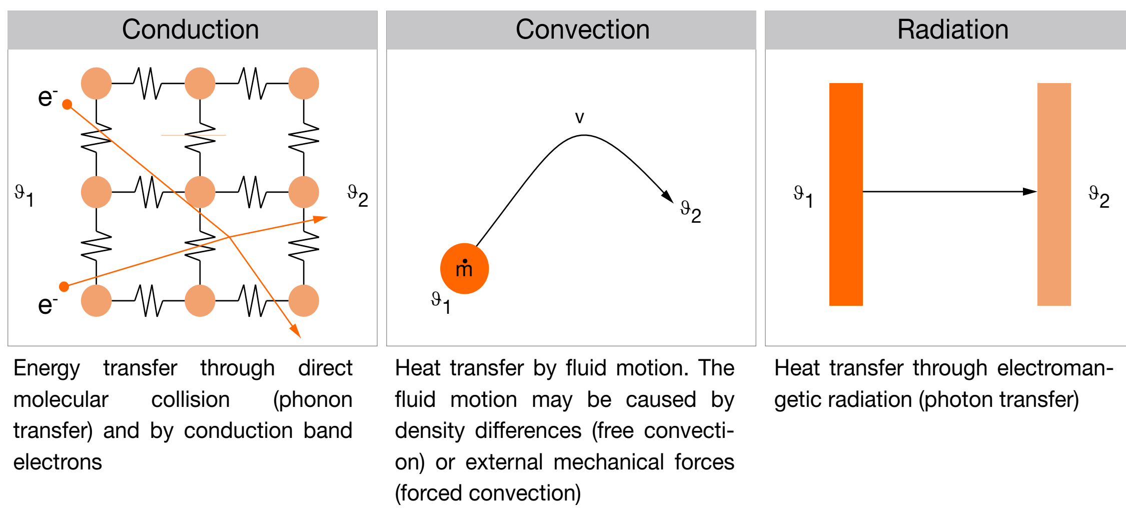
Q	Heat Total amount of energy transferred through heat transfer	[J]
$\dot{Q} = \frac{dQ}{dt}$	Heat flow (heat transfer rate) Heat transfer over time	$[W] = [Js^{-1}]$

Heat flow always takes place at points where there are temperature differences within one medium or between media with different temperatures. The energy is always transmitted from the medium with the higher temperature to the medium with the lower temperature (direction of heat flow — 2nd law of thermodynamics).

The following three basic heat transfer mechanisms are described in more detail below:

- Conduction
- Convection
- Radiation

Figure 2: Principles of heat and mass transport



1. Within solids, heat transfer is done by means of heat conduction-
2. In gases (air), heat transfer is dominated by convection and radiation

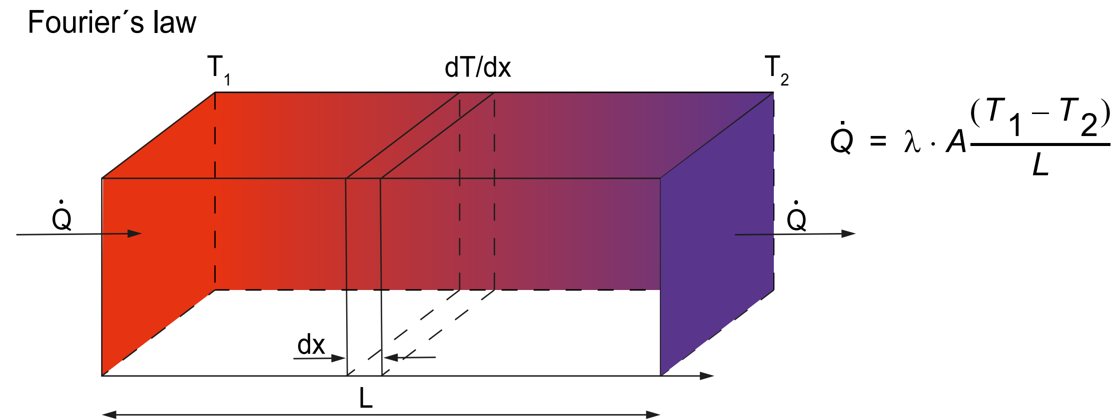
2.1 Thermal conduction

Thermal conduction is a mechanism for the transport of thermal energy that does not require a macroscopic flow of material. The exchange/transport of heat takes place between neighboring particles and can be depicted more or less as the transfer of vibration. For example, in the case

of metals the heat is transmitted between the atomic kernels via vibration energy; energy is also transported through the movement of the free electrons.

The heat transmitted through one-dimensional thermal conduction is described by Fourier's Law.

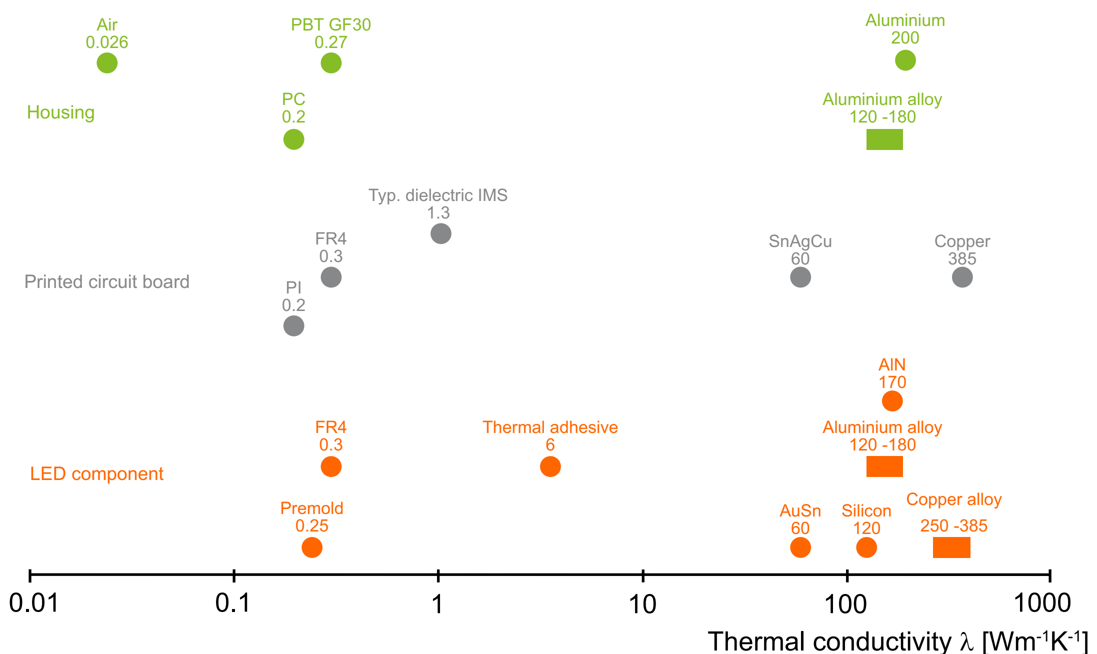
Figure 3: The basic law of thermal conduction



- The heat transfer rate $\dot{Q}$ in the rod is directly proportional to the area A and to the temperature difference along the path of the heat flow
- Proportionality ratio: thermal conductivity λ
- λ is a material property

Thermal conductivity describes the ability of a solid to transport thermal energy. The typical thermal conductivity values of materials used in an LED system are shown in Figure 4.

Figure 4: Thermal conductivity of typical materials used in LED systems



The thermal conductivity of metals is typically between 10 and 400 $Wm^{-1} K^{-1}$. Metal alloys conduct heat less well than their components. As a rule, semiconductors also have a high thermal conductivity. In contrast, organic solids such as plastics and PCB materials have a conductivity value of around 0.2 $Wm^{-1}K^{-1}$. The thermal conductivity of gases is around one tenth of this (e.g. air: 0.026 $Wm^{-1}K^{-1}$).

A noteworthy analogy can be drawn between the transport of heat and the transport of electrical current. If you apply a voltage to different surfaces of a wire, you create a flow of electrical current. Similarly, if you apply different temperatures to the same surfaces, you create a flow of heat.

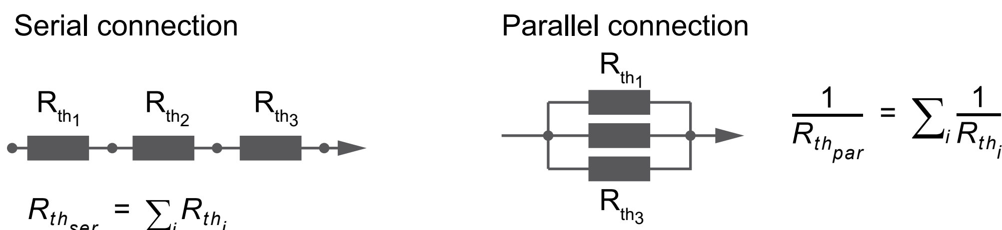
Like electrical resistance, a thermal resistance of R_{th} can be defined for one-dimensional thermal conductivity.

Table 2: Analogy between heat flow and electrical current; thermal resistance

Ohm´s Law $I = \frac{\rho \cdot A}{L}(V_1 - V_2) = \frac{1}{R}(V_1 - V_2)$	Fourier´s Law $\dot{Q} = \frac{\lambda \cdot A}{L}(T_1 - T_2) = \frac{1}{R_{th}}(T_1 - T_2)$
Definition of thermal resistance R_{th}	
$R_{th} = \frac{L}{\lambda \cdot A} = \frac{(T_1 - T_2)}{\dot{Q}}$	• Valid for steady state, one dimensional heat transfer • Thermal resistance is not a real physical value. It is only a tool in the field of thermal engineering. • In reality, heat flow and temperature distribution are 3-dimensional problems.

This thermal resistance is subject to the premise of one-dimensional heat transfer. With this restriction, thermal conductivity and temperature calculations are possible using electrical engineering methods. The laws on parallel and serial circuitry derived for electrical scenarios (Figure 5) also apply.

Figure 5: Analogy of electrical and thermal resistance network



More complex structures with three-dimensional heat flows where all heat transfer mechanisms are taken into account can usually be calculated using numerical simulations.

2.2 Heat convection

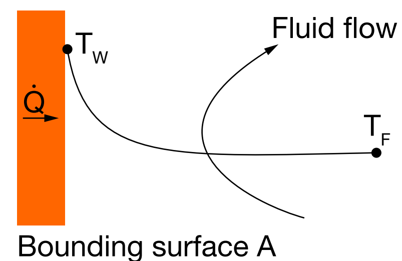
In the case of heat transfer through convection, the transfer takes place between a solid body and the surrounding liquid or gas medium. Particles are heated up firstly and then are transported to the surrounding. If the flow of the fluid takes place purely by means of uplift forces that cause temperature-dependent density gradients in the fluid, the transfer of heat is called "free convection" or "natural convection". In the case of forced convection, a flow is created by means of external forces such as fans.

In the case of convection, heat transfer takes place via the surfaces of a surrounding flow medium. The amount of heat that is transported/dissipated depends on further parameters in addition to the temperature difference and area of the boundary layer. The heat transfer coefficient is a quantitative characteristic of convective heat transfer between a fluid medium and the surface. The parameter includes the position of the boundary layer (horizontal vs. vertical), the type of convection flow (free vs. forced), the nature and speed of the fluid, and the geometry of the boundary layers.

Figure 6: Definition of convective heat transfer

Newton´s law of cooling (rate of convective heat transfer)

$$\dot{Q} = \alpha \cdot A(T_W - T_F)$$



- Proportionality ratio: heat transfer coefficient α
- SI unit: $Wm^{-2}K^{-1}$
- α strongly depends on the local conditions

In practice, the heat transfer coefficient is determined experimentally with the help of model tests. The test results can then be applied to other convective heat transfer conditions.

2.3 Thermal radiation

Unlike conductivity and convection, heat transfer through radiation takes place without a carrier medium through the absorption and emission of electromagnetic waves.

Every body above a temperature of T = 0 K emits electromagnetic radiation in the visible to infrared range (0.35 — 10 µm).

The thermal energy transmitted through radiation depends on the physical properties of the surface material and the geometrical arrangement of the transmitting and receiving surface (view

factor). The emissivity ε is the characteristic parameter for the absorption and emission of thermal radiation of a surface.

A black body (ideal heat emitter) would fully emit and absorb all electromagnetic radiation incident upon it with every wavelength (ε = 1). In contrast, the surface of a real body only emits part of this radiation. Thus, real objects are called "gray" bodies (ε < 1).

The emissivity of a body thus describes the amount of radiation that it emits in comparison with a black body.

Table 3: Important emissivities for LED applications

Emissivity ε

Surface	T in °C	e
Aluminum		
• polished	20	0.04
• heavily oxidized	20	0.25
Lacquers	100	0.9 — 0.97
Plastics	20	0.9
Solder stop mask	20	0.9

The material of a body and its surface character have a significant influence on emissivity. As a rule, non-metallic and non-transparent objects are good heat emitters, with an emissivity of > 80 %. The emissivity of metals can vary between 5 % and 90 %. The shinier a metal, the lower its emissivity. For examples of the emissivity of typical materials used in an electronic system, see Table 3.

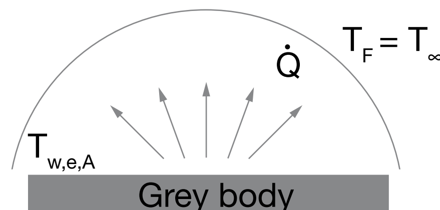
There is a standard thermal radiation equation for the special case of the emission of radiation into half-space (Stefan-Boltzmann Law). It summarizes physical and geometric influencing factors to describe the heat flow exchanged through thermal radiation.

Figure 7: Stefan-Boltzmann equation

Rate of radiative heat transfer

$$\dot{Q} = \varepsilon \cdot A \cdot \sigma\left(T_W^{\ 4} - T_F^{\ 4}\right)$$

- ε emissivity coefficient 0 < ε < 1
- σ Stephan-Boltzmann equation



In electronics cooling, cooling via thermal radiation has a significant importance for passively cooled systems (free convection). The contribution made by thermal radiation to cooling can be up to 50 %. In the case of active cooling, the dissipation of heat through thermal radiation has a lesser role in comparison to heat dissipation through convection.

At PCB level, solder resist (ε ~ 0.9) is responsible for the dissipation of heat through thermal radiation. In the case of the metal surfaces of e.g. heat sinks or package panels, paint or anodization can be used to increase emissivity and thus promote cooling via radiation.

3 Thermal management of LED light sources

For the realization of LED light sources, thermal management remains a major task and challenge.

Despite its high efficiency, even in the case of LED technology electrical power is converted into heat. In addition, the continuing miniaturization of package technology results in an increase in power and packing density, which means that the heat is incident upon and must be dissipated from an ever decreasing amount of space.

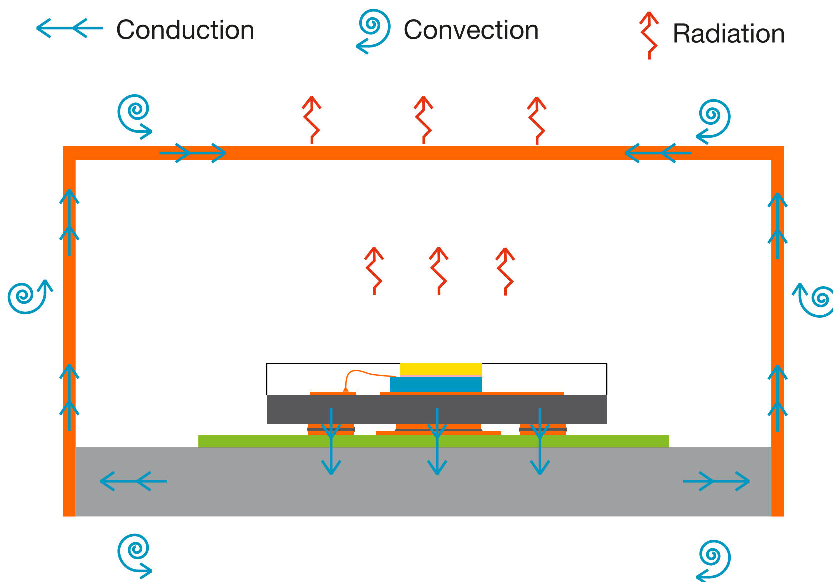
The aim of thermal management – the transfer of heat from the chip to the ambient environment – is always the same. The challenge lies in the adequate design/implementation for the specific power class and constraints of the relevant application area.

As a rule, the thermal management of an LED system can be broken down into three system levels:

- LED(s)
- PCB
- Cooling unit

The heat path for system heat transfer can be described in the same terms.

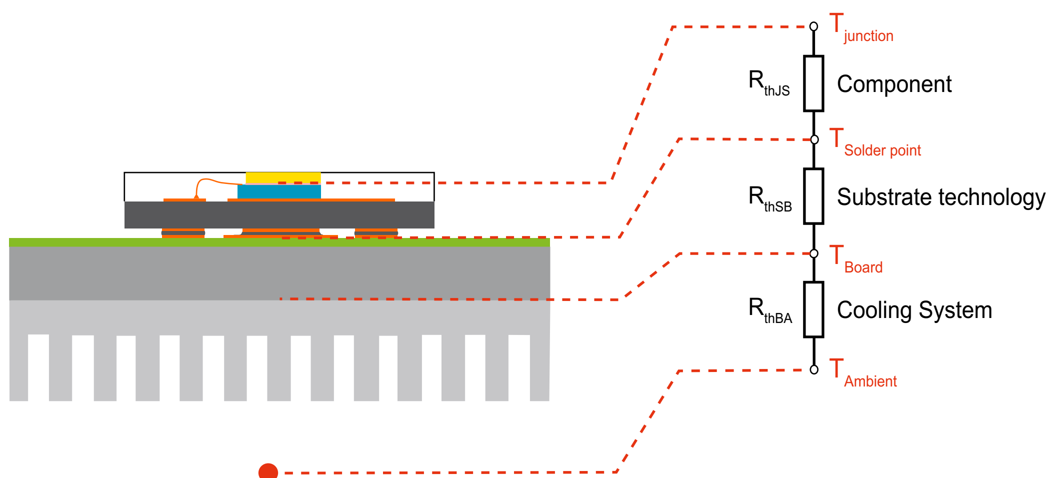
Figure 8: Heat transfer in an LED system from the die to the surrounding environment



- The heat generated in the LED epitaxial layer is transmitted by heat conduction through the LED package via the soldered joint and on to the carrier (PCB).
- At PCB level, the heat can be transported to the heat sink by various design measures (horizontal and vertical thermal conductivity.
- From the cooling unit (e.g. heat sink, system housing), the heat is finally transferred to the ambient environment through heat convection and thermal radiation.

Thermal resistances (Figure 9) are often used for visualization purposes, particularly in the case of complex systems.

Figure 9: Visualization of an LED system via a thermal resistance network



The thermal partial resistances correspond to the various functional groups in the system or heat path and characterize their individual thermal behavior.

- R_{thJS} is the thermal resistance of the LED and describes the transfer of heat within the LED package (**j**unction-to-**s**older-point);
- R_{thSB} is the thermal resistance of the PCB technology (**s**older-point-to-**b**oard);
- R_{thBA} is the thermal resistance of the transfer of heat into the ambient environment (**b**oard-to-**a**mbient).

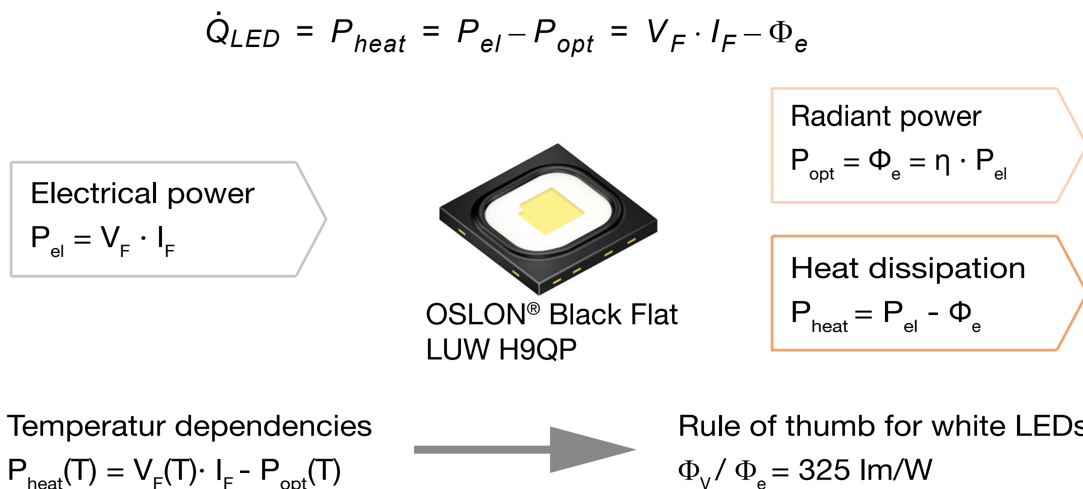
3.1 Heat generation of LEDs / thermal resistance

With classical silicon-based semiconductor components such as integrated circuits and transistors, all of the dissipation power is converted into heat. The heat flow is thus equivalent to the electrical power loss, which results in the clear interpretation of the thermal resistance.

In the case of light-emitting diodes (LEDs), however, only a part of the supplied electrical energy is converted into heat. Some of the electrical energy is emitted as light/radiation (optical energy) in accordance with optical efficiency. The heat generation of the LEDs is not equal to the electrical energy. A part of the electrical energy is converted into radiant energy (light).

Figure 10: The principles of calculating thermal resistance

$$\dot{Q}_{LED} = P_{heat} = P_{el} - P_{opt} = V_F \cdot I_F - \Phi_e$$



As an example the previously mentioned values are estimated for the OSLON® Black Flat LUW H9QP — BIN 5M for different temperatures (see Figure 11). The respective values for the calculation can be found in the data sheet. Table 4 shows further typical luminous efficacys of radiation for various colors.

Figure 11: Estimation of heat dissipation for the OSLON® Black Flat LUW H9QP

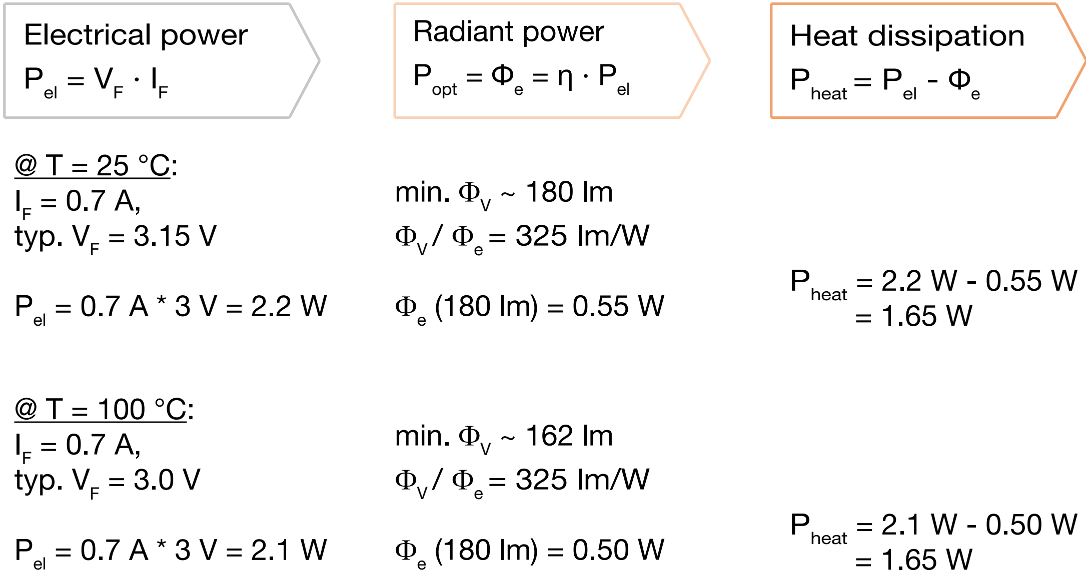


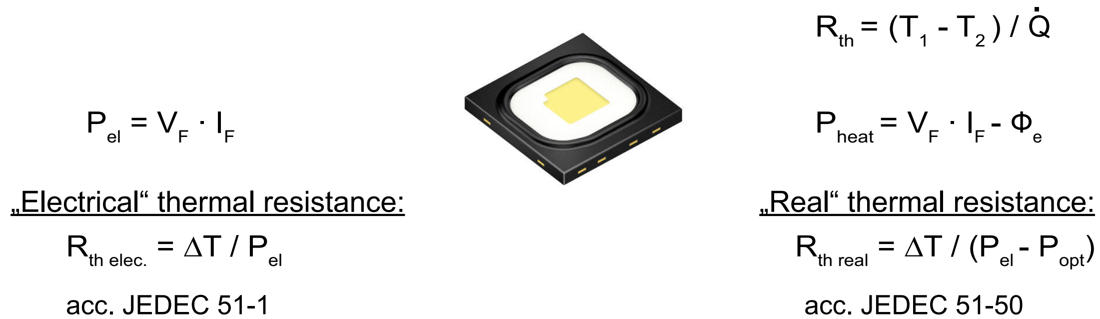
Table 4: Typical luminous efficacy of radiation

Device	Color	Φ_V / Φ_e
LA	Amber	~ 240 lm
LS	Super Red	~ 130 lm
LY	Yellow	~ 480 lm
LUW	White	~ 325 lm

Two different definitions of thermal resistance for LEDs are existing:

- Electrical thermal resistance
- Real thermal resistance

Figure 12: Electrical versus thermal resistance



3.2 Electrical thermal resistance

Thermal resistance is defined in the same manner as for traditional semiconductor components.

The decoupled energy (light/radiation) is not taken into consideration (see JEDEC 51-1).

$$P_{heat} = P_{el}$$

$$P_{el} = U_F \cdot I_F$$

$$R_{th_{elec}} = \frac{\Delta T}{P_{el}}$$

3.3 Real thermal resistance

This definition of thermal resistance considers the actual flow of heat that is dissipated through the package.

The decoupled optical power of the LED is thus taken into account (see JEDEC 51-50).

$$P_{opt} = \Phi_e$$

$$P_{heat} = P_{el} - P_{opt}$$

$$R_{th\,\mathrm{real}} = \frac{\Delta T}{P_{el} - P_{opt}}$$

$$R_{th\,\mathrm{real}} = \frac{\Delta T}{P_{el} \cdot (1 - \eta_{LED})}$$

, whereby η_{LED} is the optical efficiency of the LED.

The use of real thermal resistance when considering thermal layout can ensure that the maximum permissible junction temperature is not exceeded in all possible modes of operation.

3.4 Thermal management at LED level

At LED level, thermal management is generally predefined by the component manufacturer and is determined by the design of the LED.

The thermal resistance of an LED tells us about its thermal properties. This thermal resistance is usually stated on the LED data sheet as a characteristic parameter. As a general rule, the smaller the thermal resistance of an LED, the better the heat can be dissipated from the package.

Significant influencing factors on thermal resistance include the technology used for the package and the light-emitting semiconductor chip.

In general, the SMT LEDs available at ams-OSRAM AG can be divided into two groups:

- Lead-frame-based LED packages
- Ceramic-based LED packages

Although the thermal properties of an LED are fixed, knowledge of the heat path of the LED is decisive for the thermal design of the PCB and system.

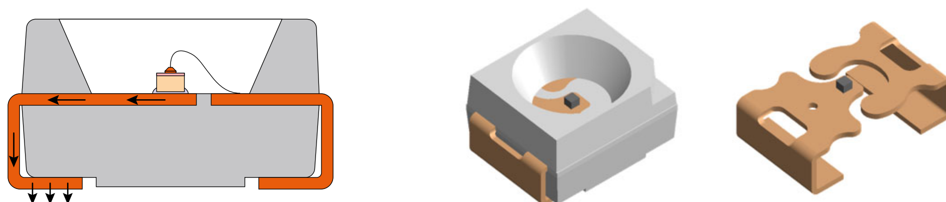
3.5 Heat path of lead-frame-based LEDs

In the case of a lead-frame-based package, the semiconductor chip is mounted on a lead frame which — in most cases — consists of a plated copper alloy.

The die attach process can be performed by gluing or soldering.

Starting from the barrier layer, heat is dissipated from the package primarily via the chip and the leadframe on which the chip is placed (Figure 13). The amount of heat transfer that takes place via the bond wire is insignificant.

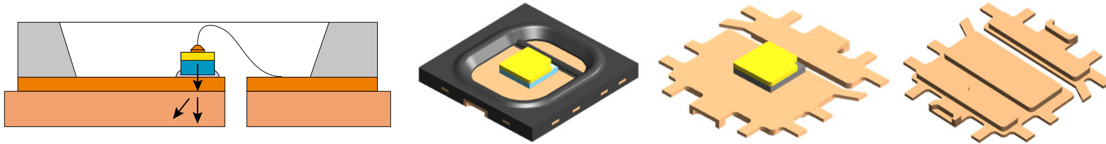
Figure 13: Heat conduction via lead(s) shown exemplary for a TOPLED®



In another variant of this group, an additional internal heat spreader is embedded in the package. The LED chip is mounted directly onto this. This means that even internally the heat is already distributed over a larger area and can be better dissipated due to the larger cross section.

This type of design is used in OSLON® Black Flat LEDs from ams-OSRAM AG, for example (Figure 14).

Figure 14: Heat spreading and conduction via heat spreader/lead



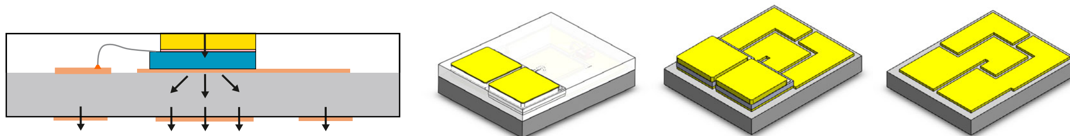
3.6 Heat path of ceramic-based LEDs

In the case of LED packages based on ceramic substrates, the semiconductor chip is attached to the metallization layer of the ceramic. Aluminum oxide and aluminum nitride are established materials here.

The good thermal conductivity (Al_2O_3: ~ 20 $Wm^{-1}K^{-1}$, AlN: 170 $Wm^{-1}K^{-1}$) of the ceramics enables efficient heat spreading. The heat which arises in the semiconductor is distributed via the metallization layer and ceramic base material and transmitted to the PCB via the solder pad.

Certain LED designs have an additional "thermal pad" in addition to the two electrical contacts. This has purely thermal function for primary heat dissipation and is electrically neutral. This helps to additionally dissipate the heat, but it should be noted that all pads transfer heat. Figure 15 shows an example for a ceramic-based package including a thermal pad, positioned below the semiconductor chip.

Figure 15: Heat conduction via ceramic substrate shown for a OSLON® Compact PL



The further distribution of the heat flow can be influenced by the PCB layout (see chapter "4 Thermal management of light sources at system level").

3.7 Summarized

The thermal behavior of the LED component is determined by the manufacturer via the internal design. The static thermal properties are described by the thermal resistance $R_{thJS\ real}$.

For thermal management, the flow of heat through the package is of significant importance. These heat paths must be taken into account for the thermal design of the PCB.

4 Thermal management of light sources at system level

For an effective thermal management the PCB plays a significant role. Once the heat from the LED reaches the PCB, the heat transfer from then on must be ensured.

PCBs consist of a series of electrically conductive (metallic) — and thus also thermally conductive — layers and electrically insulating layers (e.g. plastics and dielectrics). In advance basic considerations are required in order to enable the selection of suitable constructive measures for the PCB design:

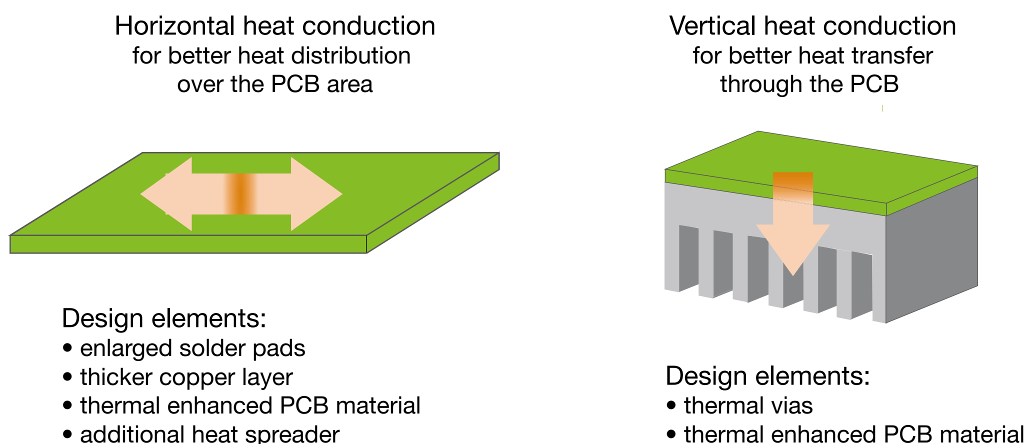
- Where are the LEDs positioned on the PCB (= position of heat sources)?
- What thermal losses need to be dissipated?
- What mechanisms are used to cool the system (e.g. heat sinks)?
- How should the heat be transmitted to the heat sinks?
- What other heat sources are in thermal proximity?

4.1 Thermal management on PCB level

Appropriate design elements are available at PCB level — primarily for standard PCBs (FR4) — on the basis of these requirements (also see Figure 16):

1. Design elements for two-dimensional heat distribution on the PCB (horizontal heat conduction)
2. Design elements for improved heat distribution through the PCB (vertical heat conduction)

Figure 16: Various thermal design elements at PCB level



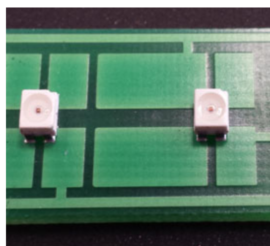
4.1.1 Horizontal heat conduction

Horizontal heat distribution achieved by variations in the design of the copper surface. In the following, some common possibilities are presented.

Larger copper surfaces

The easiest way to realize two-dimensional heat distribution is to increase the size of the copper surfaces. Figure 17 shows a TOPLED® with larger solder pads.

Figure 17: Horizontal heat conduction with larger copper surfaces



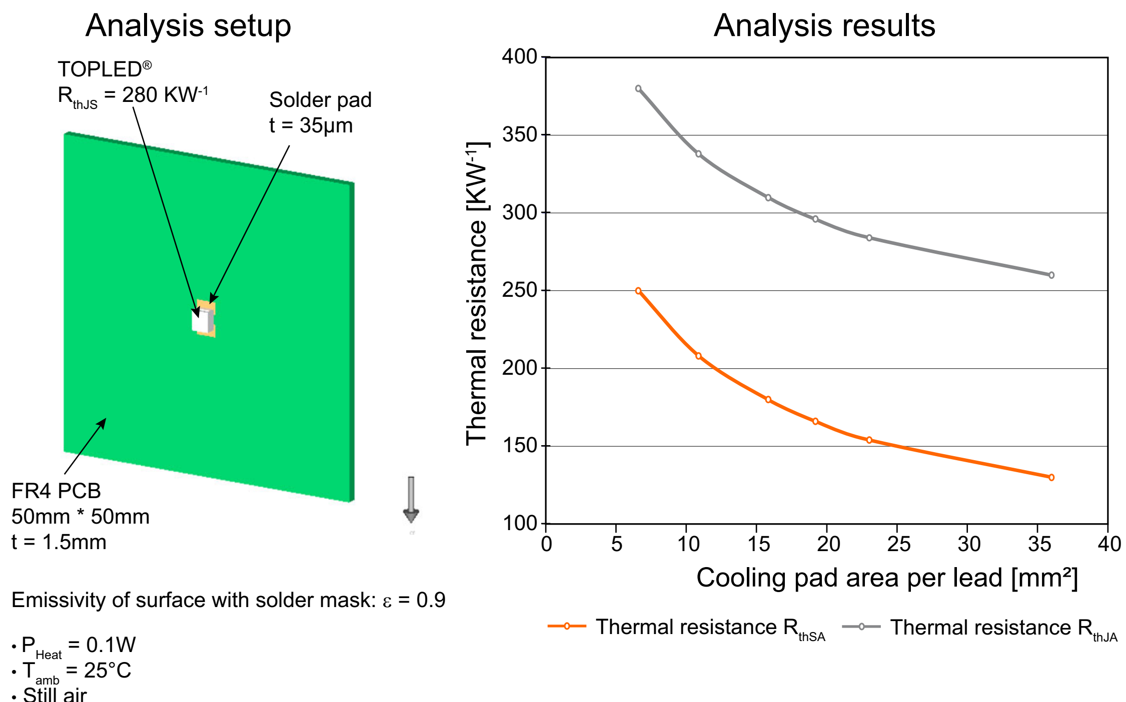
Heat spreading with enlarged solder pads

- + Simplest way to distribute the heat over the PCB
- + No additional costs
- - Low component destiny

A large surface area is key to transfer of heat between the PCB and the ambient environment and the subsequent vertical heat transfer through materials with a relatively low thermal conductivity value. The copper surfaces may need to be supplemented with leads that contribute to the cooling of the component in accordance with the LED package.

Figure 18 shows a model calculation based on a TOPLED®. The analysis results show that the larger the heat dissipation pad, the smaller the thermal resistance. This lead to a lower temperature rise of the system.

Figure 18: Example of TOPLED on FR4 PCB – influence of solder pad area on R_{thPCB}



However, for all leads in a component the use of identically sized surfaces is recommended in general. This helps to prevent unfavorable situations, conditions, and effects in the normal reflow soldering process (e.g. floating, twisting, turning, tombstone effect, etc.).

Increase in thickness of copper layers

Typically PCB copper layers have a thickness of around 35 µm. This standard thickness allows heat to be distributed over an area of a few centimeters.

Heat can be distributed over larger surface areas by means of thicker copper layers (e.g. 70 µm or 105 µm).

Substrate materials with increased thermal conductivity

Over the last few years, an increasing number of base materials with a higher thermal conductivity have been offered. In contrast to FR4 (~ 0.3 $Wm^{-1}K^{-1}$), these materials have a thermal conductivity of around 1 $Wm^{-1}K^{-1}$. This increased thermal conductivity enables improved heat distribution.

4.1.2 Vertical thermal conduction

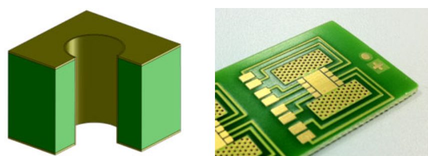
Two ways of improving vertical heat dissipation for standard FR4 PCBs are described below. Generally, both methods are used together, reduced PCB thickness in combination with thermal vias.

Thermal vias

Thermal vias (usually ø of 0.5 mm) are simple open plated through-holes or vias which are filled with epoxy and then capped with copper plate (see Figure 19)

In this case, the vias take on the heat dissipation function, thus notably improving the vertical thermal resistance of the FR4 material in a targeted and localized manner.

Figure 19: Vertical heat conduction with thermal vias



Thermal vias
+ Simple way to increase the heat transfer in vertical direction
+ Low-cost
- Effect of solder wicking

The thermal transfer capability of the vias themselves is determined by the thickness of the copper in the through-holes. A standard copper plating thicknesses of the holes of 20-25 µm have become established in the industry, but greater wall plating thicknesses are also used. As a general rule, the thicker the copper layer, the better performance — but costs increase along with thickness, too.

Reduction in PCB thickness

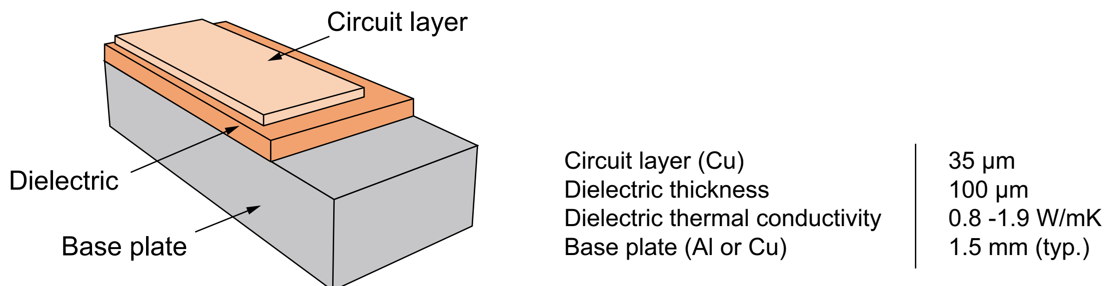
The second way to increase thermal conduction is to reduce the thickness of the PCB. Double-sided FR4 materials with a thickness of 0.4 mm ≤ d < 2.0 mm are available on the market.

4.2 Insulated metal substrate (IMS)

This PCB material consists of a metal carrier (d ≥ 1 mm) as base plate with a thin dielectric layer, usually in the range of 100 µm (see Figure 20).

The heat is transmitted through the thin insulation layer (vertical heat conduction) to the metal carrier (usually aluminum). The metal carrier is then responsible for lateral heat distribution.

Figure 20: Typical layer construction of insulated metal substrate PCB (IMS)



In the most simple scenario, the dielectric is an FR4 prepreg (fiberglass impregnated with resin).

In the case of IMS PCBs, thermal performance can be further improved by means of thermally optimized insulation material. From the point of view of thermal management, variants on this technology include flexible circuit carriers and multilayer substrates laminated onto an aluminum base plate.

In addition, there are further special technologies for use in thermal management at PCB level, e.g.:

- Ceramic circuit carriers
- Inlay technology
- and more...

4.3 Thermal management at module level

In the case of thermal management, the system layer is generally the end of the heat path. In a sense, it constitutes the point of transition to the ambient environment (air). This means that from this point the generated heat can only be dissipated via convection or radiation.

Mostly, heat sinks (passive method) or a combination of heat sinks and fans (active method) are used as traditional heat dissipation components here.

In general, the term "heat sink" is fairly broadly defined. For example, a metallic package can contribute to the cooling function and thus act as a heat sink.

In addition to simple, traditional cooling methods, other technologies such as Peltier elements, heat pipes and water cooling can be used, where appropriate.

5 Summary

LED-based light sources require adequate thermal management. This is the only way to enable optimum performance and reliable operations.

The objective of thermal management is thus to safeguard the heat path over the system levels in order to achieve good heat transfer from the chip to the ambient environment.

The scope and complexity of thermal management depend on the amount of lost heat, the size of the source, and the anticipated ambient conditions. The function itself is based on three heat transfer mechanisms: Thermal conduction in the solid and both convection and radiation at the point of transition to the ambient environment.

Normally, thermal resistance is used to describe and enable an initial estimation of thermal properties.

However, in practice it has proven useful to carry out a thermal simulation to assess different cooling concepts with known marginal conditions and loads. Knowledge on the heat path of the LED package is important in order to enable the correct choice of subsequent system components (PCB, solder pads, and so on).

ams-OSRAM AG supports its customers during their development and design processes in order to help them to find the best possible solution for a specific application.

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