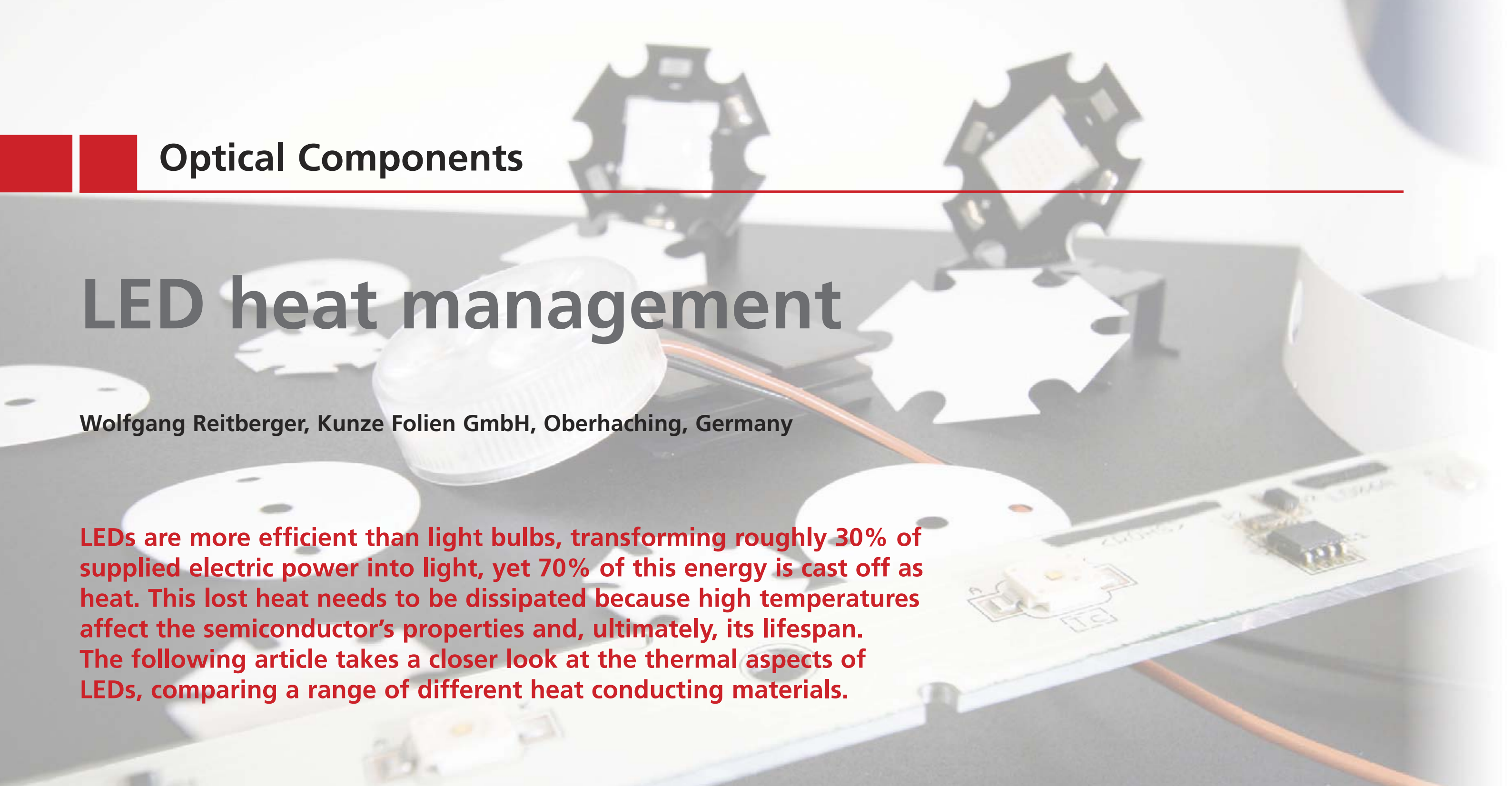

LED heat management

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LEDs are more efficient than light bulbs, transforming roughly 30% of supplied electric power into light, yet 70% of this energy is cast off as heat. This lost heat needs to be dissipated because high temperatures affect the semiconductor's properties and, ultimately, its lifespan. The following article takes a closer look at the thermal aspects of LEDs, comparing a range of different heat conducting materials.

Since the development of high-performance Light Emitting Diodes (LEDs), this technology has spread to new applications in the automotive industry, in displays and mobile devices, and in the lighting of roads and buildings. LEDs are small and operate at low voltages. LEDs are more robust than conventional lamps, and now offer superior energy efficiency and durability too. However, the intensity LEDs produce depends strongly on the following factors:

- current feed and controlling
- ambient temperature
- colour temperature
- build quality
- heat management

In practical applications, heat management should be given utmost priority to avoid premature ageing and damage. Although the greater part of the electric power supplied to LEDs and other semiconductors devices is transformed into waste heat, equipment manufacturers often assume incorrectly that LEDs don't heat up at all. Unlike incandescent light sources, LED emission itself has no infra-red wavelengths and delivers no heat. Yet the electrical generation of LED emission does cast off heat. In the development of an LED, therefore, high-quality thermal management is critically important to achieving the desired properties.

1 Thermal stress as a cause of ageing

Depending on the energy source (DC battery, AC line current, charge pump), trigger circuits for linear or clocked power supplies are employed. To boost an LED's light emission, the electrical wattage can be increased. As this power boost also necessarily increases the LED's Joule heating (thereby raising its temperature), the component's durability is reduced. As a remedy, special LED and carrier builds (cf. **figure 1**) efficiently conduct heat away from the chip and allow for greater light efficiency while avoiding a significant reduction of its lifespan. Constantly high ambient temperatures or highly fluctuant temperatures may also shorten a component's physical life. Therefore, thermal stress should be kept low and heat accumulation inside the LED must be avoided.

LEDs should always be operated at temperatures of 30–35°C below the maximum junction temperature (Tj_{max}) as stated by the component manufacturer. A typical example would be Tj_{max} = 120°C. Because access to the barrier layer for measuring is difficult, the operating temperature Ts at the solder point is usually taken as a basis for an estimate of the difference to the junction temperature. The resulting correction value Tc is calculated from the thermal resistance R_{th} of the LED (see paragraph below), the forward bias U_F and the forward current I_F. Below, a sample calculation [1] for a 4W-LED at 25°C ambient temperature:

$$Tc = R_{th} \cdot I_F \cdot U_F = 6°C/W \cdot 0.56\ A \cdot 9.3\ V = 31.25°C \quad \text{(Eq. 1)}$$

$$Ts_{max} = Tj_{max} - Tc = 120°C - 31.24°C = 88.75°C \quad \text{(Eq. 2)}$$

This means that an LED specified for Tj_{max} = 120°C may be operated at a maximum temperature Ts_{max} = 88.75°C, measured at the solder point – better still at 30–35°C below that value.

If the operating temperature Ts of medium brightness LEDs is increased from 25°C to about 85°C, its average lifespan drops to a fifth of expected values – from about 50,000 to a mere 10,000 operating hours.

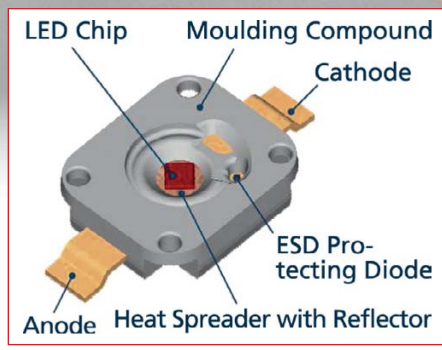

Figure 1: Typical LED
(Image: Osram Opto Semiconductors)

In extreme applications at Ts = 150°C and Tj = 175°C, the average lifespan even nosedives to just 100 operating hours [2].

2 Thermal resistance of an LED

An important parameter in the thermal design of an LED is its thermal resistance R_{th}, stated independently of its ambient conditions. R_{th} is inversely proportional to the size of the contact area A and thermal conductivity k, and proportional to layer thickness d:

$$R_{th} = d/(k \cdot A) \quad \text{(Eq. 3)}$$

The total thermal transfer resistance $R_{th\ Total}$ is commonly stated in K/W (or °C/W) and is calculated as follows:

$$R_{th\ Total} = R_{th\ JS} + R_{th\ SB} + R_{th\ BA} \quad \text{(Eq. 4)}$$

In the equation, the indices J, S, B and A stand for junction, solder point, board, and ambient, respectively (see **figure 2**). In order to maintain the operating temperature and to not exceed the junction temperature, developers must not only be aware of the thermal transfer resistance $R_{th\ JS}$ within the LED and $R_{th\ BA}$ of the LED

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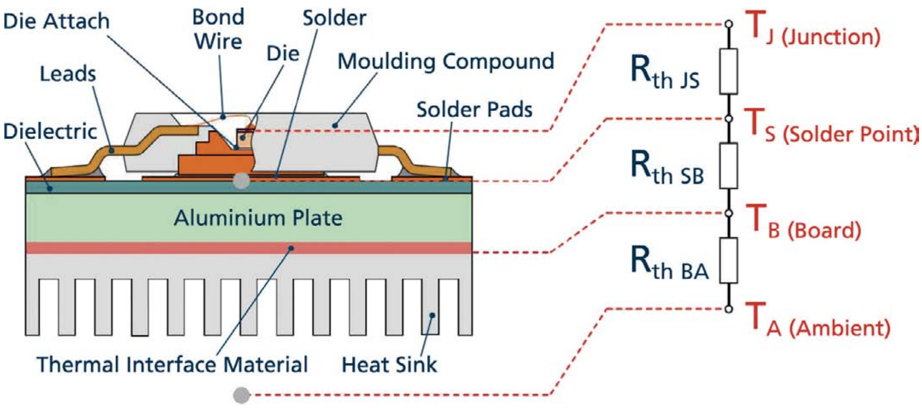

Figure 2: Build of an LED module and thermal system configuration with thermally conductive material *(Image: Osram Opto Semiconductors)*

to its environment, but also of the contact resistance $R_{th\ Sb}$ between solder point and board, located virtually in the centre of the assembly. To keep this resistance as low as possible, while ensuring optimum contact independently of surface quality, a thin layer of thermally conducting dielectric material is applied between board and heat sink.

Additionally, component-specific irregularities may appear in the assembly. This requires the calculation of correction factors, which need to be included in the thermal contact resistance. These irregularities may be of influence regarding thermal conductivity between the layers involved. All surfaces are somewhat irregular, and the pockets of air enclosed within these irregularities impair heat conduction due to their low conductance value while diminishing the effective contact area, especially in large surfaces paired with rigid shapes. Thus, thermal contact resistance depends on several factors, including surface area, surface quality, evenness, mechanical adaptability of the thermally conductive material, and pressure.

In practice, the measurements of contact surfaces are prescribed by the component casings. Minimum gauge of thermally conductive layers is limited with regard to its dielectric strength as well as to irregularities or burrs which need to be evened out.

3 Overview of different thermally conductive materials

Using an IR camera to examine the back side of an Ostar LED without adequate heat management, a situation will arise as in shown in **figure 3**: the LED overheats to 130°C. **Figure 4**, in contrast, illustrates the result of an ideal heat management solution involving thermally conductive material and a cooling element. The following paragraphs take a closer look at a variety of thermally conductive materials.

3.1 Elastomers

In the 1980s, elastomeric insulation materials were introduced as a substitute for thermally conductive paste. These materials consist of an elastomeric binding agent combined with thermally conductive fillers. Under pressure, elastomers show an excellent ability to adapt to contact surfaces, providing low thermal contact resistance between them.

The most commonly used among elastomeric binding agents is silicone rubber,

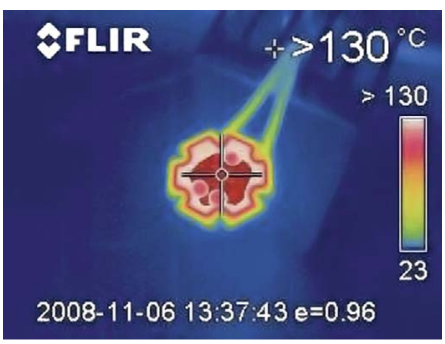

Figure 3: Heat image of an Ostar-LED (4 W), 10 secs. without cooling element

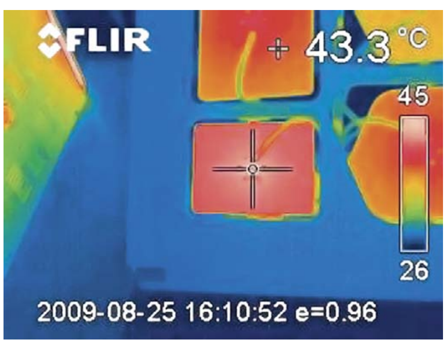

Figure 4: Heat image of an Ostar-LED (4 W), 10 mins. with cooling element and thermally conductive material

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which allows for compensation of ±500 µm or more. In its application, however, several crucial factors must be taken into consideration to achieve maximum heat flow. The ideal compression rate is typically between 10 and 40%, depending on softness and gauge. Contingent on total material thickness, air pockets may be bridged, e.g. up to 2 mm at a total gauge of 5 mm. Additionally, silicone rubber boasts high dielectric strength as well as superior chemical and thermic durability. By optimizing contact pressure, total thermal contact resistance can be ideally adjusted.

As silicone rubber's degree of cross-linking is high, few silicone molecules leak from it over time.

Elastomeric binding agents by themselves possess low thermal conductivity, but they are able to absorb great amounts of thermally conductive fillers. By adding ceramic powders, their heat conductivity can be modified considerably. The lowest-priced ceramic filler is aluminium oxide (Al_2O_3). Thermal conductivity of elastomers filled with this material is lower than that of ceramic insulators, but sufficient for most applications. And because they are elastic, their effectiveness is greater across broader tolerances – whereas ceramics can reach their full thermoconductive potential only when contact surfaces are absolutely even.

Another filler is boron nitride (BN). It is more fine-grained and less dense than Al_2O_3, making the rubber more pliable and soft. The thermal conductivity of BN is far superior to that of Al_2O_3, but BN is also more expensive. Elastomeric layers filled with BN adapt more easily to surface irregularities, minimizing thermal contact resistance.

Ceramic-filled elastomers may also be mechanically stabilized by substrate carriers such as fibreglass, metal or polyimide foils.

3.2 Graphite foils

Graphite (carbon) possesses outstanding thermal conductivity. At high purity levels near 97–99%, graphite resists temperatures of up to 450°C. High-performance carbons offer temperature stability up to 650°C. These parameters make graphite better suited for LED cooling than most other materials.

Because graphite foils consist of compacted flakes, their thermal conductivity is anisotropic: they allow for especially fast dissipation in xy-direction as well as efficient conduction in z-direction. Their primary disadvantages are the facts that they are not electrically insulating and that they can only compensate for minor surface irregularities such as light scratches. Therefore, superior surface quality is prerequisite for optimal heat flow. To allow for easy handling in assembly, one-sided adhesive graphite foils are available. However, these one-sided foils possess higher thermal contact resistance.

3.3 Polyimide foils

Polyimide foils are used mainly for electric insulation in component parts. They possess great dielectric strength, while being both mechanically resistant and flexible at once. Despite their relatively low thermal conductivity, polyimide foils may be used as conductive material at gauges of 25–125 µm due to their low thermal contact resistance. However, high-quality surface finishing is essential, as the rigid structure of polyimide foils does not allow for adequate compensation of air pockets. The stability of polyimide foils, on the other hand, makes them excellent substrate carriers for thermally conductive silicone coating as well as phase-change conductive wax.

3.4 Phase-change materials

Thermally conductive substances, which soften at a predefined temperature due to phase changes, may be used for LED cooling. When temperatures fall below the phase-change point, the medium returns to its solid state. When changing the phase from solid toward liquid, the material actively expands, covering contact surfaces, expelling air pockets from micropores and evening out irregularities. This reduces total contact resistance significantly and maximizes heat transfer. For mechanical stabilization, phase-change materials may be, according to requirements, either applied to electrically insulating carriers such as polyimides or other plastics, or to electrically conductive metals like aluminium. Some phase-change material advantages include constant layer thickness, quick and clean handling, and high process reliability.

3.5 Ceramics

Ceramic insulator disks consist primarily of aluminium oxide or aluminium nitride. Their thermal conductivity and electric insulation is outstanding. However, to make up for contact surface irregularities, ceramics require a plastic interface. Ceramic disk thicknesses from 0.5 to 5 mm may be used, sometimes thicker as applications merit. Unfortunately, thick ceramic disks are very brittle and costly.

4 Summary and conclusion

Both in the development and application of LEDs, component cooling is always an issue to consider. Whenever cooling is neglected, most semiconductor devices suffer irreparable damage, diminishing their durability and process safety.

Fortunately, LED manufacturers address the device cooling issues seriously. Questions concerning the cost-benefit-ratio, available space, and application efficiency need to be discussed at an early stage of the device design process. The fast-paced technological progress of the past three years, combined with the ever-increasing power density of high-performance LEDs, brought many new heat-management challenges to LED manufacturers and users alike.

Outdoor and automotive applications are especially subject to extreme changes in temperature and other ambient factors, which can lead to unpredictable effects in lighting. While the indispensable employment of cooling materials increases production costs, the careful choice of suitable heat management materials and the early reckoning in the device development process can minimize any additional costs.

Because the assembly of devices including LEDs requires the electric insulation of the semiconductor, the use of ceramic-filled thermo-silicone is recommended. It possesses excellent thermal conductivity and dielectric strength, low thermal contact resistance and superior double-sided adhesion. Compared to double-sided adhesive acrylic tapes, it is more heat resistant, process reliable, and user friendly. The material should, however, be stabilized by mechanical means against environmental stress.

In the case of electrically insulating LED applications, other thermally conducting materials are employed for cooling, such as phase-change materials or graphite foils. Here, too, maximum surface contact is achieved through mechanical means like screws or brackets.

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[1] Citizen Electronics Co., Ltd, CITILED, CL-L251-C4N
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