Superior Heat Management for LEDs

Owing to their durability, efficiency and long lifespan, LEDs are considered the illuminants of tomorrow. But their superior light yield comes at the cost of the production of waste heat, which can lead to overheating of the component part. Therefore, optimum thermal management is the only way to guarantee the use of high-power LEDs' full potential.

The LED's triumphant success set in, at the latest, with the development of high-power LEDs. Continuous improvement regarding light yield, colour, and cost efficiency has opened up ever new areas of application. LEDs are more durable than conventional lamps, they possess better energy efficiency and lifespan, and they require little space and low operating voltage. Yet, their light yield strongly depends on current feed and control, on ambient temperature, quality of the assembly and, last but by no means least, heat management. Especially the latter must be taken into consideration during operation of the component, in order to avoid its premature ageing and deterioration. Even though, in a semiconductor, a considerable portion of the electric feed is lost in the form of thermal waste, many suppliers still seem to presume that LEDs do not suffer from heating. The LED's light itself, of course, does not produce heat (in absence of IR emissions), but its production does. When developing a high-quality LED, sound thermal management is, therefore, indispensable for the realization of the desired product.

Ageing factors

Several kinds of energy sources (e.g. mains current, battery, charge pump) may be used as trigger circuits for linear or clocked power supplies. To increase light emission by an LED, the wattage may be increased. As this also implies increased jouleage (heat dissipation), resulting in a rise of temperature within the component, the LED's lifespan is considerably reduced. Producers of LEDs may achieve effective dissipation of heat away from the chip through special builds of the LED and its carrier plate without significantly affecting the LED's lifespan. High or highly variable ambient temperatures may also shorten an LED's operating life.

LEDs should always be operated at a distance of 25 to 27% below the maximum junction temperature T_{jmax}, as stated by the manufacturer. A typical given would be, e.g., T_{jmax} = 120°C. As the junction within the semiconductor is usually difficult to access for measuring, it is common procedure to measure the operating temperature T_s at the soldering point and the make an estimate regarding the difference to the junction temperature. This correction value – called T_c – is calculated on the basis of the LED's thermal resistance R_{th}, the forward voltage U_F, and the forward current I_F. Here is a sample calculation [1] for a 4W LED at 25°C ambient temperature:

$T_c = R_{th} \times I_f \times U_F = 6°C/W \times 0.56\ A \times 9.3\ V = 31.25°C$ (eq. 1)

$T_{smax} = T_{jmax} - T_c = 120°C – 31.24°C = 88.75°C$ (eq. 2)

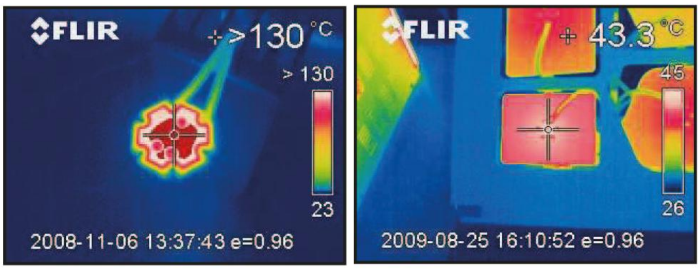
This calculation shows that an LED specified for T_{jmax} = 120°C must not be operated at temperatures greater than 88,75°C (T_{smax}), measured at the soldering point during operation. To be safe, operating temperatures should even be kept some 30 - 35°C below that value.
When the operating temperature T_s of medium brightness LEDs is increased from 25°C to 85°C, their average lifespan drops to one fifth, from around 50,000 to 10,000 operating hours. In extreme scenarios of application at $T_s \approx 150°C$ und $T_j \approx 175°C$, the average operating life even plummets to a mere 100 hours [2].

Thermal resistance of LEDs

One important parameter, when developing thermal management solutions for LEDs, is their thermal resistance R_{th}, stated independently of the ambient conditions. It is inversely proportional to the size of the contact area A and the thermal conductivity k, and directly proportional to the material thickness d:

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

Total thermal transfer resistance R_{th} Total is usually stated in °K/W (or °C/W), and is calculated as follows: R_{th} Total = $R_{th\ JS} + R_{th\ SB} + R_{th\ BA}$ (eq. 4). In the above equation, J, S, B and A stand for junction, soldering point, board, and ambient, respectively.



On the left, IR image of an Ostar LED (4W), 10 secs without heat sink , on the right, IR image of same LED with heat sink and TIM after 10 mins in operation

LED developers, therefore, not only need to know the thermal transfer resistance within the LED, $R_{th\,JS}$, as well as $R_{th\,BA}$ from the LED to its environment, but also the thermal contact resistance $R_{th\,SB}$ between soldering point and carrier board, located right in the middle of the assembly. To minimize this resistance and make for optimal contact independently of surface qualities, a thin layer of highly conductive Thermal Interface Material (TIM) is applied between carrier board and heat sink. When all this is observed, ideal operating temperatures can be achieved and junction temperatures kept under control.

It is common for variances to occur in assemblies which make it necessary to calculate correction factors. These values need to be included when calculating thermal contact resistivity, as they influence heat flow between the surfaces involved. Surfaces are always somewhat uneven. The air pockets resulting from surface irregularities inhibit thermal transfer and reduce effective surface contact. This is especially significant in the case of large surfaces and rigid geometries in the assembly. Thermal contact resistance thus depends on surface area, surface quality/evenness, adaptability of the TIM, and pressure. In practice, surface area is usually limited by the component casing. Minimum thickness of the thermally conductive TIM is determined by its puncture strength, as well as by surface irregularities or burrs which need to be evened out.

Thermally conductive materials: an overview

When an IR picture is taken of the back side of an Ostar LED during operation without adequate heat management, the result is an image as in fig.1 on the left: the LED overheats to 130°C.
Fig.1 on the right, on the other hand, shows the result of optimal heat dissipation using thermally conductive material and a heat sink. The following is a short overview of thermally conductive materials.

Graphite films

Graphite (carbon) possesses excellent thermal conductivity, and (at 97 to 99 per cent purity) is temperature resistant up to 450°C; high-performance carbons may even boast resistance up to 650°C. It is better suited for LED cooling than most other materials. As graphite films consist of compacted flakes, their dissipation is anisotropic: this means extremely fast heat spread in the X-Y (in-plane) direction as well as efficient dissipation in the Z (through-plane) direction. However, graphite films are not electrically insulating and are unable to compensate more than minuscule surface irregularities such as slight scratches. Superior surface finishing is therefore essential to ensure optimal heat transfer.

Polyimide films

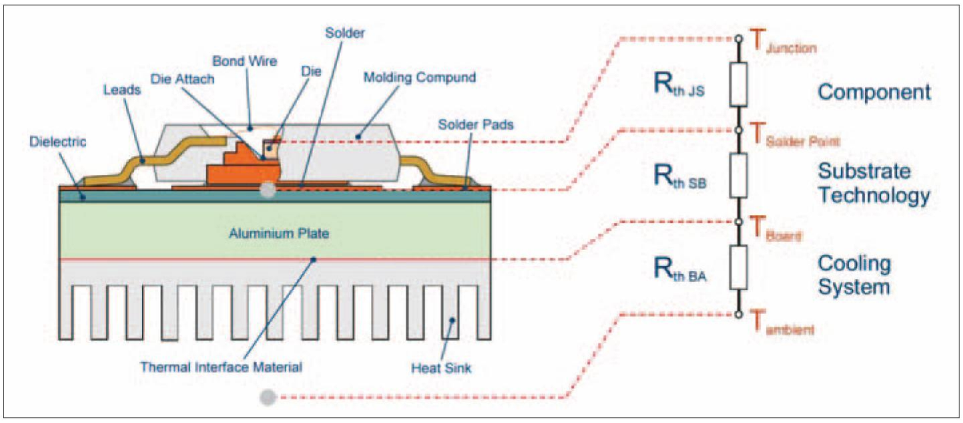
In assemblies, polyimide films are most commonly used for electric insulation. They possess very high dielectric strength while being both tough and flexible at the same time. Despite their relatively poor thermal conductivity, they may be used as TIMs at gauges between 25 and 125 µm owing to their low thermal transfer resistance. Again, superior surface treatment is indispensable, as the films' firm structure does not adapt to major irregularities. Due to their stability, they make for ideal substrate carriers for coating with thermally conductive silicone or phase-change thermally conductive wax.

Phase-change materials

Phase-change materials consist of a special mixture of thermally conductive waxes which change their state from solid to soft at 50 – 60°C, expanding by around 10 per cent in doing so, compensating any possible surface irregularities. Air is expelled from potential pockets in this process to ensure excellent thermal contact. Once temperatures drop below phase-change, the material returns to its solid state without deterioration of the contact surface connection. This is usually the method to achieve the lowest possible thermal transfer resistance. Depending on the supplier, phase-change materials are available in a range of delivery forms, from films (the application of which is relatively complex) to double-sided coating on a very thin substrate carrier which, as the requirements may be, is either electrically insulating or conductive.

Ceramics

Ceramic insulating plates are mostly made of aluminium oxide or aluminium nitride. They possess both outstanding electric insulation and thermal conductivity. For compensation of contact surface irregularities, a suitable, malleable interface material is required. Ceramic plates are typically used at gauges between 0.5 and 5 mm.



Build of a typical LED

Elastomers

The most common elastomer is silicone rubber. Beside high dielectric strength and chemical stability, this material possesses high temperature resistance. In silicones, thermal conductivity in combination with good electric insulation is achieved by filling with thermally conductive ceramics such as silica, Al_2O_3, aluminium or boron nitride. The higher the percentage of the ceramic filler, the better the material's thermal conductivity – but also its hardness.

Silicone provides excellent electric insulation, is resistant to ageing, very soft and malleable. It is, however, susceptible to slight outgassing, making it unsuitable for certain applications. Due to its softness, it makes for relatively easy handling and the manufacturing even of complex geometries. These films' maximum thermal conductivity usually ranges from 1 to 5 W/m x K, in particular cases even 10 to 15 W/m x K. They are available in gauges between 0.1 and 15 mm. For enhanced mechanical stability, they can be reinforced with fibreglass or applied on a substrate carrier. For easier mounting, they also come self-adhesive on one or both sides. Films thicker than 0.5mm are commonly employed as gap fillers whose softness makes for ideal compensation of tolerances and irregularities. Compression rates may be up to 40 per cent, depending on hardness and filling ratio. By optimizing surface pressure, thermal transfer resistance can be minimized.

Conclusion

The rapid evolution and ever-increasing power density of high-performance LEDs has manufacturers and users facing a number of challenges regarding optimal heat management. In order for semiconductors not to suffer permanent damage, it makes sense to include heat management specialists already at an early stage in the development and implementation of LEDs. When factors such as the requirements regarding functionality and durability of the application, operating conditions of the TIM, surface quality (curvature, finish) etc. are taken into account, the best possible interface material can be found. Cost efficiency, space, and application efficiency are matters to be discussed in the process.
Leading manufacturers have been acknowledging that taking heat management seriously has positive effects on product safety and durability.

Further reading

[1] Citizen Electronics Co.,LTD CITILED, CL-L251-C4N
[2] R. Huber, LED-Kühlung, Tagung Elektronikkühlung, HdT Essen, 2008/02/27