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LpR

The technology of tomorrow for general lighting applications.

Nov/Dec 2007 | Issue 04

Thermal Management

White LED Challenges

LED Lighting Control Systems

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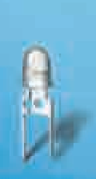

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LIGHTING FOREVER

The thermal challenge – a physical contradiction

Thermal Management is a key issue in LED lighting systems because main system parameters as light output, light quality and lifetime are depending on it. The temperature as a result of inefficiency becomes the most critical design parameter starting from the LED die with its junction temperature and ends up in the luminary housing with its maximum surface temperatures defined in international standards.

The basic system function of "generating light" is getting more and more linked to the question of "dissipating heat". Proper design of a LED system should ensure continuation of thermal flux from the heat source into the system surrounding atmosphere. Considering the overall efficiency from the mains to the light output about 75% of a LED lighting system are losses nowadays. Even with future highest efficient LEDs (150lm/W) about 50% of input power needs to be dissipated. The goal is to decrease the thermal resistance of the entire LED lighting system.

A LED lighting system has an inherent physical contradiction. On one hand the LED current should get high to generate desired lumen outputs but on the other hand the LED current should get low to reduce losses and heat. Physical contradictions can be solved by applying the so called four separation principles namely: separation in time, separation in space, separation on system level and separation on condition. In many cases in which optimizations come to its limits, separation is the right answer.

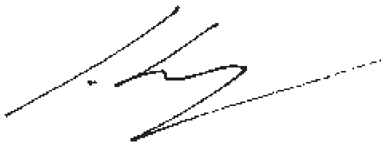
And there are lots of answers available on the market. New thermal materials and concepts as e.g. substrates with metal cores, CoB technologies, "look through" or air jets designs will improve the overall system performance. Thermal modeling techniques also play an important role to understand and finally "optimize" LED systems.

The challenge of a sophisticated LED design is to combine the optical and thermal design disciplines to continuously improve the overall system efficiency and hence its light quality including the electronic driving system as well.

With the November issue of the LED professional Review (LpR) a lot of thermal management topics are covered in depth.

Please send us your feedback about the LpR content. We would like to get your opinion on how to continuously improve our services to you. Furthermore take the opportunity for your own contribution as well.

Yours Sincerely,



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Project News

Colorful Time for Regensburg, a World Heritage Site

The pyramids of Giza, the Great Wall of China and Stonehenge. An impressive list, and for the past year the old city center of Regensburg has rightfully been mentioned in the same breath as these remarkable structures. To celebrate the presentation of the official charter, LEDs from OSRAM Opto Semiconductors bathed three historical monuments in Regensburg's official municipal color of red. A lighting installation that perfectly combined tradition, historic atmosphere and ultra-modern technology.

All day long the people of Regensburg celebrated the new status of their city. There are around 1000 historic monuments here packed into a small area. Three of them appeared throughout the celebration in bright red, the official color of Regensburg. The light show was set up by the Regensburg-based lighting designers LI-EX. They placed red Golden Dragon LEDs in the 85 windows of the Dollingersaal, the Salzstadel and the Runtingersäle, to create a memorable impression of these historic buildings.

Brilliant Golden DRAGON LEDs bring the windows of the "Salzstadel" to life

Architectural Lighting with chip technology:
Golden Dragon LEDs are exceptionally bright and are therefore becoming established as the light sources of choice for bold and atmospheric architectural lighting. Thanks to the new thin-film chip technology from OSRAM, the LEDs are now even brighter than ever before because almost all of the light generated in the semiconductor chip is emitted at the top. This takes lighting installations such as this to new levels of brightness, bathing even large imposing buildings in intensive light.

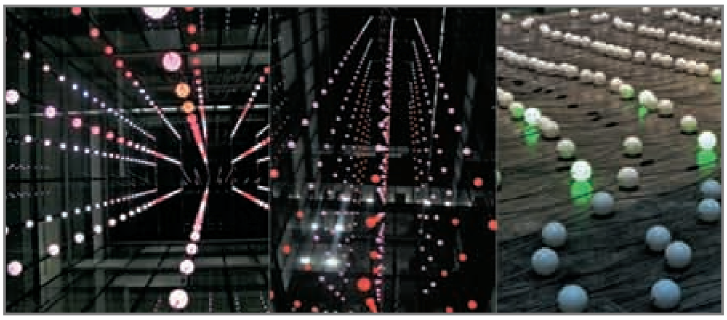
Light at any temperature:
The tiny light sources are extremely robust and durable, and operate reliably at temperatures from minus 40 to plus 100 degrees Celsius. They can be installed quickly and easily, making them ideal for temporary or retrofitted lighting systems such as those used for the celebrations in Regensburg. The red LEDs with their wavelength of 625 nanometers blended perfectly with the architecture of the Regensburg buildings, creating the ideal atmosphere for celebrations well into the night. ■

Modern Interpretation of Light Cloud Composed of More than 600 LED Globes

A three-dimensional matrix of 624 globes, each fitted with 24 LEDs, provides a compelling lighting scenario in the atrium of law firm Allen & Overy's office building in Bishops Square, which was designed by Foster and Partners. The concept and design of the "Pixel Cloud" was developed and produced by the Jason Bruges Studio in London and Ledon.

LED globes consisting of 12 surfaces and 24 LED - 624 LED globes stretch across eight floors and open up an immense colour spectrum of 16 million colours at the headquarter of Allen & Overy.

The LED light sculpture is suspended from the ceiling of the 10-storey atrium in the office building of the prestigious law firm like an oversized chandelier, its intermittently controlled dynamic changes in colour and light invoking the international reach of Allen & Overy's world-wide network. The Pixel Cloud extends over eight floors and, with its impressive design, conjures up a striking lighting scene. 624 milky-white polycarbonate globes, each with a diameter of 120 mm, combine to form a three-dimensional network. Each of eight parallel high-gloss polished stainless steel sections supports three arms which each carry 26 globes. The globes are fitted with 24 LEDs and are individually controllable. Inside the globe, a dodecahedron-shaped flexible circuit board ensures each globe is uniformly illuminated. 8-bit resolution in the primary colours red, green and blue opens up an immense colour spectrum of 16 million colours.



The spectacular lighting solution with its diverse range of lighting moods and appearances

Every globe is individually controllable thanks to specially developed software. Real-time colour and light updates perpetually change the three-dimensional LED lighting installation's appearance, which lends it an amazingly live effect. The server generates an extremely wide variety of modes. A sky-watching camera installed on the roof is used to transfer images of passing clouds onto the Pixel Cloud. This diverse, ever-changing LED application includes films or sequences of prepared individual images and even supports interactive involvement of web communities. Colourful animations and playback of local weather phenomena provide constantly evolving spectacular simulations in the atrium space. Jason Bruges Studio has adjusted the spacing of the Ledon globe matrix so that it matches the grid of the façade designed by Foster and Partners. The internal glass façade is transformed by changes in colour and light. One bar at a time lights up, bringing the outdoor lighting mood indoors, from top to bottom, sharing it with those working in the offices. ■

Product News

OSRAM's New Diamond Dragon: So Bright, so Cool – Even up to 175°C

At the start of 2008 OSRAM Opto Semiconductors will be launching a white super-bright LED by the name of Diamond Dragon. This LED combines impressive brightness of 250 lm (at 1.4 A) with a very low specific thermal resistance of 2.5 K/W, all in a SMT package. The LEDs will cover the entire white range and will also be available in all other colors. They will therefore be suitable for both indoor and outdoor general lighting applications and also for the automotive sector in daytime running lights or rear fog lights.

The exceptionally low thermal resistance of Rth = 2.5 K/W in the SMT package means that the heat produced in the chip can be efficiently removed. The maximum junction temperature of 175°C makes the LED extremely robust and allows solutions where the LED cannot be ideally cooled. These properties enable the LED to be easily integrated for example in small spotlights, retrofit applications and recessed ceiling luminaires, where they can even replace small halogen lamps. The LED can withstand even high temperatures with no damage at all. The silicon lens can be handled using standard SMT processes and does not require any change of process..

OSRAM's new Diamond Dragon in action

The high-brightness single-chip LED is based on a 2 mm2 chip manufactured in Thin-GaN technology with chip level coating. With its typical power rating the Diamond Dragon adds to the OSRAM LED portfolio in the 5 to 8 W range and forms the link between the established 1 to 3 W LEDs (Platinum Dragon) and the 10 W LEDs (OSTAR). It is compatible with the other Dragon footprints and can therefore be integrated in existing designs without modification. The LED produces its impressive brightness of 250 lm at a typical operating current of 1.4 A (max. 2 A) in continuous operation. The LED can achieve a lifetime of more than 50,000 hours.

Extremely low thermal resistance coupled with low cooling requirements makes the Diamond Dragon ideal for use in recessed lights. Thanks to their small size they can be used instead of conventional halogen lamps for unobtrusive lighting. ■

LEXEDIS Lighting Releases High Efficiency Digital Light Source: powerXED

powerXED demonstrates all the benefits of the LEXEDIS XED range: smallest form factor, excellent thermal management and Chip in Silicon packaging. These properties are now further enhanced by a first in the industry – introducing indeXED 90 – powerXED features a Colour Rendering Index (CRI) of up to 90 in the warm white range.

The name powerXED is synonymous with excellent light homogeneity, superior colour rendering and luminous performance. This power emitter is capable of delivering up to 60 lumens for cool white at a rated current of 350 mA. The device's high Colour Rendering Index (Ra8) of up to 90 in the warm white range is expected to fulfil architects, lighting designers and lighting engineers' requirements of high-performance light sources by exceeding the Colour Rendering Index of 70 – 80 Ra8 prevalent in fluorescent lighting.

powerXED: The industry's smallest form factor (2.5 mm x 2.5 mm x 0.6 mm) powerXED is available in 4 standard correlated colour temperatures (CCT) in the white-light range: 3,000 K, 4,200 K, 5,700 K and 6,500 K. Due to its high CRI powerXED emits a quality of natural light which makes it the perfect choice for application in retail, medical and dental lighting as well as both linear architectural and façade lighting applications.

powerXED features the properties which make LEXEDIS products stand out: the industry's smallest form factor (2.5 mm x 2.5 mm x 0.6 mm), a 120° Lambert beam pattern and its unique Zero Colour Bin guarantee (Step 6 MacAdam's ellipse). The use of inorganic materials ensures durability, reliability and a long service life of in excess of 50,000 hours.

Combining the properties of XED and a Colour Rendering Index of 90. Introducing indeXED 90, powerXED a new highlight in high-quality white light. ■

Revolutionary Syn-Jet Coolers for PAR38 and MR16

Nuventix unveiled two new LED cooling modules. These two products, utilizing Nuventix' SynJet™ technology, provide high reliability, low audible noise and low power consumption cooling technology for two industry standard lighting configurations. Using the SynJet approach allows twice the light output compared to passive LED thermal management designs.

PAR-38 LED lamp with SynJet cooling system

The MR-16 SynJet cooling module was developed by Nuventix for cooling 15W heat source in a LED lighting application. The cooler is designed to fit the form factor of an MR-16 bulb and provides 300,000 hours L10 life at 60C.

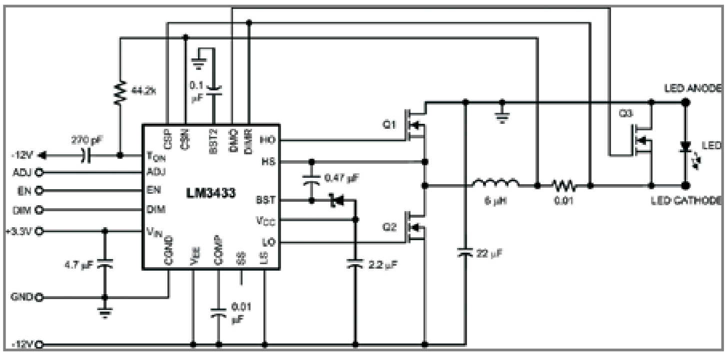
The PAR-38 is also a SynJet cooling module developed by Nuventix for active cooling of a LED PAR-38 light source. It can be integrated with a wide array of electronic and optical solutions in the PAR-38 form factor. The module cools 35-50 watts, provides 300,000 hours L10 life at 60C and meets PAR-38 form factor while providing near silent acoustics.

"Finally the LED Industry has a cooling technology that is perfectly suited for LED illumination," said Jim Balthazar, president and CEO, Nuventix. "General lighting LED solutions today are limited by the amount of heat that can be cooled. SynJet technology will allow the LED industry to double its light output in general lighting today, without compromising power efficiency and reliability. ■

HB-LED Driver from National Semiconductor

National Semiconductor Corporation introduced the industry's first common-anode, current-mode, high-brightness light-emitting diode (LED) driver with pulse-width modulation (PWM) dimming. The LM3433, a member of National's PowerWise® energy-efficient product family, drives high-power, high-brightness LEDs in backlighting, projector and solid-state lighting applications.

National's LM3433 LED driver opens the way for high-reliability LEDs to be used in large-screen liquid crystal display (LCD) television (TV) backlighting applications where a common anode approach offers a thermal advantage. In another example, LEDs can be used in today's shrinking "pocket projector" designs for a wider color gamut, higher reliability and longer life expectancy than the ultra-high performance (UHP) lamps used today.



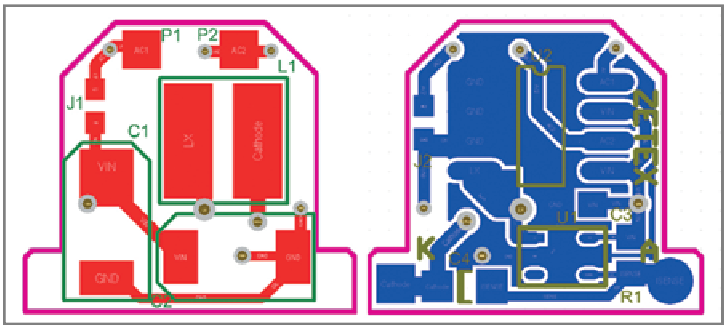
LM3433 Block Diagram

National's LM3433 is a constant on-time DC-DC buck (step-down) constant-current regulator. It outputs a negative constant current for lighting high-power, high-brightness LEDs. The negative voltage option allows the anode of the LED to be tied directly to the ground-referenced chassis for maximum heat sink efficacy. The short constant-on-time architecture allows the use of small external passive components and no output capacitor. Two current control modes modulate LED brightness. An analog current control input is provided so the LM3433 can be adjusted to compensate for LED manufacturing variations. The other current control is a logic-level dimming input for PWM control of LED brightness. The PWM functions by shorting out the LED with a parallel switch, allowing high PWM dimming frequencies up to 40 KHz. Additional features include thermal shutdown, VCC under-voltage lockout and logic-level shutdown mode. ■

Zetex: Novel Dedicated Chipset for MR16-Compatible LED Lamps

Zetex Semiconductors has developed a novel dedicated chipset and reference design for MR16-compatible LED lamps. Reducing the component count of existing solutions by up to 50%, the chipset significantly decreases the size and weight of the PCB in the neck of the lamp and the overall cost of lamp manufacture.

The highly integrated MR16 chipset handles all associated power rectification, LED current control and protection functions. MR16, the standard format for halogen reflector lamps, is used extensively in directional lighting applications in residential, retail and office environments. LED based variants can offer dramatic improvements in efficiency and reliability.



Layout proposal - Top Copper and Silkscree (left), Bottom Copper and Silkscreen (right)

The main features of the ZXLD1350:

- Up to 380mA output current
- Wide input voltage range: 7V to 30V
- Internal 30V 400mA NDMOS switch
- High efficiency (>90% possible)
- Up to 1MHz switching frequency

The ZXLD1350 is designed for LED current drive applications of up to 350mA. The monolithic NMOSFET is sized appropriately to provide a cost-effective die size and is rated to 400mA, which with the hysteretic mode of operation (the inductor current waveform will ramp +/-15% about the nominal current set point). ■

LLF's High CRI Warm-white PAR 38 Self-Ballasted Lamp Consumes Less Than 6 Watts

LED Lighting Fixtures, Inc. (LLF), which developed and markets the only viable indoor light fixture for general illumination from LED light sources, announced today the results from its prototype PAR 38 self-ballasted lamp. LLF's LRP-38 lamp set a new standard for energy efficient lighting by producing 659 lumens at a mere 5.8 watts of wall-plug power, resulting in 113.6 delivered lumens per watt. The LLF lamp would use less than 9% and 30% of the energy consumed by incandescent and fluorescent sources, respectively. Using LLF's proprietary technology platform, the lamp emitted a warm incandescent-like color of 2760 Kelvin with a superb color rendering index of 91.2 and does not contain any toxic mercury. Steady state testing was conducted by the National Institute of Standards and Technology (NIST) in Washington, DC.

Gerry Negley, LLF's Chief Technology Officer said, "The results of this prototype clearly demonstrate that LLF's LED technology will surpass all existing forms of lighting in terms of performance. It further validates that LLF has created a unique method for maximizing solid state lighting efficiency while delivering a lighting experience that is better than incandescent and fluorescent sources. The prototype lamp verifies that the LLF platform can be deployed in any form factor which will allow full penetration of the global lighting market. We used Cree, Inc. XLamp and OSRAM Opto Semiconductors Golden Dragon products in the lamp, which we believe are the best LEDs available to maximize our proprietary system performance. We appreciate the support we've received from these key suppliers."

Chuck Swoboda, Chairman and Chief Executive Officer of Cree, Inc. commented, "This is an impressive demonstration. LLF has given us a look into the future of lighting."

According to Tony van de Ven, LLF's Hong Kong Managing Director, "We are very encouraged by our LRP-38 technology demonstration, as it is clearly the most energy efficient, high CRI white lighting solution ever developed. While there is currently no timetable for a production release, this result shows that LLF's technology with LED light sources has the ability to surpass 100 lumens per watt from a fixture, which is a revolutionary milestone for significant world-wide energy savings." ■

Research News

DOE Releases 3rd CALiPER Report: Progress in Product Efficacy

Round 3 of CALiPER testing included a very wide range of products for a wide variety of applications, from a low wattage 0.6 W replacement lamp to a 189 W outdoor area light. While the majority of products tested in Round 3 performed quite well, some products performed poorly. Because of the wide variation in performance, it is essential for buyers to request explicit indications of luminaire output and luminaire efficacy from vendors. Application-specific decisions regarding SSL alternatives must be made carefully following analysis of product performance.

On average, the SSL downlights are providing light output levels on par with 45-65W incandescent reflector lamps, and greatly surpassing them in efficacy. They are also now clearly rivaling similar downlight CFLs, with one SSL product significantly surpassing the CFL benchmarks in performance.

The Round 3 results also show that SSL undercabinet and desk lights are now able to perform better than benchmarked halogen and fluorescent task lights, and would do so even more consistently if their off-state power consumption were eliminated.

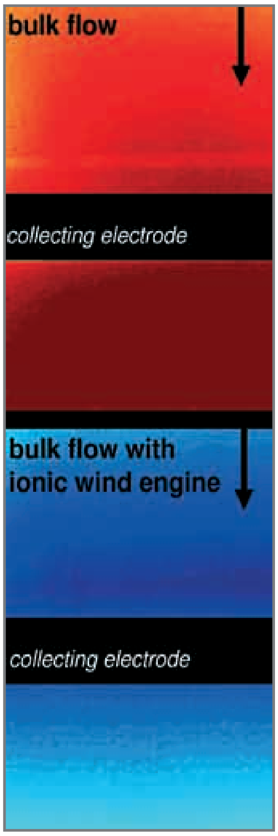
Several products tested in Round 3 that would meet the criteria for luminaire output, luminaire efficacy, and color quality requirements of the ENERGY STAR® Program requirements for Solid State Lighting.14 Version 1.0 of the ENERGY STAR requirements for SSL defines requirements for a number of application categories: undercabinet (kitchen and shelf-mounted), desk lamps, downlights, and outdoor.

Product literature regarding SSL luminaires and replacement lamps is still inconsistent and does not always provide reliable or straightforward product performance information. However, the significantly more accurate performance claims seen in product literature for products that were submitted as samples to the DOE SSL commercialization support programs (for SSL demonstrations and Lighting for Tomorrow) is encouraging.

While the generally strong performance of Round 3 SSL products implies great promise for the upcoming generations of commercially available SSL luminaires, SSL product performance still should not be generalized. The large divergence in performance characteristics means that buyers will need to consider the performance of each product separately and require clear (and accurate) luminaire performance information from manufacturers for each product under consideration.

A detailed report can be ordered from DOE.
The abstract is available at http://www.netl.doe.gov/ssl/comm_testing.htm.

New technology has dramatic chip-cooling potential



Infrared Image of cooling with ionic "wind engines"

The Purdue University researchers, in work funded by Intel Corp., have shown that the technology increased the "heat-transfer coefficient," which describes the cooling rate, by as much as 250 percent. "Other experimental cooling-enhancement approaches might give you a 40 percent or a 50 percent improvement," said Suresh Garimella, a professor of mechanical engineering at Purdue. "A 250 percent improvement is quite unusual."

This breeze increased the airflow on the surface of the experimental chip:

Infrared imagesConventional cooling technologies are limited by a principle called the "no-slip" effect - as air flows over an object, the air molecules nearest the surface remain stationary. The molecules farther away from the surface move progressively faster. This phenomenon hinders computer cooling because it restricts airflow where it is most needed, directly on the chip's hot surface.

The new approach potentially solves this problem by using the ionic wind effect in combination with a conventional fan to create airflow immediately adjacent to the chip's surface, Fisher said.

The device was created at Purdue's Birck Nanotechnology Center in the university's Discovery Park. The researchers quantified the cooling effect with infrared imaging, which showed the technology reduced heating from about 60 degrees Celsius - or 140 degrees Fahrenheit - to about 35 degrees C, or 95 F.

The researchers also have developed computational models to track the flow of electrons and ions generated by the device, information needed for designing future systems using the technology.

The next step in the research will be to reduce the size of components within the device from the scale of millimeters to microns, or millionths of a meter. Miniaturizing the technology will be critical to applying the method to applications, allowing the device to operate at lower voltage and to cool small hot spots, Garimella said.

Another challenge will be making the technology rugged enough for commercial applications.

Patents are pending for the new design.

Thermal Management for LED Luminaires

> Dr. Keith Bahde, Gallium Lighting Systems

This article provides an overview to effective thermal management for LED luminaires. First, a number of LED thermal issues are presented, including the three primary modes of heat transfer, maximum LED junction temperatures, the importance of overcoming thermal resistance, the key impacts of poor LED thermal performance, and the common methods for measuring LED thermal performance. Next, a number of methods for improving LED luminaire thermal performance are presented, including the application of both passive cooling technologies. Finally, a brief case study illustrates the use of these principles in a high-performance LED luminaire.

LED Thermal Issues

Recent advances in LED technology are revolutionizing the worldwide lighting industry by making possible the design of luminaires that are more energy-efficient, longer-lasting, more durable, and more environmentally friendly than existing lighting technologies. However, proper design of LED luminaires requires that luminaire designers address a number of challenges unique to LEDs. One of the most important of these challenges is proper thermal management, which is required due to the significant heat created by LEDs.

Modes of Heat Transfer

Three modes of heat transfer are studied in the field of thermo-dynamics: (1) Radiation, which occurs when heat is emitted from an the surface of an object into the surrounding environment; (2) convection, which transfers heat in a liquid or gas; and (3) conduction, which transfers heat through direct surface contact. Most standard luminaires using incandescent, fluorescent, and high intensity discharge (HID) lamps rely primarily on a combination of radiation and convection to dissipate heat from the lamp to the external environment. However, since LEDs produce no electromagnetic radiation in the infrared zone, they radiate little or no heat. Further, without the addition of special equipment, LEDs are unable to effectively dissipate heat through convection. Thus, the primary mode of heat transfer in LEDs is conduction.

The most widely used LEDs in recent years, the so-called 5mm type used primarily as indicator lamps, lack the physical structure to transfer significant heat through conduction, and are therefore limited to relatively low levels of power. In contrast, high-power LEDs are manufactured with a heat sink embedded in the base of the LED case. When properly attached to special types of printed circuit boards (PCBs) and other thermal management equipment, these LED heat sinks provide the capacity for one or more watts or power (see Figures 1-3, which depict the differences in construction of 5mm and high-power LEDs).

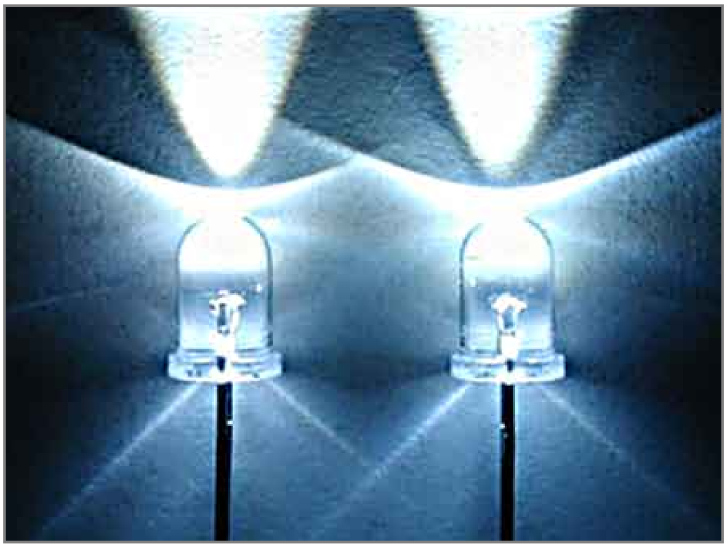


Figure 1: 5mm LEDs

Figure 2: Power LED

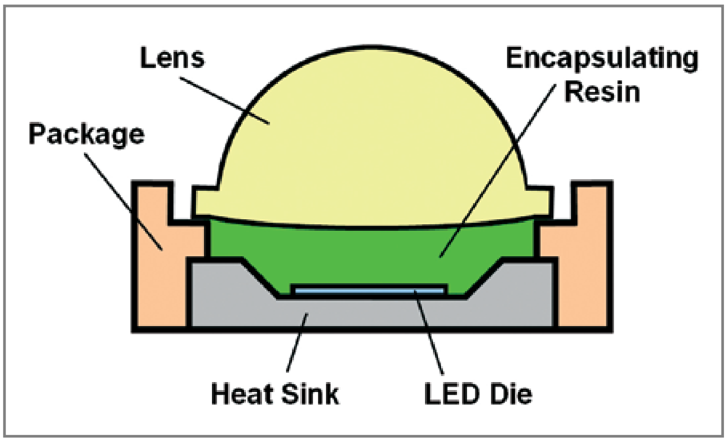


Figure 3: Cross-Section of Power LED

Maximum LED Junction Temperatures

The heart of the LED is called a die (see Figure 3), which includes the positive-negative junction (or p-n junction) at which the LED creates photons from electricity. Most LED manufacturers publish the maximum temperature at which the die can operate without damage. For example, the major LED suppliers used by Gallium Lighting publish maximum die temperatures ranging from 120°C to 150°C, and some LED suppliers also specify a maximum case temperature. However, operating LEDs at or near these maximum levels is not recommended for several reasons outlined below, and most LED suppliers suggest that luminaires be designed so that LED junction temperatures are maintained well below 100°C in typical applications. In practice, reputable LED luminaire manufacturers attempt to minimize junction temperatures using combinations of cost-effective thermal management technologies.

Thermal Resistance

Thermal resistance refers to the ability of a component to transfer heat, and it is commonly measured by the degrees (in Celsius) per watt of power (°C/W). For example, a device rated at thermal resistance of 10°C/W will increase in temperature by 10°C for each additional watt of power. Thus, LED luminaire manufacturers attempt to select components with lower levels of thermal resistance so LED junction temperatures are maintained as low as possible at higher levels of power.

Luminaire manufacturers focus on three primary locations in which thermal resistance can adversely affect the function of a LED lighting system: (1) from the LED junction to the LED case; (2) from the LED case to the heat sink; and (3) from the heat sink to the external environment. The thermal resistance of the first of these locations is determined by the construction of the LED, and how well the design of the LED heat sink and case provide for heat transfer from the die to the heat sink. The major LED suppliers used by Gallium Lighting publish levels of thermal resistance ranging from 7.3°C/W to 10°C/W. The thermal resistance of the second of these locations is determined primarily by the type and design of PCB selected, the type of thermal interface material used, and the methods of attaching the LED, PCB and heat sink. Finally, the thermal resistance of the last of these locations is determined by the design and placement of the heat sink. Characteristics of each of the components in the second and third location are discussed further below.

Impacts Of Poor LED Thermal Performance

Although LED junction temperatures impact a wide range of variables including the voltage and current levels of the LED, luminaire designers focus on the following three areas of performance.

Reduced Lumen Output and Efficacy. One of the key impacts of increased LED junction temperature is reduced lumen output and, as a result, reduced energy efficiency (which is measured in lumens per watt). Lumen output levels decline as roughly a linear function of increasing junction temperatures, and at a level of roughly one percent per three degrees (C) of junction temperature increase. Thus, a LED rated to produce 100 lumens at a junction temperature of 25°C (the typical level used by LED manufacturers to specify performance) will produce only about 80 lumens if the junction temperature increases to 80°C.

Reduced LED Expected Life. The expected life of a LED an also be reduced if the maximum temperatures published by LED manufacturers are exceeded. For example, one LED supplier publishes data showing that the expected life of their LEDs begins to decline at junction temperatures of a bit over 125°C, despite the fact that maximum junction temperatures are specified at 150°C. However, well-designed luminaires should never operate at these extremely high temperatures, except when used in extremely demanding ambient conditions (i.e., high temperatures and low air flow).

Color Shift. As junction temperatures rise, the color of light emitted by white LEDs also shifts slightly toward the cooler tones of white (i.e., slightly higher Kelvin temperatures). However, these modest color shifts are largely unnoticeable since these effects are relatively modest, are likely to shift gradually as junction temperatures gradually rise, and are likely to impact all luminaires installed in a common area at the same level.

Measuring LED Thermal Performance

As noted above, the critical measure of LED performance occurs at the LED junction. However, as Figure 3 shows, this junction is encapsulated within the LED case, and is therefore inaccessible. Thus, in practice there are two primary methods for measuring LED thermal performance, each of which is described below.

Change In LED Voltage. Since LED voltage declines as junction temperature increases, one method of measuring junction temperature is to take voltage readings immediately after starting the LED, and then again after the LED luminaire has reached a level of thermal equilibrium (generally one to two hours after starting the LED). Using a formula provided by the LED manufacturer, LED junction temperatures can be estimated based on the change in voltage. However, in practice this method is subject to a high degree of error, and provides only a rough estimate of junction temperature.

Thermocouple. A more reliable method of measuring junction temperature is measuring the temperature rise at the fixed location on the PCB or heat sink after the LED luminaire has reached thermal equilibrium. However, this method requires the calculation of the thermal resistance of all components between the LED junction and the placement of the thermocouple. For example, if a thermocouple is placed on the heat sink directly below the base of the LED, one must adjust the thermocouple reading for the resistance contributed by both (1) the LED junction to the LED case, and (2) the LED case to the heat sink. As noted above, the thermal resistance of the LED junction to the case is typically published by the LED manufacturer, so the impact of this component is easily measured. However, the impact of the PCB and interface materials used to bond the PCB to the heat sink must also be measured. Alternatively, a small hole may be drilled into the heat sink directly below the LED base, and the thermocouple may than be placed directly on the LED heat sink. By doing so, the impact of all components except for the LED junction to the LED case can be ignored.

Improving LED Luminaire Thermal Performance

Luminaires designed for use with incandescent, fluorescent or HID lamps are unlikely to offer thermal management functions adequate for LEDs. Luckily, LED luminaire designers can utilize many of the technologies employed in the field of semiconductor cooling for use in computers and other devices utilizing semiconductors.

Passive cooling technologies are generally preferred for LED fixtures because they employ no moving parts and require no energy for their operation. In the sections below, commonly used passive cooling technologies such as PCBs, heat sinks and thermal interface materials are briefly described.

PCBs. One of the most commonly used materials for PCBs is FR-4 material, which is short for flame resistant 4. Although this material provides the basic functions of a PCB—including the mounting of electronic components and providing the circuits to connect the components—FR-4 PCBs generally lack the thermal management characteristics required for LEDs2. Instead, most reputable LED luminaire designers employ metal core printed circuit boards (MCPCBs), which are also called insulated metal substrates (IMSs).

Power LEDS are soldered directly to metal core of MCPCBs, ensuring effective heat transfer from the LED heat sink to the PCB. Luminaire designers must take care to design a PCB of adequate size so that the LEDs are properly spaced for effective heat transfer. Depending on the design of the MCPCB and the requirements of the LED, this may be all that is required for adequate thermal management. However, in most cases an external heat sink is also utilized.

Heat Sinks. Heat sinks provide increased surface area to more effectively dissipate heat from semiconductor devices to the external environment. They can be designed for either (1) natural convection, which uses the free flow of air circulating in the natural environment to cool the heat sink; or (2) forced convection, which uses a fan or blower to provide additional cooling capacity. Heat sinks are produced using a variety of metal-forming approaches, including extrusion, stamping, casting, milling, and bending.

Key heat sink performance parameters include (1) a large surface area to spread the heat generated by the LED and provide access to circulating air; (2) a flat contact area to provide effective heat transfer from the PCB; (3) an effective aerodynamic design to ensure effective air circulation; (4) effective thermal transfer within the heat sink; and (5) a secure method of mounting the heat sink to the PCB, which is also required to provide effective heat transfer from the PCB3.

Thermal Interface Materials. Even properly designed PCBs and heat sinks will typically have minor surface imperfections, which impede effective thermal transfer because the surfaces of the two materials are partially separated by air pockets. To address this, properly designed LED thermal management systems employ various types of thermal interface materials to bond PCBs and heat sinks. These materials increase the thermal conductivity of a LED luminaire by filling in surface imperfections with highly conductive substances such as zinc oxide or various metals.

Thermal Modeling Software

Each LED luminaire design presents unique thermal challenges based on the number of LEDs used, the current at which they are driven, the physical characteristics of the luminaire housing, and a variety of other factors. Designers can experiment with a number of standard thermal management technologies to achieve desired LED junction temperatures, of they can use specialized thermal modeling software to help estimate the LED junction temperature based on number of key inputs. Such software is now available from a variety of providers, including some LED manufacturers.

Case Study

To illustrate the effective use of the principles outlined above, this section describes a simple but effective application of passive cooling technologies in a LED luminaire that produces lumen output equivalent to 26-32 watt compact fluorescent luminaires, but uses significantly less power.

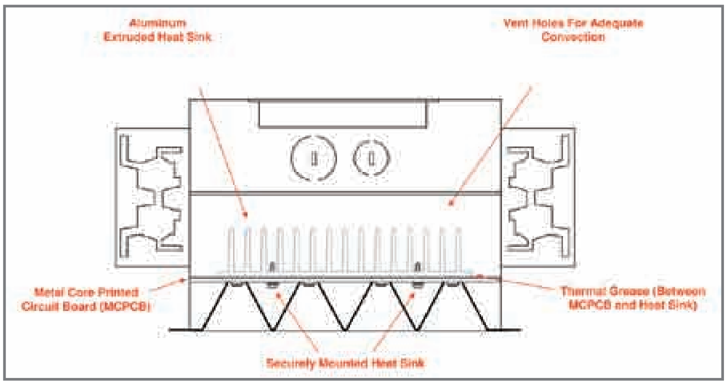


Figure 4: Gallium GS6 LED Luminaire

As shown in Figure 4, the Gallium GS6 LED luminaire employs the following thermal management technologies:

- Metal Core Printed Circuit Board (MCPCB): LEDs are wave-soldered on an aluminum MCPCB, and are spaced at conservative 1 ½" intervals to provide a high degree of heat dissipation.
- Aluminum Extruded Heat Sink: A heavy-duty aluminum extruded heat sink provides significant surface area to dissipate the heat transferred from the LEDs to the MCPCB, and onto the heat sink.

- Thermal Interface Material: The MCPCB and heat sink are bonded with high-quality thermal interface material, which maximizes thermal conductivity and reduces the LED junction temperature.
- Securely Mounted Heat Sink: The heat sink is securely mounted to the MCPCB to ensure effective thermal transfer.
- Vent Holes For Effective Convection: A significant number of vent holes are machined into the luminaire housing to ensure effective air flow and heat dissipation through convection into the surrounding environment.

The results: Using Lumileds Rebel LEDs, for which the maximum published junction temperature is 150°C, the Gallium GS6 LED luminaire produces a junction temperature of less than 75°C when operated in a 25°C ambient environment with LEDs driven at 350mA. This conservative thermal design provides the capability to produce over 1,000 lumens from a LED luminaire utilizing sixteen LEDs, each of which produces a minimum of 100 lumens (when operated at 25°C). This design also ensures the long life expectancy promised by the LED manufacturer, and minimizes color shift due to high junction temperatures.

Conclusions

The thermal issues created by high-power LEDs present unique challenges to luminaire designers experienced with traditional light sources, such as incandescent, fluorescent and HID lamps. The effective design of high-performance LED luminaires requires an understanding of LED thermal issues and the available methods for improving LED luminaire thermal performance. This article presents an overview of each of these issues, and illustrates how the effective application of these principles can produce a high-output LED luminaire that outperforms comparable compact fluorescent luminaires.

Lighting specifiers should ensure that the LED lighting products they select have been designed to properly address thermal performance, and should use caution if thermal performance data is not available from the manufacturer. Further, LED products designed to be retrofitted into existing fixtures can be especially problematic since it is impossible to verify the thermal performance of retrofitted products in each possible type of existing housing. Only by specifying LED luminaires designed as integrated systems can thermal and photometric performance be assured. ■

Footnotes:

1 For an extended discussion on modes of heat transfer in lighting technologies, see: Petroski, J. (2006). Thermal challenges in LED cooling. Electronics Cooling, 12(4), pp. 28-32.

2 Note that some specially designed FR-4 PCBs can provide excellent thermal management, but special LED and PCB designs are required.

3 See http://www.heatsink-guide.com/ for a comprehensive overview of MCPCBs, heat sins, and other semiconductor cooling technologies.

Biography:

Dr. Keith Bahde, President

Dr. Bahde has 20 years of lighting industry experience with three of the four largest lighting fixture manufacturers in North America. Keith was quick to recognize the benefits of white LEDs for general illumination, and founded Gallium Lighting to accelerate the adoption of LED technology in mainstream architectural applications. His academic credentials include an MBA and a Ph.D.

Technologies

Challenges Still Linger for Mainstream White LEDs

> M. Nisa Khan, Ph.D., Optoelectronic & SSL Technologist

Despite the vast LED, or solid-state lighting (SSL) market growth in the last 5 years, the most powerful application of LED - namely the general illumination of homes and offices (also known as white high-brightness LED or HB-LED), still faces significant challenges. These challenges are multifold and perhaps somewhat controversial in the industry currently because they involve both business and technical issues, both leading to a high-cost scenario that prevents most companies and regulators from adopting the necessary changes. In order to overcome these challenges, we must first understand the true nature of them, which will then help the LED and lighting manufacturers focus on the right solutions. This will convince the public and the regulators of the cost and environmental benefits and the markets will then start to develop rapidly. The main business challenge is how to overhaul the incumbent products (i.e., incandescent and fluorescent lights) that are well-accustomed and generate enormous revenues and profits for large companies, in the midst of certain technical SSL challenges. The main technical challenges appear to be effective communication among the LED, luminaire (a complete pluggable light unit such as a bulb) and lighting companies in the supply chain, lack of testing standards, and inadequate demonstration of product characteristics such as LED module lifetime and performance over lifetime. As you may have guessed, these challenges add to the former business challenge, further complicating the market development of white HB-LEDs. Let us delve further into these challenges and see how we can discover some solutions that may expedite the market penetration of LEDs for general illumination.

The business challenge is a familiar one, namely, how do large companies slow down their current 'bread and butter' product revenues in the hope of improved products from a new technology that still have unsolved technology issues and require large development investments and resources? For any semiconductor-based new technology, primarily semiconductor optoelectronics, this is especially a difficult challenge since it is a very specialized field where only a relatively few are familiar with its core science, making business executives further unsure. This was clearly observed for lasers, although, the challenge there was not as great because the laser industries (e.g. in fiber-optic telecom and medical) are "low-volume/high-cost" and therefore, such a high-tech solution has been adopted more easily. However, in the case of "very-large-volume" general lighting, consumers demand a very low-cost and 'easy-to-use' product. Furthermore, residential consumers prefer the "warm glow" of the incandescent bulb, which is currently difficult to produce in both fluorescent (e.g., CFLs) and LED lights.

So, where are we in addressing the challenges above in the technical domain? A LED luminaire is a system, integrated of many components such as the LED chip, encapsulation, driver electronics, cooling heat-sinks and fins, beam control optics, and others. For a general-illumination LED luminaire, an HB-LED is required, which is typically constructed using several phosphor-coated LED chips or an ensemble of multiple-color LED chips, each ensemble producing a similar white light. In either configuration, the amount and the quality of "white" light degrade over time as high-density current passes through the LED chips for operation. The minimization of this degradation depends particularly on LED chip design, thermal design, phosphor technology, and requires sophisticated systems engineering optimization methods. I believe this multi-disciplinary core competency is rare in the industry and therefore most suppliers are not able to produce the desirable high performance that a few companies have been able to supply. Moreover, the industry is facing a measurement and calibration discrepancy for light output and efficacy (Lumen/Watt) values as recently echoed by the August 2007 DOE report. This divergence is further magnified when CCT (correlated color temperature) and CRI (color rendering index), and lifetime performances are combined. Various standards organizations have been working together to adopt some standards that the industry urgently needs.

One key parameter that helps to determine the lifetime of LEDs is the p-n junction temperature, known as "TJ". Although various formal and informal articles have been published in the technical, business, and general communities on TJ, the focus has been on the generalized affects TJ has on LEDs (brightness, wavelength, and forward voltage are the three main parameters of a LED, affected by TJ), and its measurement techniques. However, in the SSL industry, so far no one has either provided an analytical expression (i.e., an accurate quantitative definition) of TJ, nor has anyone listed the key parameters that TJ depends on. Without such formulation, it will be difficult to accurately compare the lifetimes and time-varying performance of LEDs from different suppliers, which often misleads the lighting companies. In the interest of limiting content for this article, I shall only mention here certain key parameters of TJ that can help towards a quantitative definition. The key parameters belong to two groups, 1) chip current density: depends on semiconductor bandgap (i.e., the energy difference between the conduction and valence band), material morphology and chip layout design, 2) module design: thermal, electrical, mechanical, and optics construction that collectively determine how the heat is removed from the junction area. Such material, design, and packaging technologies then determine how the ambient temperature will translate into TJ and what level of TJ will be destructive to LEDs. Clearly, a more rigorous study is required to define TJ and to correlate it more accurately with LED lifetime for various chip and module configurations. While certain groups have extrapolated the LED lifetime from TJ using some indirect measurements (e.g., infrared imaging, forward voltage) combined with extrapolation of statistical data, these cannot be applied for LEDs in general because of the different chip and module designs, and also because some measurement standards are lacking. Although higher TJ may be tolerated in some LEDs, typically a TJ much beyond 85°C is not recommended for durable HB-LEDs.

Signage and display luminaires can utilize low-current LEDs and hence the increase in TJ has small effects on degradation. If needed, degradations in these applications can also be dealt with electronic tuning. However, general lighting requires power ratings of 0.5 Watt and above, and adding sophisticated tuning features may not be realistic for most residential lighting.

Many in the industry often tout the latest Lumen/W values for white HB-LEDs as part of the technology breakthroughs. But, the real improvements lie in consistently achieving this efficacy equal or well beyond that of the CFLs while maintaining CCT, CRI, luminous intensity, long lifetime, minimal degradation, and of course, low cost. For wider acceptance within the supply chain, we must establish accurate understanding of LED characteristics and system level performance requirements. For such, we need further development of white HB-LEDs as well as their standards adoption for accurate and reliable measurements. We need to substantially diminish the confusion that currently lingers between the LED and luminaire suppliers and provide consistent and credible feedback to the lighting companies. As the clouds clear for the lighting companies and the regulators, they can expedite the market penetration to the mass media by widely offering general-illumination HB-LED products and education. Indeed, we need to be mindful of the experience of previous "disruptive" lighting technologies such as the CFL, which despite being regarded as technologically superior to incandescent lighting, have endured a slow rate of adoption. Conquering the above challenges will prepare us for the SSL industry's most potent dream: general illumination within a few years from now. ■

LED Lighting Control Systems: The Next Generation of Lighting

> Abhay Gupta, Echelon Corporation

As worldwide energy demand far outstrips generation capacity, there has been a dramatic increase in lighting systems based on light-emitting diodes (LEDs), as well as the technological innovations that enhance such systems. Market indicators show that LED lighting has the potential to succeed incandescent, fluorescent, and halogen lighting over the next 10 years. The reasons for this are clear:

LED lights consume an average of 1/10th of the energy used by incandescent bulbs with the equivalent lumens output.

The burn lifetime of a LED light is more than 100,000 hours; an incandescent bulb, 600-1,000 hours. Thus, a LED light that burns for 5 hours a day would last about 55 years.

LED lights burn much cooler than conventional lights. Reduced cooling requirements help lower energy use in enclosed spaces such as offices.

Although these benefits are enough for consumers and manufacturers to begin the move to LED lighting, using control networks for LED lighting systems can provide even greater benefits. For example, mixing red, green, and blue LEDs in an array can produce warmer or cooler white light environments that provide greater occupant comfort or create real-time ambient lighting conditions. By applying sequencing to diodes—especially those capable of multi-color output—you can provide information on billboards or emergency services such as fire/safety signage. You can improve street, tunnel, and bridge lighting by gradually increasing and decreasing lumen output and color based on vehicle speed and light-level variations at tunnel exits and entrances. You can even improve workplace productivity by changing the light spectrum based on the type of job and the time of the day. (For example, recent field tests by Philips found that increasing the amount of blue light in workplace lamps boosted employee performance by at least 10 percent. [1]) Lounges, restaurants, and hotels can use different light configurations to create a variety of moods for the same room.

While LED light manufacturers are trying to capture a share of the 13-billion incandescent bulb market with screw-in LED lamp replacements, LEDs don't work the same way as conventional lights do, which has led to system failures and negative publicity for LED-based lights. To take advantage of LED technology, new lamps must be designed to maintain constant current and monitor the junction temperature of LEDs. But the full potential of LED lighting cannot be explored unless LED lights are embedded with control technology. Providing enhanced lighting functions—such as configurable switch control and dimming features, and on-demand, dynamic lighting color changes—through a control network can help you achieve faster adoption rates and higher margins.

Lighting systems that incorporate multi-color LEDs with control technology can be used for a wide variety of creative applications, limited only by your imagination.

Lighting Market Segments

The market for LED lighting can be broken into five segments, each with its own power and control requirements:

- Architectural/Outdoor
- Residential/Commercial
- Hospitality (restaurants, lounges, hotels, and warehouses)
- Theater/Stage
- Display/Shelf

These segments can be further defined by their power and control communication bandwidth requirements. For example, architectural lighting for a bridge is a high power consumption/high wattage application with little need for real-time or frequent lighting effect changes. By contrast, stage lighting uses powerful lights (though not in the same realm as bridge lighting) and requires very frequent real-time lighting effect changes—up to hundreds of changes over several hours. The more lighting effect changes you need, the more benefits you'll get from control technology. Figure 1 shows the market segments' different power and bandwidth requirements.

Control Solutions

Since different lighting segments have different requirements, no single control networking technology can serve the entire market optimally. Echelon's two control networking platforms present a variety of options to serve these lighting segments.

The LonWorks® Control Platform

The LonWorks control networking platform is an open, interoperable technology defined by the ANSI/CEA709.1-B and EN 14908 standards. It's a peer-to-peer technology with distributed intelligence across the network devices. LonWorks technology, when using power line (PL) technology as the physical media, lets you send control signals over the AC mains lines over very long distances (up to 2 miles on unpowered lines). This provides unlimited power to the devices and dramatically reduces installation costs because no new wires are needed; however, extremely reliable power line-based communications necessarily limits the control bandwidth. The typical throughput on such a network is 5.4Kbps (20 data packets per second with packet overhead); however, as a peer-to-peer technology, messages on a LonWorks control network can be multicast or broadcast. This lets them communicate with multiple devices without using much control bandwidth.

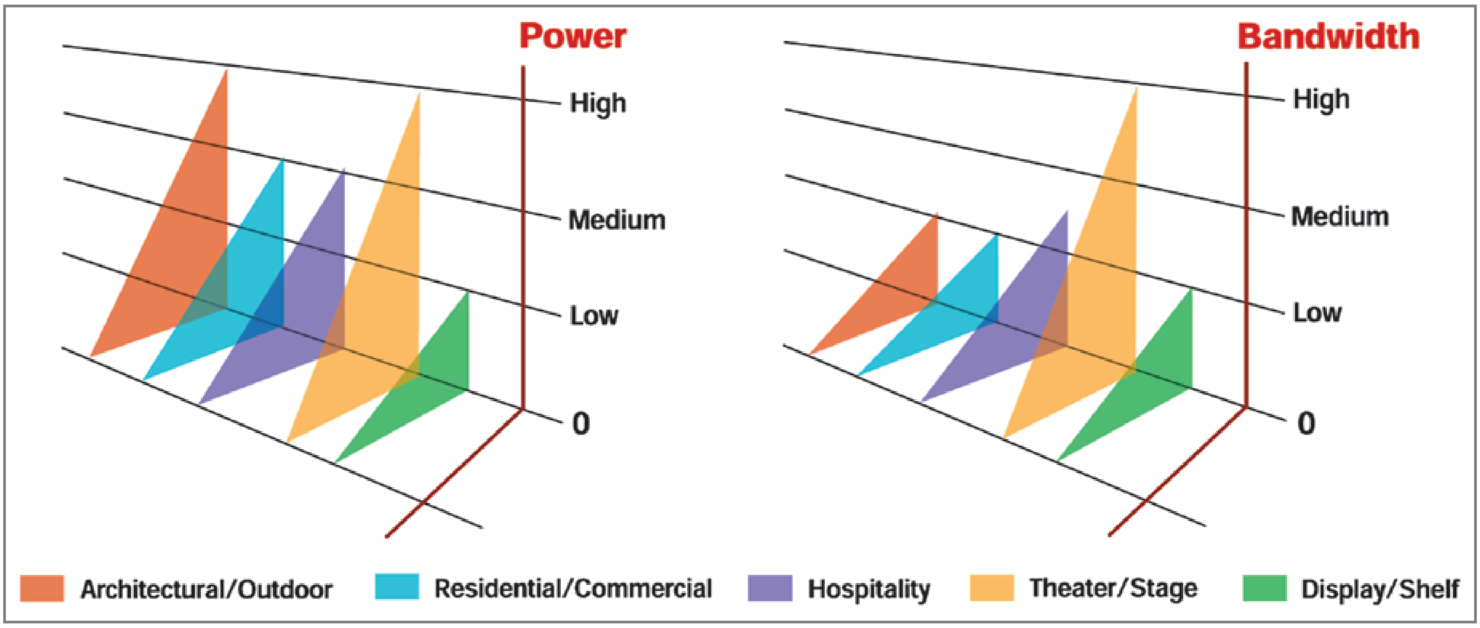


Figure 1: Market Segments: Power and Bandwidth Requirements

The Pyxos® Platform

The Pyxos networking platform differs from the LonWorks platform in a number of ways. It's a master-slave network with deterministic response times of 25ms or less and network throughput of 312.5Kbps. Pyxos networks use a twisted pair of wires as physical media and have cyclic redundancy check (CRC) error detection as well as 2-bit forward error correction built into the protocol. Pyxos networks also support power and data over the same wire, a feature defined by the term link power. The amount of power sent over a Pyxos network depends on the distance, the typed of wire used, and the number of devices using power from the network. Link power becomes all the more relevant for LED lights since they consume 1/10th of the power of an incandescent bulb. Many LED lighting applications may qualify to be powered by a Pyxos link-power network.

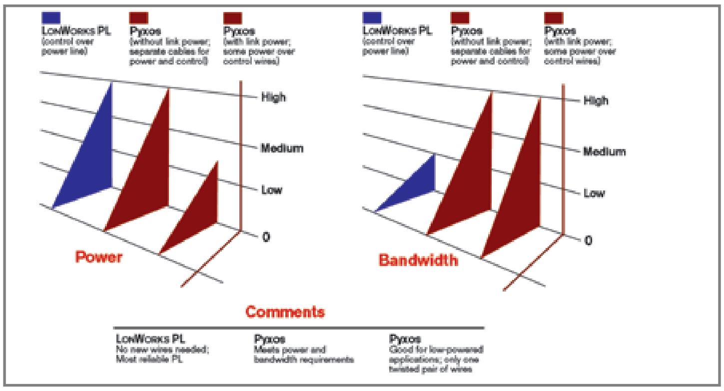


Figure 2: How LonWorks and Pyxos technologies compare in power and bandwidth characteristics.

Matching the platform characteristics to market segment needs gives us the following applications matrix:

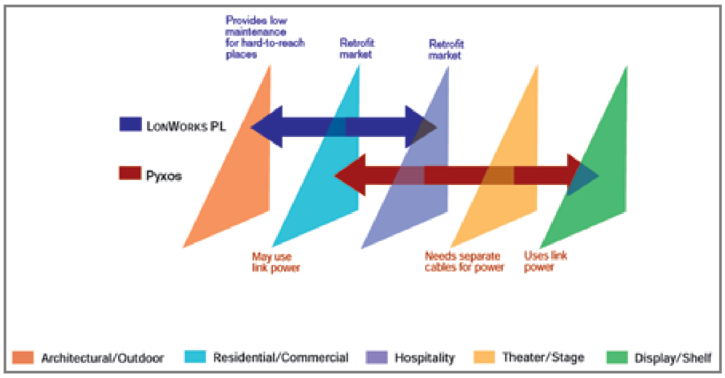


Figure 3: Matching Technology with Market Segment Requirements

A LonWorks/Pyxos Hybrid Solution

The two platforms work synergistically. The master in a Pyxos network can typically also be a LonWorks device. This means any number of Pyxos networks can be incorporated into a single control solution using a LonWorks backbone. The information from each 32-node Pyxos network is treated as the I/O from the single Pyxos master controlling each network.

I community, all of the clusters of Pyxos based LED lighting segments are tied together with a LonWorks control network that may also include security and access. The LonWorks network gives the property manager access to any individual LonWorks device as well as the Pyxos masters and their I/O—in this case, the LED lights. This hybrid approach provides Internet access to all the devices (via the LonWorks network), the ability to move data across any distance and any media, and low-cost, high-performance lighting control.

Technology Comparison

DMX512 is a control technology used for some LED lighting applications. Designed and traditionally used for stage and theater lighting, it has also gained traction in some other lighting segments such as architectural lighting. DMX512 is a simplistic protocol that runs over an RS-485 twisted pair network. The protocol has 512 slots with 1 byte of information in each slot. It has no built-in features for CRC error detection, error correct, acknowledgement, or security.

DALI is another lighting protocol used in some conventional lighting applications. Designed for traditional lighting, where dynamic color and pattern control isn't available or needed, DALI suffers from very low bandwidth (1.2 kbps). Hence, it might have a tough time serving the needs of the LED lighting control market.

Table 1 compares Pyxos technology to DMX512 and DALI. While DMX512 works fine for stage lighting and DALI for certain commercial, general illumination applications, the Pyxos platform offers several superior features, making it a better choice for most LED lighting applications.

Both DMX512 and Pyxos technology use a twisted pair of wires as physical media. However, the physical layer transceiver in Pyxos technology provides much better common-mode noise rejection and reliability over RS-485, the physical layer used by DMX512.

Feature	Pyxos Network	DMX512 over RS-485	DALI
Self-organizing network	☑	☒	☒
Deterministic operation	☑	☑	☑
≤25ms response time	☑	☑	☑
High-speed control signaling	☑ 312.5 kbps	☑ 250 kbps	☒ 1.2 kbps
Direct digital I/O without a microcontroller	☑	☒	☒
Bus topology distance	☑ 400m	Variable	
Free topology wiring	☑ 100m	☒	☑
High common-mode immunity *	☑*	Variable; depends on the RS-485 transceiver used	☒
Power and data combined on polarity-insensitive wire pair (link power)	☑	☒	☑ Only 2mA per node
18-bit packet CRC error detection	☑	☒	☒
Error correction for up to 2-bit errors per packet	☑	☒	☒
Simple interface to LonWorks networks	☑	☒	☒

Table 1: Comparison of Pyxos technology, DMX512 and DALI.

** 3 out of 4 coupling options offer the same or better common-mode noise rejection.*

Conclusion

LED lighting offers significant benefits over conventional lighting, namely lower power use and longer burn time. Without a control network, however, many benefits will remain unrealized and widespread adoption will be slow. Echelon's synergistic control technologies – LonWorks control networking over PL and Pyxos embedded networking – now make it economically feasible to address the key market segments of the LED lighting industry. ■

References:

[1] http://www.lighting.philips.com/gl_en/news/press/product_innovations/press_2006/activiva.php?main=global&parent=4390&id=gl_en_news&lang=en

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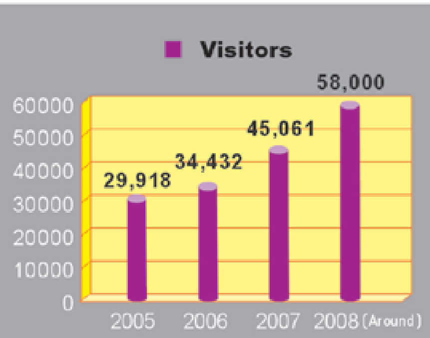

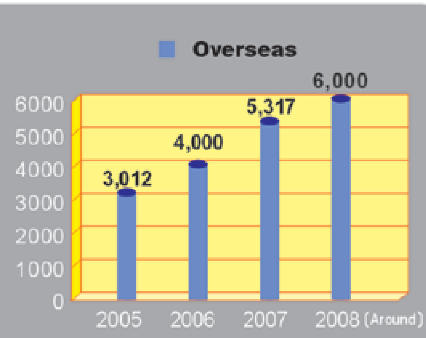

Preview of LED CHINA 2008

In 2008, LED CHINA, SIGN CHINA and NEON SHOW will be held under the same roof again. The total exhibition area will be up to 50,000 square meters, and LED CHINA area will be more than 10,000 square meters with around 450 standard booths.

Concurrent Activities

- SIGN CHINA 2008
- NEON SHOW 2008

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Thermal Management in High Power LED Systems

> Paul Scheidt, CREE

Thermal management is a key issue in LED system design because the LED lifetime and lumen maintenance are directly related to the thermal design of the project. Long operational lifetimes and energy efficient light are two key benefits of LED light. Despite their high efficacy, LEDs still do generate heat in addition to light. If the heat isn't managed properly and temperatures rise, this heat will shorten the LED lifetime and make the LED less efficient.

LED lifetime is actually measured in lumen maintenance, as a high power LED will almost never "blow" and go completely dark like an incandescent bulb will.

The Lighting Research Center of Rensselaer Polytechnic Institute recommends defining the end of a LED lifetime when the LED reaches "L70", or when the LED has degraded to 70 percent of its original brightness. Poor thermal management can make a significant difference in the lifetime of a LED. If a LED system is designed with proper heat management, there's no reason the LED couldn't last for 100,000 hours or more; but high temperatures could cut that to less than 1,000 hours. Obviously, for the true benefits of LED lighting to be reaped, the LED system must utilize proper thermal management design.

Thermal management on the component level

The majority of LED failure mechanisms are temperature-dependent. Elevated junction temperatures cause light output reduction and accelerated chip degradation. Junction temperature is primarily affected by three parameters: ambient temperature of the LED's immediate surroundings; the thermal path between the LED junction and ambient conditions; and the power dissipated by the LED.

LED manufacturers can control the thermal resistance of an individual LED, which means how easily the heat flows from the LED chip inside the package to outside the package. The lower the thermal resistance number is, the easier the heat flows. This is the only aspect of thermal management that LED manufacturers can control. The unit of measure for thermal resistance is degree C/watt or Kelvin per watt which means the more wattage running through the LED, the greater the temperature difference between the bottom of the package and the LED chip For example, Cree's XLamp® XR-E LED has a thermal resistance of 8°C/W. Operating at 350 mA (equivalent to 1.15 W, typically) the LED junction is 9°C higher than the temperature of the thermal pad.

There is a limit to what can be done regarding thermal management on the component level. When considering thermal management, a lot of what must be done is beyond the LED—such as the circuit board on which it's mounted, the heat sink, and the system housing.

In general, the total wattage of the system will dictate its thermal design. A rule of thumb typically used is that 4 square inches of heat sink are needed per watt of LED power consumption. While some designs require a heat sink component, other solutions to the thermal management challenge—mainly utilizing the actual fixture itself to act as the heat sink, are available without adding an additional part or greater surface area. This approach works best when the LED is mounted on a PCB and the board is then mounted to some type of aluminum or copper fixture, which acts as a large heat sink itself. This approach generally does not work if the housing is steel or plastic. Adding a heat sink may be an option, but air flow and heat dissipation problems may arise when a heat sink is mounted inside a fully enclosed space, defeating the purpose of installing the heat sink.

How heat sinks work

Whether the heat sink is external or derived from the fixture design, transmission of heat from a heat source via the heat sink into the surrounding medium takes four steps: transfer from heat source to the heat sink; conduction from within the heat sink to its surface; transfer from the surface into the surrounding medium by convection; and radiation depending on the nature of the heat sink's surface.

The efficiency and capability of a heat sink are a function of the heat transfer modes used. Heat sinks provide a path for heat from the LED to flow through conduction. The heat "trapped" in the heat sink must be dissipated in order for the power from the source to continually flow. If the heat remains trapped in the sink, the temperature will rise and eventually overheat the source. Heat sinks can dissipate power in three ways: conduction (heat transfer from one solid to another), convection (heat transfer from a solid to a moving fluid—for most LED applications the fluid will be air), or radiation (heat transfer from two bodies of different surface temperatures through electromagnetic waves).

The three most common types of heat sinks are flat plates, die-cast finned heat sinks, and extruded finned heat sinks. The material normally used for heat sink construction is aluminum, although copper may be used with an advantage for flat-sheet heat sinks.

Heat sink thermal radiation is a function of surface finish, especially when the heat sink is at higher temperatures. A painted surface will have a greater emissivity than a bright, unpainted one. The effect is most remarkable with flat-plate heat sinks, where about one-third of the heat is dissipated by radiation. Both anodizing and etching will decrease the thermal resistance.

Heat sink selection

When selecting a heat sink, surface area is an important factor. Thermal transfer takes place at the surface of the heat sink. Therefore, heat sinks should be designed to have a large surface area. This goal can be reached by using a large number of fine fins or by increasing the size of the heat sink itself.

Aerodynamics is another factor in heat sink choice. Heat sinks must be designed in a way that air can flow through easily and quickly. Heat sinks with a large number of fine fins with short distances between the fins may not allow good airflow. A compromise between high surface area (many fins with small gaps between them) and good aerodynamics must be found.

Thermal transfer within the heat sink is another important consideration. Large cooling fins are ineffective if the heat can't reach them. The heat sink must be designed to allow adequate thermal transfer from the heat source to the fins. Thicker fins have better thermal conductivity; so again, a compromise between large surface area (many thin fins) and good thermal transfer (thicker fins) must be found. The material used has a major influence on thermal transfer within the heat sink.

In regard to flatness of the contact area, the portion of the heat sink that is in contact with the LED or MCPCB must be perfectly flat. A flat contact area allows the use of a thinner layer of thermal compound, which will reduce the thermal resistance between the heat sink and LED source.

Finally, the mounting method must be considered. For good thermal transfer, the pressure between the heat sink and the heat source must be high. Heat sink clips must be designed to provide high pressure, while still being reasonably easy to install. Heat sink mountings with screws or springs are often better than regular clips. Thermoconductive glue or sticky tape should only be used in situations where mounting with clips or screws is not possible.

The thermal resistance of a heat sink depends on numerous parameters that cannot be predetermined. These parameters include but are not limited to the position of the LED on the heat sink, the extent to which air can flow unhindered, the screening effect of nearby components, and heating from other components in the fixture. It is always advisable to check important temperatures in the finished fixture under the worst possible operating conditions and calculate the LED junction temperature. Measuring the exact thermal path temperature of a mounted LED is almost impossible. In practice, Cree recommends measuring the temperature as close as practically possible to the bottom or side of the LED package.

The fixture as heat sink

In a case where the fixture itself is acting as the heat sink, these same factors must be taken into consideration in designing the fixture.

Every fixture is different—from materials to space limitations—so it is imperative that the fixture manufacturer design a heat dissipation system that works best with the chosen materials, wattage and size.

The fixture manufacturer is probably the most important contributor to the thermal management of a particular LED installation because they have the greatest influence on what the fixture is made of, the heat-sinking options, and so on. Therefore, they have the best vantage point for bridging the gap between LED makers and lighting designers, who are often more concerned with light quality and aesthetics than with heat dissipation and thermal management. Unfortunately, light output may not meet expectations in the end if the proper attention is not given to thermal management at the start of the design process. If a designer just haphazardly throws LEDs into a fixture (especially one designed around traditional light bulbs), there can be disastrous results.

An example of this was seen when street lighting customers first adopted LED technology. [there may be attempts we don't know about] Designers tried to put LEDs into the traditional cobrahead fixtures—possibly the worst choice of fixture design from a thermal perspective. Cobrahead fixtures are very thick steel, which is a very poor thermal conductor —they were putting LEDs into a steel container with no way for heat to escape, essentially "suffocating" the LED. (There were additional optical problems with the fixtures, as well.)

The next step was the development of a "surfboard" fixture that provided proper heat-sinking, but since it was a flat board the optics still did not reach expectations (or light output requirements). Many believed this was a sign that LEDs would never work in outdoor lighting, but some fixture manufacturers continued to experiment and finally discovered that to reap the benefits of LED technology, they needed to find a completely new design that took these thermal and optical needs into account. Fixture manufacturers finally realized that, at least with outdoor lighting, they had to stop thinking of LEDs as just another kind of light bulb.

Designing appropriate fixtures that provide proper thermal management may also be one of the biggest issues hampering widespread adoption of LEDs for indoor residential lighting applications. While Cree has manufactured LEDs that provide warm white light for such applications and have reached lumen outputs that make indoor lighting bright enough and cost-effective enough, the hurdle that remains is finding a way to actually mount the LEDs in a luminaire so that it is both aesthetically pleasing and makes the most of the differentiating features of the LEDs: brightness, long life and energy efficiency.

Thermal management in lighting systems

When designing lighting systems using high-power LEDs, a number of issues need to be considered. The most important consideration for successful thermal design is to minimize the amount of heat that needs to be removed. It is important to separate the LED drive circuitry from the LED board so that the heat generated by the driver will not contribute to the LED junction temperature.

The next most effective strategy is to minimize the ambient temperature inside the fixture. This can be achieved by paying attention to several design parameters such as a conservative design that does not allow the upper limit on overall system power density to be reached. Maintaining clear and clean airflow paths for natural convection cooling is vital as well.

Enhancing thermal conductivity between the heat sinks and the LED is most preferable for thermal management. Even though the heat removal from the heat sink is via convection, the path from the LED to the heat sink depends upon conduction.

Finally, the orientation of the LED PCB/heat sink should be considered carefully. It is important to not position the board directly above the heat sink. Having the board directly above the heat sink will block the formation of air convection currents and substantially reduce the cooling capability of the system.

Lighting applications featuring LEDs maximize light output and increase design flexibility while minimizing environmental impact. They are used in a broad range of specialized and general lighting applications. When designing lighting systems using LEDs, one of the most critical design parameters should be the system's ability to draw heat away from the LED junction. High operating temperatures at the LED junction adversely affect the performance of LEDs, resulting in decreased light output and lifetime.

Thermal Management of LED Technology in Applications

> Rainer Huber, Osram Opto Semiconductor GmbH

Introduction

The application field of Solid state lighting, in the form of light emitting diodes (LEDs) has changed from traditional indicator functions to illuminator applications. With traditional light sources such as incandescent lighting, much of the energy required to generate visible light is dissipated as heat in the radiant beam of light. LED light sources do not radiate heat energy within the light beam. The heat generated by the chip heats up the device itself. This phenomenon of self-heating affects the performance of the LED regarding light output and reliability. To achieve reliability and optimal performance of LED light sources like the Golden Dragon®, proper thermal management is necessary.

Influence of Junction Temperature

Basically, the maximum allowable junction temperature should not be exceeded, since this can lead to irreversible damage to the LED and spontaneous failure. Due to the fundamental physical interdependencies which arise during the operation of light emitting diodes, changes in the junction temperature TJ within the allowable temperature range have an effect on several LED parameters. These effects are reversible in nature. The forward voltage, luminous flux, wavelength (color) and lifetime of the LED are all influenced by the junction temperature.

Depending on the given requirements, this can finally affect the application.

- Influence of Forward Voltage V_f and Luminous Flux Φ_v

  For LEDs, an increase in junction temperature leads to a decrease in the forward voltage V_F (Figure 1), as well as a reduction in luminous flux Φ_v (Figure 2). This physical effect on the light output is known as degradation; the amount of degradation strongly depends on the LED technology employed

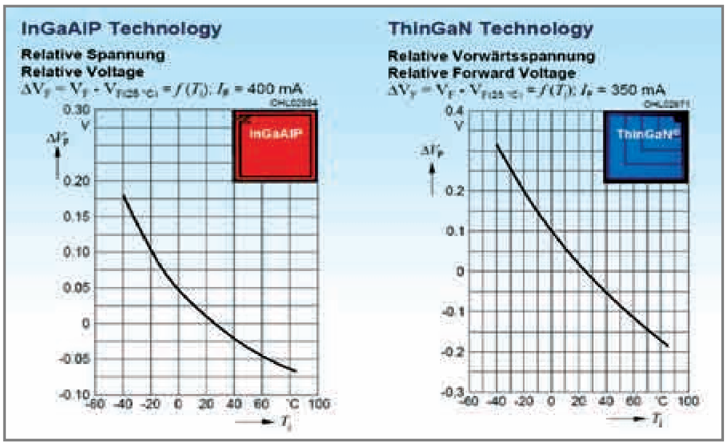


Figure 1: Relative Forward Voltage vs. Junction Temperature (e.g. Golden Dragon®)

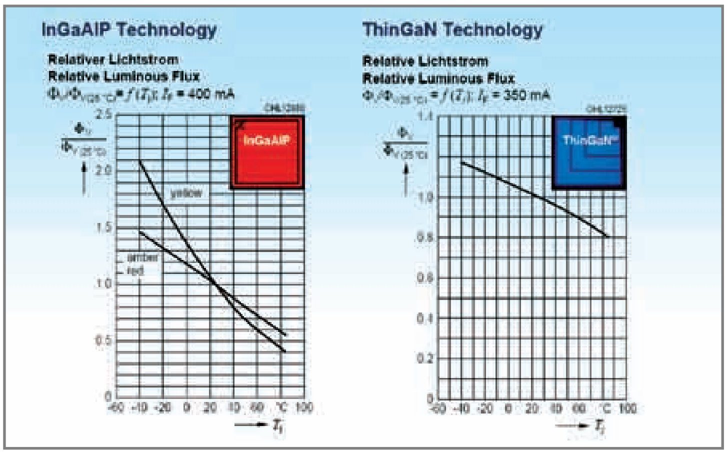


Figure 2: Relative Luminous Flux vs. Junction Temperature (e.g. Golden Dragon®)

In this case, the resulting changes are reversible. That is, the output values return to their original level when the temperature change is reversed.

For the application, this means that the light output increases with a decrease in the junction temperature T_J.

- Wavelength (λ_{peak} and λ_{dom}) and Color Coordinates (x, y)

  The influence on the wavelength of saturated LEDs and respectively color coordinates of white LEDs by a change in junction temperature appears as a reversible shift in the output values. The amount of the shift can be calculated by means of the respective temperature coefficients (Figure 3).

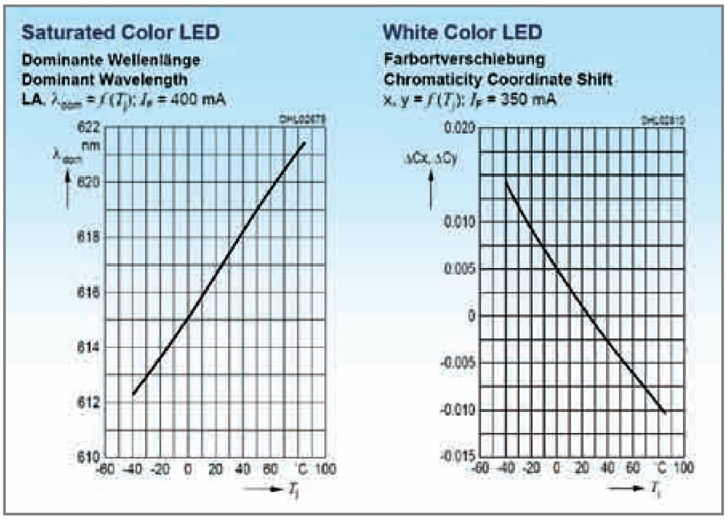


Figure 3: Example of Junction temperature influence on Dominant Wavelength λdom and Color Coordinates

An increase in junction temperature of 40°C, for example, leads to a shift of the dominant wavelengths in the red range of nearly 3 nm from 617 nm to 620 nm. This shift leads to a change in the color settings and appearance, and can have an influence on the application, depending on the given requirements. Depending on the application, it must be determined if this shift can be tolerated, or that appropriate measures can be taken to avoid or at least compensate for temperature related effects.

- Reliability and Lifetime

  Moreover, regarding aging, reliability and performance, driving a LED at its maximum allowed junction temperature is not recommended. With increasing temperature, the lifetime of the module decreases and the probability of spontaneous failures increases. The lifetime of a LED refers to the time in which the light output falls to less than 50% of its original value.

Considering all these aspects, thermal management plays a significant role and has to be addressed in the early stages of development. The three primary objectives are: ensuring reliable operation of the LEDs, ensuring a normal LED life time and optimizing the optical performance of the LEDs.

Heat flow and thermal resistance

The power dissipation PD at the chip junction is distributed within the package, circuit board and the lamp housing by means of heat conduction and is transferred from the free surfaces to the environment by means of radiation and convection (Figure 4). "Junction" refers to the p-n junction within the semiconductor die. This is the region of the chip where the photons are generated.

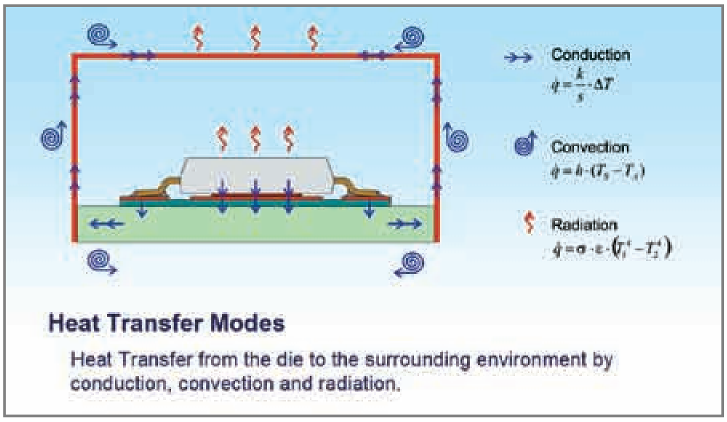


Figure 4: Heat Transfer Modes in Electronics Cooling

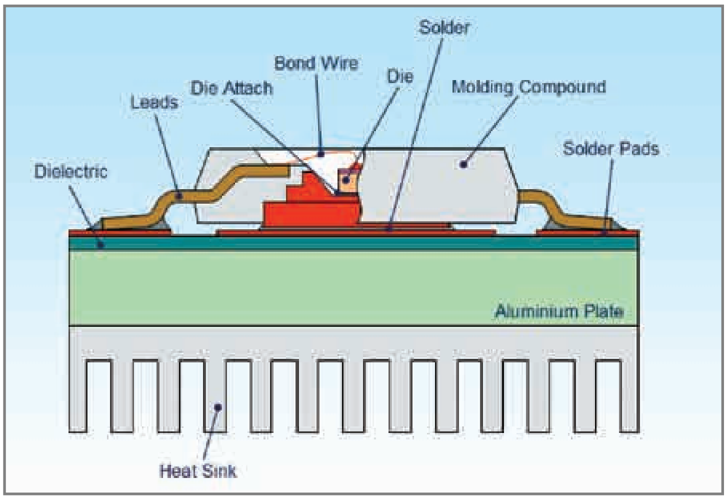


Figure 5: Internal Structure of Golden DRAGON® LED Package

To facilitate discussion of the static properties the Golden DRAGON® LED is chosen as an example. The internal structure of the Golden DRAGON® and its method of mounting on the substrate is illustrated in figure 5. The LED consists of a chip mounted on a chip carrier (heat spreader) by solder or bonding adhesive. The heat spreader consists of a high-conductivity material such as copper.

The associated static equivalent circuit diagram is shown in figure 6. The following analogies with electrical quantities have been used:

- The power dissipation PD occurring close to the chip surface is symbolized by a current source.
- The "resistance network" is essentially a serial connection to the ambient temperature. As a first approximation, the parallel-connected thermal resistance of the plastic housing can be neglected.
- The ambient temperature Ta is represented by a voltage source.

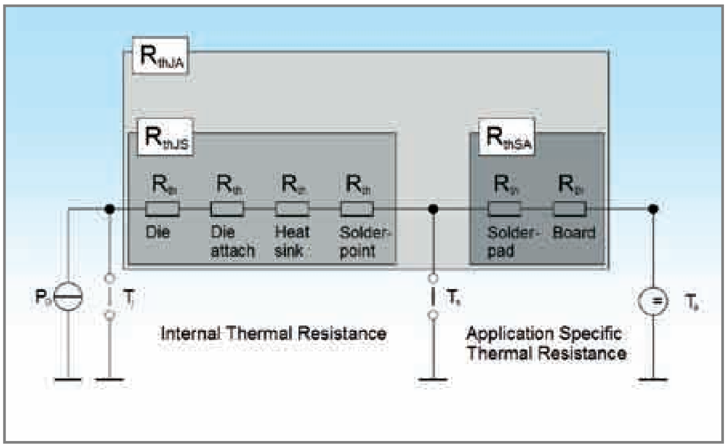


Figure 6: Static Equivalent Circuit

In accordance with the analogy, the thermal current P_D = Q/t can now be calculated from the "thermic Ohm's law".

$$U = I \cdot R \text{ as } T_j - T_a = P_D \cdot R_{thJA}$$

For the purpose in application, the junction temperature T_j is of practical interest.

$$T_j = R_{thJA} \cdot P_D + T_a$$

The total thermal resistance RthJA of this configuration can be broken down into the individual contributions along the heat transfer path from the component junction to its ultimate environment.

At the component level the internal thermal resistance exists between the junction and exposed side of the internal heat spreader.

The external level resistance is the application specific resistance to the heat that flows from the internal heat spreader to the surrounding environment. This thermal resistance value can be divided into the thermal resistance solder point to board RthSB considering the heat transfer through the printed circuit board and the thermal resistance board to ambient RthBA considering the heat transfer to the surrounding fluid. The RthBA characterizes the heat transfer to ambient, e.g. external heat sinks.

These thermal resistances are in a series configuration (figure 7).

$$R_{thJA} = R_{thJS} + R_{thSB} + R_{thBA}$$

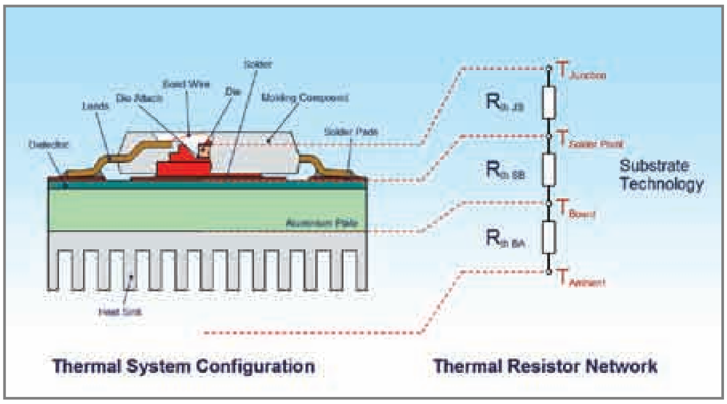


Figure 7: Resistances Serial Configuration

Summarize the explanations; in general thermal management can be divided into internal thermal management and external thermal management. Internal thermal management handles the thermal resistance from junction to the package case and external thermal management handles from the package case to the ambient. In this case the external thermal management plays a significant role. External thermal management includes the selection of the cooling mode, heat sink design, selection of substrate material and attachment process. After the cooling mode is determined, the cooling system can be designed. The thermal resistances RthSB and RthBA have to be optimized for the application.

Internal thermal resistance RthJS

For OSRAM SMT LEDs, the thermal resistance, RthJS, refers to the thermal resistance between the junction and solder point. The solder point temperature is defined as the temperature of the solder joint of the internal heat spreader in case of the Golden DRAGON®.

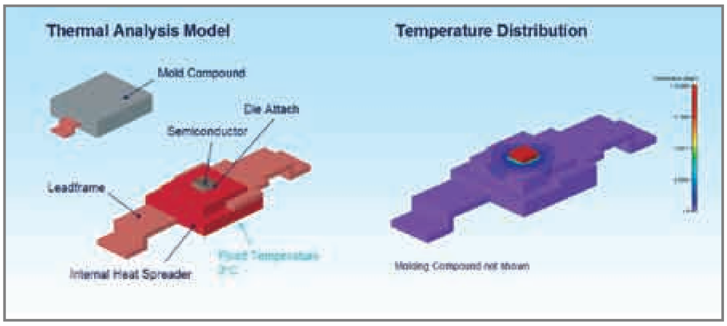


Figure 8: Internal Thermal Resistance RthJS

In general the value of RthJS is defined by the package construction (e.g.: the leadframe geometry), the materials used and the chip type. This is illustrated by means of thermal analysis (see Figure 8).

The trend towards high power packaging is also taken into account in the package construction. In Figure 9, the decrease in thermal resistance RthJS can be seen.

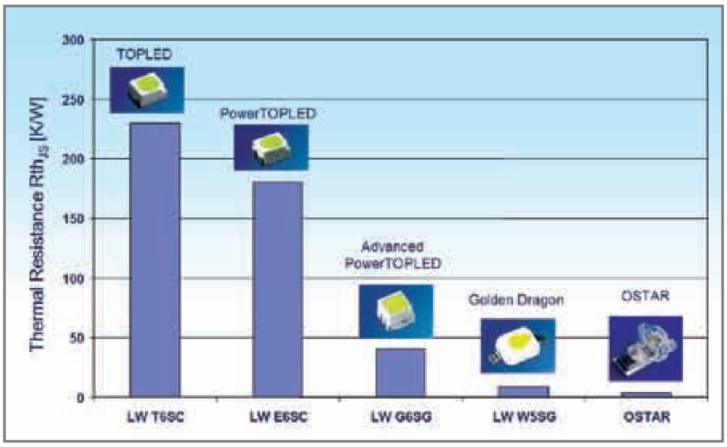


Figure 9: Trend in package thermal performance

External thermal resistance Rth_{SB} and Rth_{BA}

The external resistance of an application can be expressed as the sum of the individual resistances of the thermal path from solder point to the ambient environment. The corresponding components are the thermal resistance from solder point to board and thermal resistance from board to ambient environment.

Thermal Resistance RthSB

PCB layout is not so simple. Several things must be taken into account, among them, the thermal design. The thermal resistance, RthSB, is strongly influenced by various factors including solder pad design, substrate material, and component placement.

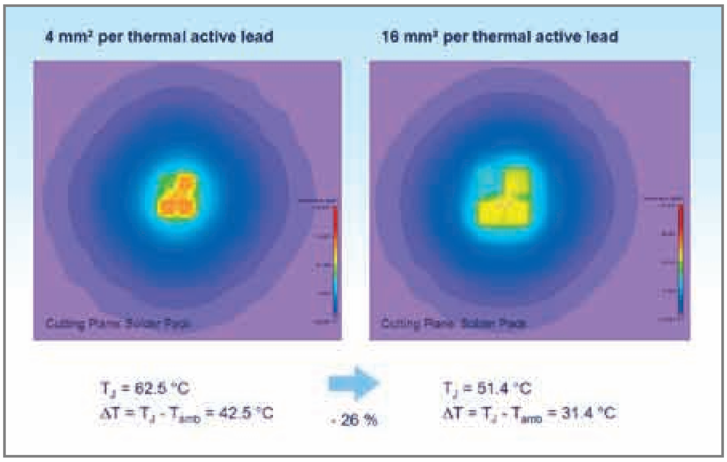


Figure 10: Influence of solder pad area

As an example, the thermal resistance value RthSB can be lowered by enlarging the solder pad area. The heat flows into the solder pads and spreads in the in-plane direction. The thermal analysis results show the effect of decreased solder pad area on thermal performance. The temperature level of a LED with a total solder pad area of 48 mm^2 is about 10 °C lower than that of the LED with a solder pad area of 12 mm^2 (figure 10). As a consequence, the thermally active pads have to be maximized in order to optimize the thermal spreading over the printed circuit board.

Another factor that impacts the thermal resistance from solder point to board is the board material. The thermal CFD Analysis in figure 11 shows two printed circuit boards, one made of FR4, the other is a metal core printed circuit board (MCPCB), each populated with two high power LEDs in natural convection. The heat flow for the FR4 PCB does not spread in the in-plane direction. This results in regional hot spots across the PCB. In this case, the temperature level is around 170°C. For the MCPCB, the temperature distribution is entirely different. Through the heat spreading of the metal sheet, the heat is distributed over the PCB area. In this case, junction temperature level is around 100°C.

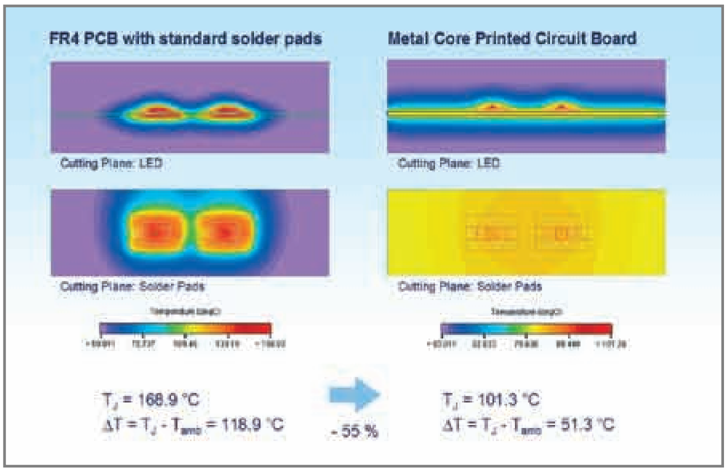


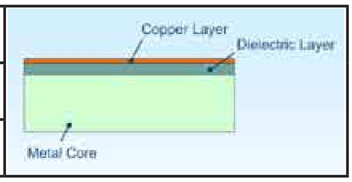
Figure 11: Temperature Distribution for an FR4 PCB and a MCPCB

As the overall board thermal conductivity increases, the heat spreading enlarge and a larger board area becomes available for the heat transfer. In general, all PCBs are laminates constructed in layers. Electrically conductive (and therefore thermally conductive) layers alternate with insulation layers. In order to improve the heat dissipation, different techniques can be used such as thermal vias, a thicker Cu layer or gluing to metal with pressure sensitive adhesive (PSA). In addition to the standard substrates such as FR4 PCB material, thermally enhanced technologies are presently employed, particularly, the use of metal core PCBs.

MCPCBs incorporate a base metal material as an integral part of the circuit board which functions as a heat spreader. Single Layer MCPCB provides a very thermally conductive base material for heat spreading. Furthermore, MCPCBs can take advantage of the high thermal conductivity of the dielectric polymer layer.

In the table below typical thicknesses of the base layers are listed:

Copper Layer	35 – 200 µm
Dielectric Layer	75 – 100 µm
Metal Layer	1 – 3 mm

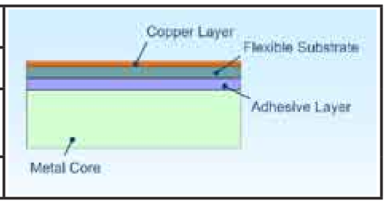


In the flowing considerations a thickness of 100 µm for the dielectric is used. The metal core consists of aluminum alloy, with a thickness of 1.5 mm. For the copper layer the standard thickness of 35 µm is used.

The lowest thermal resistance can be reached with a thermal enhanced dielectric layer. The thermal resistance RthSB is in the range of 3.5 K/W assuming a thermal conductivity of 1.3 $Wm^{-1}K^{-1}$ for the dielectric layer. The use of FR4 as the dielectric layer increases of the thermal resistance to 7.3 K/W.

Another possible solution is mounting the LED on a flexible substrate such as PEN or PI material placed on an aluminum heat sink using a pressure sensitive adhesive (PSA). Like the metal core of the MCPCB the aluminum acts as a heat spreader. The typical construction of a single layer flexible printed circuit board (FPC) on aluminum is listed in the following table:

Copper Layer	35 µm
Dielectric Layer	50 µm
Adhesive Layer (PSA)	50 µm
Metal Layer	1.5 mm



Compared to the MCPCB with FR4 dielectric the thermal performance decreases in the range of 30 %. Using a thermal conductive adhesive layer can further optimise this concept. This step improves the thermal performance to a similar performance than MCPCB with FR4. Further improvements can be done by the use of a two layer FPC with thermal vias.

A standard substrate material such as pure FR4 doesn't provide a proper thermal management through the low thermal conductivity of FR4. An analysis of a FR4 PCB (thickness t = 1 mm) glued on aluminum plate using standard pressure sensitive adhesive shows an high RthSB in the range of 50 K/W.

The performance can be significantly improved by actions like array of thermal vias and the usage of Multi Copper - Layer PCBs. The principle design is shown in figure 12. Thermal vias are often used to reduce the thermal resistance of materials with low thermal conductivity like FR4 PCB. A pattern of thermal vias is incorporated in the PCB under the LED and the opposite side of the PCB is connected to a metal plate. In this way, the thermal via array in the PCB acts as a pathway for the heat energy to reach the metal plate. The total thermal resistance depends on the density and size of the thermal vias and other many factors, e.g. hole diameter, pitch or copper plating thickness. This thermal resistance of the array of vias can also be optimized.

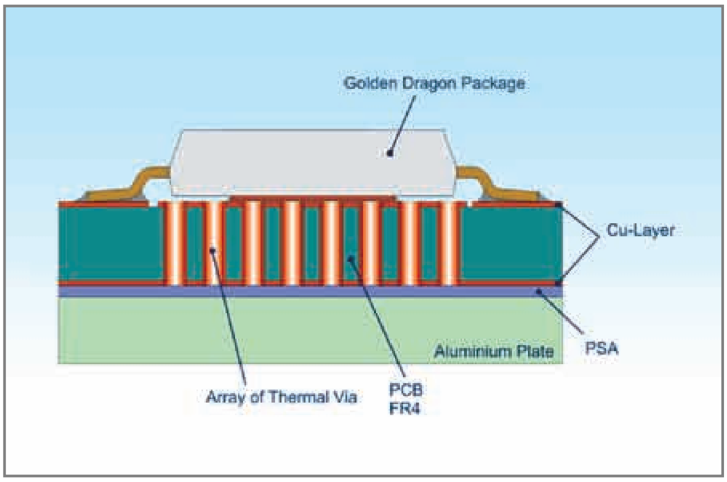


Figure 12: Principle Design of FR4 with thermal vias

The thermal resistance from solder point to board RthSB is summarized in the figure below (Figure 13). The values are based on numerical analysis under the same environmental conditions (PCB on cold plate).

The results indicate that the use of standard FR4 for high power LEDs with further improvements is possible but strongly depends on the construction of the PCB, e.g.- use of thermal vias, gluing to metal plate. The lowest thermal resistance can be achieved with an MCPCB with a thermally enhanced dielectric.

Thermal Resistance RthBA

The thermal resistance RthBA is defined to be the resistance between the board temperature and the ambient temperature and can be considered as the heat transfer from a solid body to the surrounding environment. Inspection of the convective heat transfer rate equation shows that for a given heat dissipation, the temperature difference is determined by the heat transfer coefficient and the area exposed to air flow. Increasing the heat transfer coefficient is usually not easily to achieve in natural convection. The increase of the heat transfer surface area is most often a more effective method to accomplish the desired performance improvement.

The simplest method is to enlarge the size of flat heat spreader, like a metal sheet. The graph shown in figure 13 illustrates the thermal impact according to a single high power LED mounted on flat MCPCB.

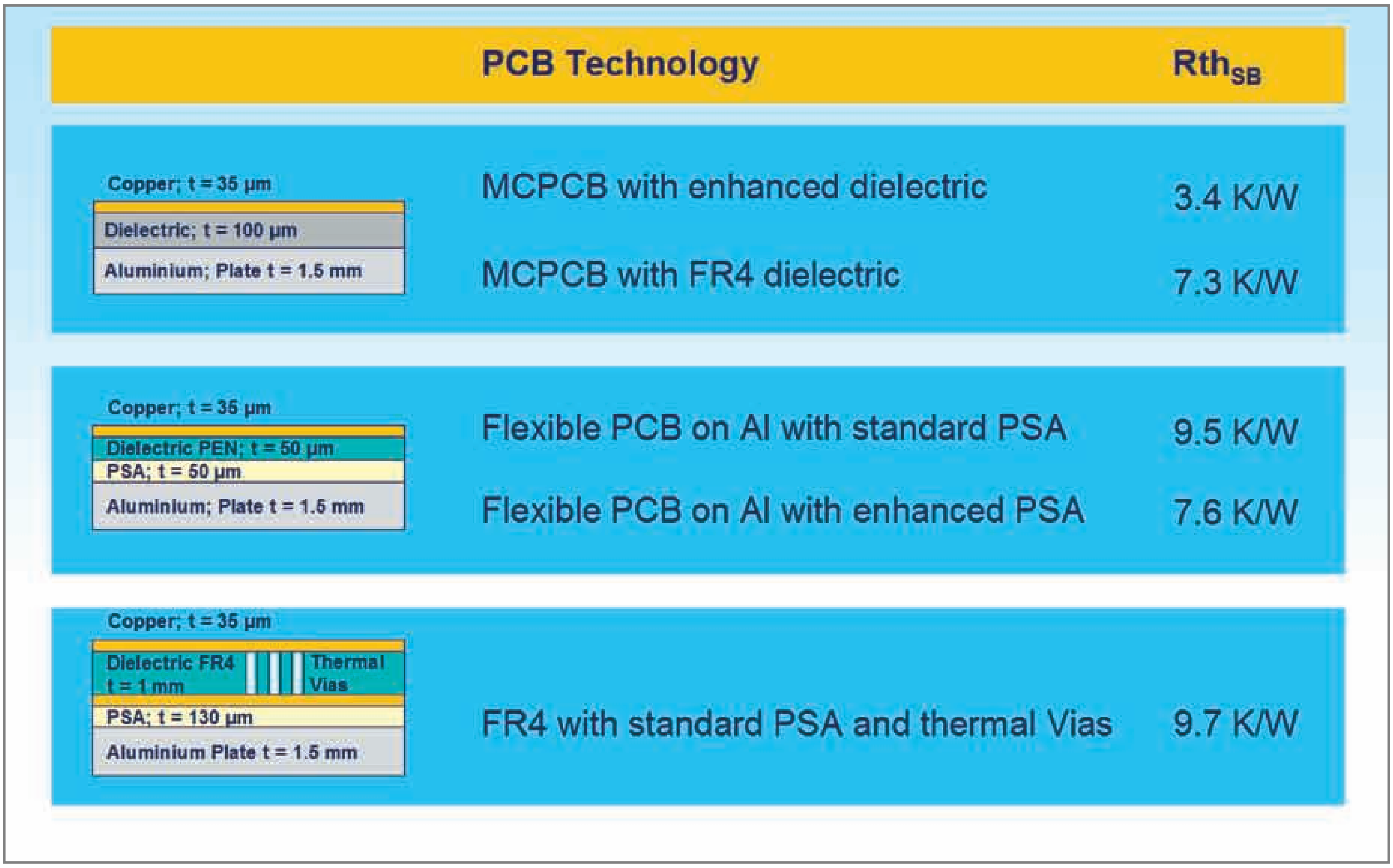


Figure 13: Thermal Resistance RthSB for different PCB technologies

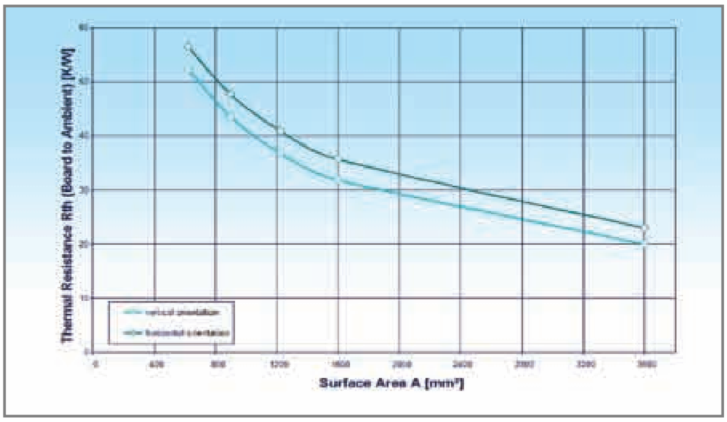


Figure 14: Thermal Resistance RthBA vs. Substrate Area

Another common method to extend the surface area to the coolant is the usage of heat sinks. Heat sinks vary in shape, size and material depending on application. The example below illustrates the effect of a finned heat sink in still air environment.

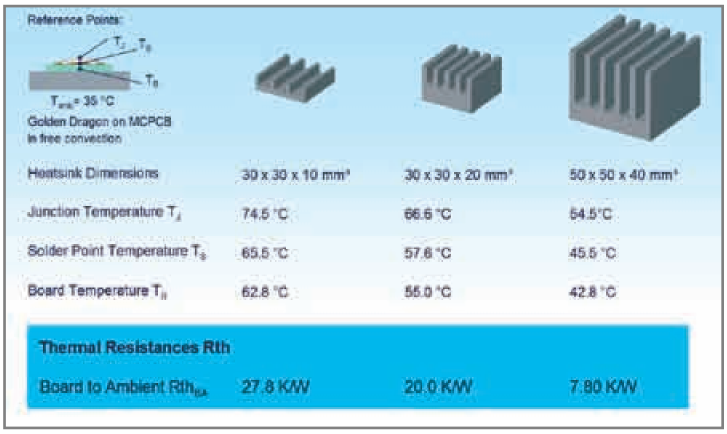


Figure 15: Thermal Resistance RthBA of different heat sinks

The selection or construction of the heat sink strongly depends on the boundary conditions, e.g. velocity, orientation to gravity. In the above section the contact between heat sink and substrate was considered as ideal. In reality a thermal interface resistance formed between heat sink and the mounting area has taken into account. Under some circumstances, this contact resistance can be substantial, impeding heat flow and reducing the overall effectiveness of the heat sink.

Also the housing can also be used to improve the heat transfer to the environment. In this case, the selection of the housing takes on a new importance, since this non-conductive body now assumes the role of conducting heat from the LED to the atmosphere. Therefore, materials with higher thermal conductivity should be considered. Depending on the polymeric composition, fillers and adhesives used, the thermal conductivities of plastics can vary by a factor of 3 over those of standard plastics. The results of the thermal analysis shown in figure 16 indicate that through the use of a thermally conductive polymer for the housing, the junction temperature can be decreased by around 19%. A similar effect can be reached with the usage of additional heat spreaders like metal or graphite sheets

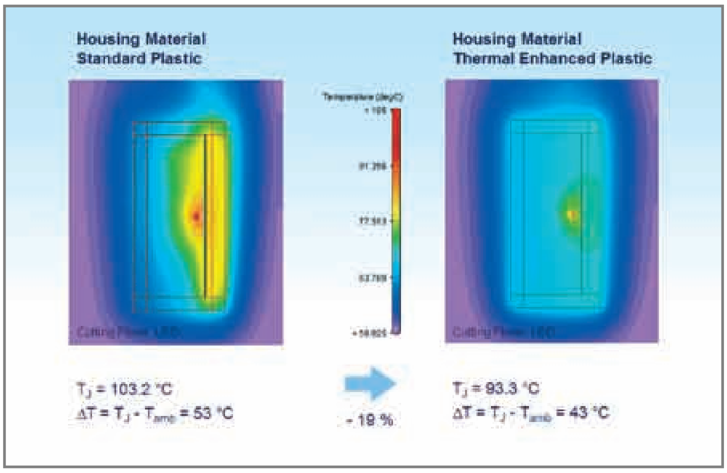


Figure 16: Thermal Impact of the housing material

Summary

Since LEDs have different thermal and optical characteristics from those of incandescent lamps, their use in lighting requires special considerations in order to meet the performance requirements of the design and at the same time, fulfill the thermal requirements of the LEDs. The thermal path from the chip to the environment also plays a role and can be optimized for each specific application. A general recommendation cannot be given due to the variety of application specific boundary conditions. Nevertheless important design rules are:

The thermal resistance from the LED junction to the coolant must be kept to an optimum to ensure an operation within the allowable limits according to the application specific boundary conditions. The operating environment has been carefully analyzed.

Other electrical components, e.g. resistors, transistors have to be placed far away from LEDs. They can act as additional heat sources and influences the thermal behavior of the LED.

Depending on the environmental conditions in most cases an additional heat sinking is required.

During the design phase, the expected ambient temperature range needs to be examined. Numerical methods such as thermal analysis software can also be used to assist the design process. When physical prototypes of the application are available, it is very important to evaluate the design according to the thermal behavior. Within the evaluation the expected ambient temperature range have to be examined.

High Power LED Thermal Modeling and Effect of Thermal Interface Materials

> Oon Siang Ling, Solid-State Illumination Division, Avago Technologies

Abstract

The Computational Fluid Dynamic (CFD) modeling of light emitting diode (LED) components becomes increasingly more important as it spreads into the design process. This article compares the results of an experiment using a high power LED package on a metal core printed circuit board (MCPCB) and a double layer FR4 substrate with a heat sink. Following the comparison discussion, a thermal modeling technique for LED packaging with heat sink will be highlighted. The results of CFD modeling are impressive, and illustrates that this technique can be used for LED system level evaluation. This article will also discuss the effects of using thermal interface materials in a LED package.

Introduction

Being able to predict the thermal performance of LEDs is becoming a necessity in helping to reduce the LED designers design time to market for their products. However, with the increasing heat flux and package density, the heat dissipation of the LED package module is becoming more challenging, and the thermal analysis and design of LED modules are becoming even more important. As a result, Computational Fluid Dynamics (CFD) simulation has become a widely used method for thermal analysis of electronic products in the early design stage. CFD is concerned with the numerical simulation of fluid flow, heat transfer and other related processes such as radiation.

This article presents the work that has been done to create a high power LED package on a MCPCB with a double layer FR4 with heat sink. First, a detailed model of a LED package-on-substrate is created, then a heat sink is created on the bottom of the LED package. Finally, this simulation data is compared to experimental data.

Another area of focus of this article is on the effects of thermal interface materials (TIMs) on the LED package. The objective is to show the TIMs characteristics with different bond line thicknesses (BLT) and the percentage of void trapped inside the TIM.

Thermal Modeling Technique

The LED package, an MCPCB, double layer FR4 and heat sink were modeled using Flotherm, which is a CFD tool from Flomeric.

Description of Models

Detailed and compact models of the various heat sinks were developed to compare the error percentages between the two models. The detailed geometry parameters of the LED package and thermal conductivity of the package materials are shown in Table 1:

	Component	Material	Thermal conductivity (W/m.K)	Dimension
1	Lead frame	Cu	364	Refer to above
2	Reflector	PA9T	0,2	8.5 mm x 8.5 mm x 3.3 mm
3	Chip	Sapphire	23	Junction about 0.11mm from bottom.
4	Die-Attached	Ag Epoxy	2,5	10 um in thickness
5	Encapsulant	Silicone	0,2	
6	PCB base	Aluminum	200	37 mm x 26 mm
		Double Layer FR4	0,3	1.6 mm in thickness
7	Metallization	Cu	385	35 µm in thickness
8	Dielectric layer	Aluminum Oxide	8	75 µm in thickness
9	TIM1		1.5 - 60	10 um to 50 um in thickness
	Thermal tape		2	Thickness of 0.125 mm
10	Heat sink	Anodized Aluminum	200	110 fins, base 23 mm x 23 mm x 1.5 mm
				Fin height 8 mm, thickness 0.8 mm,
				Fin pitch size 1 mm

Table 1: Construction Details of the LED Package with Heat Sink and Thermal Conductivity of the Package Materials

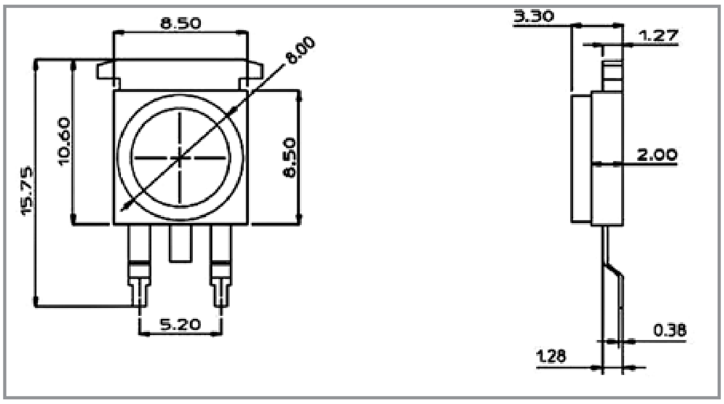


Figure 1A: Front and side view of Avago Technologies' Moonstone™ Power LED package

A schematic of the front view and layout of the LED package is shown in Figure 1A and 1B. The solder paste is filled in between the package and the substrate. When the package reaches the maximum power of 1.3-Watts, the standard natural and forced convection cooling of air cannot maintain the junction temperature within the acceptable range of 125°C and below. The additional heat sink works to help meet the desired temperature requirements. To mount the heat sink onto the LED, an adhesion thermal tape is attached to the backside of the heat sink, and the heat sink is placed on the bottom of the LED substrate.

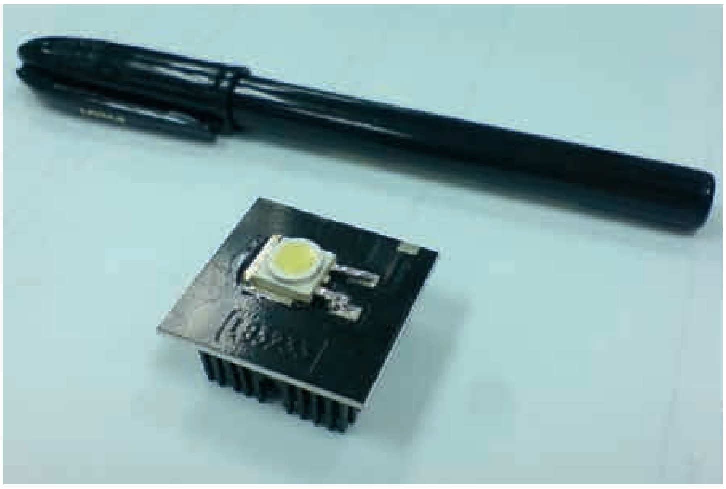


Figure 1B: LED package on substrate with heat sink

Grid and Boundary Conditions

For CFD analysis, the following properties are assumed:

- Three dimensional
- Steady state
- Still air
- Air properties are constant
- Ambient temperature is 25°C
- Computational domain is 305 mm x 305 mm x 305 mm
- Heat is dissipated through natural convection, conduction and radiation

Total grid cells for the LED package-on-substrate with both the detailed heat sink model, and the compact heat sink model are about 600,000 and 150,000 cells respectively. For the grid cells setup, it is recommended that at least three cells be used between the fins of the heat sink.

Results

Thermal Resistance Calculation

To calculate thermal resistance the heat flowing vertically through the dice, die attach layers, die pad, TIM, heat sink and dielectric layer to the substrate are measured. With each layer having its own thermal properties (refer to Table 2), the thermal resistance across the die (junction) to the ambient, RJA, can be calculated by using the following equations:

$$RJA = RJ\text{-}MS + RMS\text{-}A \qquad (1)$$

$$RMS\text{-}A = (TMS - TA) / Power \qquad (2)$$

Where RJ-MS = 10 °C/W (Refer to Moonstone data sheet)

The RJA represents how well the heat is dissipated out from LED chip to the ambient, which means that the lower value of RJA will result in better thermal performance.

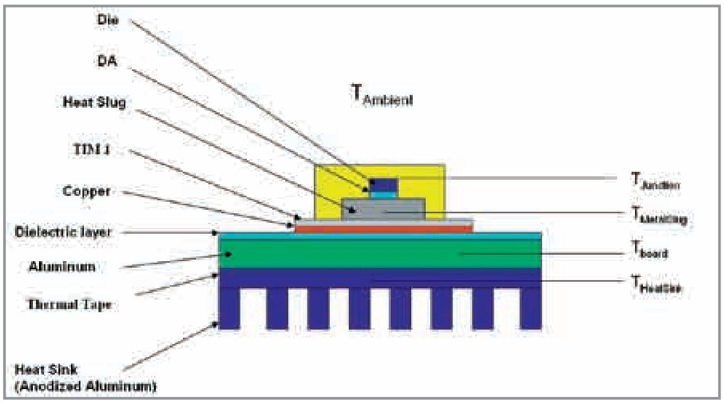


Figure 2: 2D cross section view of LED package on MCPCB with heat sink

Numerical vs. Experimental

The LED package is mounted on a MCPCB and double layer FR4. Its dimensions are 32 mm x 27 mm x 1.6 mm. The heat sink, which is a typical finned-type with 110 fins and a base made of extruded aluminum, is attached to the back of the MCPCB and double layer FR4 with thermal tape. The package is driven at 1.2W and the temperature of the solder point (TMetalSlug) is measured at the metal slug of the package.

Figure 3: Moonstone LED package

Measurement data comparisons of the detailed model heat sink and the compact model heat sink are shown in Table 2. The visualization simulation results are shown in Figure 4A and 4B. As the approximation gets coarser, the agreement with real data diminishes. However, the percentage of error within the range of 15 to 20 percent is acceptable for industrial applications. When the simulated temperature is higher than the measured temperature, it indicates that the numerical model failed to account for some of the cooling phenomena.

	Measured R_{BA} (°C/W)	Simulated R_{BA} (°C/W)	Error (%)
LED package on MCPCB with detailed model heat sink	35	33	6
LED package on MCPCB with compact model heat sink		37	6
LED package on FR4 with detailed model heat sink	47	45	4
LED package on FR4 with compact model heat sink		42	11

Table 2: Simulated Results vs. Measured Results

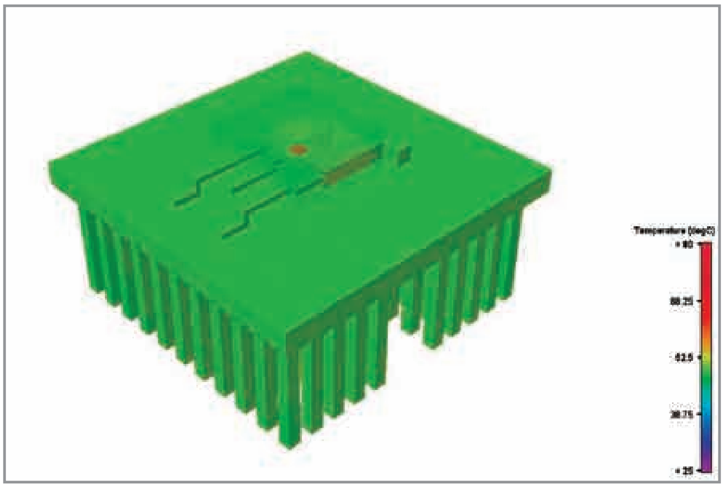


Figure 4A: Visualization result of LED package on MCPCB with detailed heat sink model

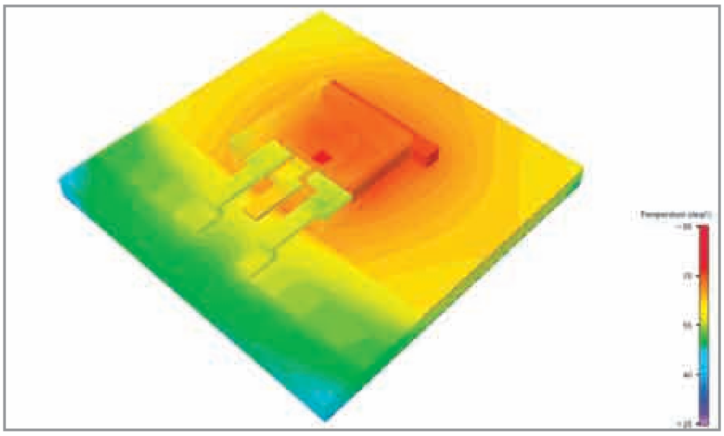


Figure 4B: Visualization result of LED package on FR4 with compact heat sink model

The Impact of Thermal Interface Material and Discussion

Thermal interface material (TIM) plays a key role in dissipating the heat out from the LED package to the board or heat sink. In Figure 2, TIM 1 is located between the LED package and substrate. Using a different thermal conductivity value and different bond line thickness the simulation works.

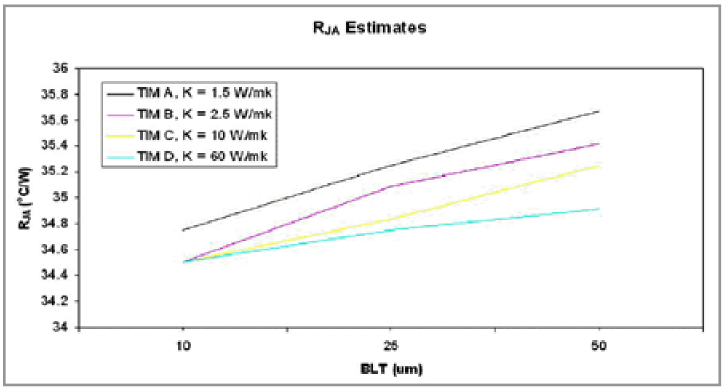


Figure 5: The impact of TIMs on RJA

The effects of TIM 1 thermal conductivity increases on the interface thermal resistance as the bond line thickness increases for the Moonstone package on substrate with heat sink are illustrated in Figure 5. The illustration shows the increase of thermal resistance is more sensitive to thermal conductivity as the bond line thickness increases. However, the impact of different thermal conductivity values and different bond line thickness is not significant.

An air gap between two non-conforming solid surfaces will reduce the thermal conductivity while the TIMs will conform to the microscopic surface contours of the adjacent solid surfaces and increase the area of contact between the LED metal slug (Heat source), and the Metal core PCB/FR4 PCB (Heat sink). As a result, it is able to reduce the temperature drops across this contact. The RJA estimates in Figure 6 are the result of a numerical simulation study of the TIM 1 contact quality effect on thermal performance. The single void is assumed to form at the center region of the total volume.

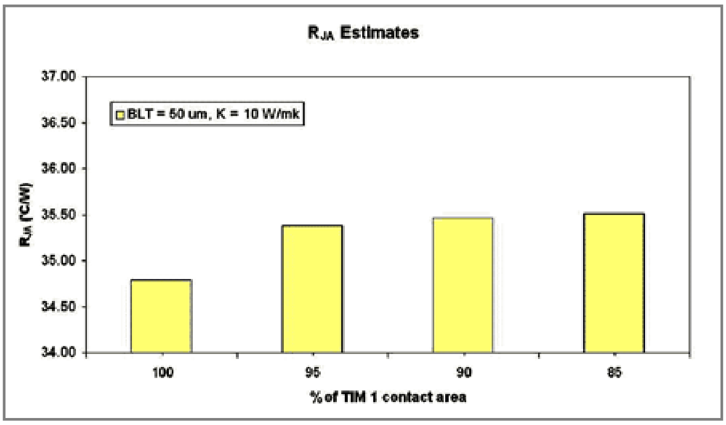


Figure 6: RJA effect versus percentage of TIM 1 contact area

The max RJA increase is estimated to be ~2 percent increase with 85 percent contact area only. This concludes that the void trapped inside the TIM 1 is acceptable up to 15 percent and it will not cause any significant thermal performance drops. The predicted results have an error rate of up to 20 percent due to modeling assumptions. An experimental study is required to verify the numerical data.

Material Type	Typical composition	Advantages	Disadvantages	BLT (mil)	Thermal conductivity (W/m-K)
Grease/Gel	AIN1, Ag, ZnO, Silicon oil	Re-usable	lower thermal conductivity	1.0-2.0	3 to 5
Silver filled Epoxy	Epoxy resin, Ag	Applicable to most of the surface type, Simple process and easy handling	Not re-usable	1.0-2.0	2 to 20
Solder	Pure In, In/AG, Sn/Ag/Cu, In/ Sn/Bi	High thermal conductivity	High temperature reflow needed, Not re-usable,	2 .0-5.0	30 to 50

Table 3: Properties and applicability of TIMs. These TIMs are common in the market.

Thermal Design Consideration

Besides using TIM to enhance the thermal performance, the following are the other thermal design aspects to improve it:

- Heat sink geometry and surface texture
- System enclosure air flow path design to promote natural convection cooling
- Use of an active cooling system such as fans and a heat pipe to remove the heated air and to augment natural convection cooling

Conclusion

This study illustrated how the CFD modeling technique can be used for simulating the LED package-on-substrate with a heat sink. The results clearly show that the detailed and compact heat sink models provide good results to the actual measurement, however, the detailed heat sink model can be more time consuming, especially if it comes from multiple LED packages. The compact heat sink model is good for doing a quick analysis because the percentage of error is acceptable for industrial applications and it saves time. The CFD is a good tool to assist in the design of the power LED into the real application. The increase of thermal resistance is more sensitive to the area of contact to compare TIM thermal conductivity as the bond line thickness increases and the void trapped inside the TIM 1 (up to 15 percent) is acceptable, and it will not cause any significant thermal performance drops.

Glossary of Terms

RJA	Junction to ambient thermal resistance (°C/W)
RJ-MS	Junction to metal slug thermal resistance (°C/W)
RMS-A	Metal slug to ambient thermal resistance (°C/W)
TJ	Junction temperature (°C)
TMS	Metal Slug (solder Point) temperature (°C)
MCPCB	Metal core printed circuit board
TIM	Thermal Interface Material
BLT	Bond Line Thickness
CFD	Computational Fluid Dynamics

Acknowledgment:

The author would like to thank Mok Thye Linn for providing the support and information needed to write this article..

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Direct Copper Bonded Ceramic Substrates for Use with Power LEDs

> Dr. Jürgen Schulz-Harder and Alfred Dehmel, Electrovac curamik

Abstract

The past years saw a marked increase in power density for packaged LEDs and also an increase in requested lifetimes for the same modules. This leads to the need for substrate materials that show an improved thermal conductivity and reliability over standard FR4 or insulated metal substrates. Direct copper bonded (DCB) substrates offer a significantly lower thermal resistance and have already become the standard carrier for high power, high voltage inverters and solid state relays.

DCB process

The manufacture of DBC substrates is performed by a special melting fusing technique. A copper sheet which receives a thin layer of copper oxide before or during the process is in close contact with Al2O3 ceramic and is heated up to a temperature of 1065°C to 1085°C (Figure 1 and Figure 2).

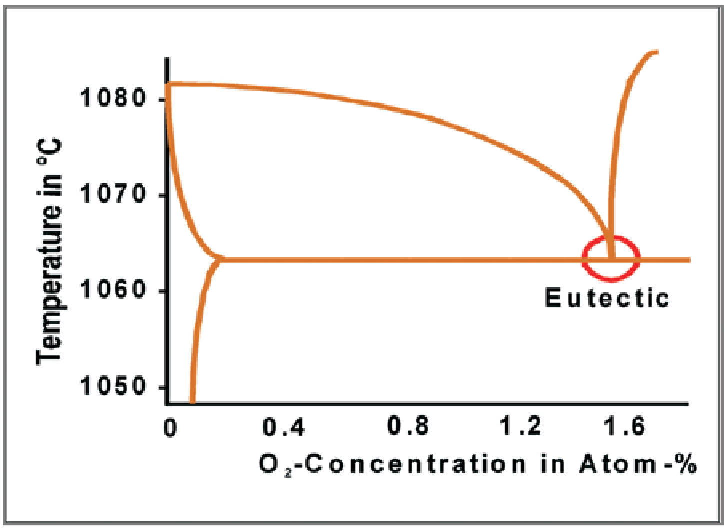

Figure 1: Eutectic of oxygen and copperoxide

The eutectic melt meets the ceramic while the copper sheet itself remains solid. The excellent wetting behaviour of Al2O3 ceramic is due to the forming of a spinell reaction: CuO + Al2O3 = Cu Al2O4

The following features have caused the replacement of traditional materials by DBC in power multichip modules.

- Low thermal coefficient of expansion (7.2 x 10-6) in spite of relatively thick copper layers (0.3mm)
- High peel strength of the copper (>50N/cm)
- Very low thermal resistance of the substrates due to the efficient heat spreading of the thick copper and due to the direct bond to the ceramic
- High mechanical and environmental stability

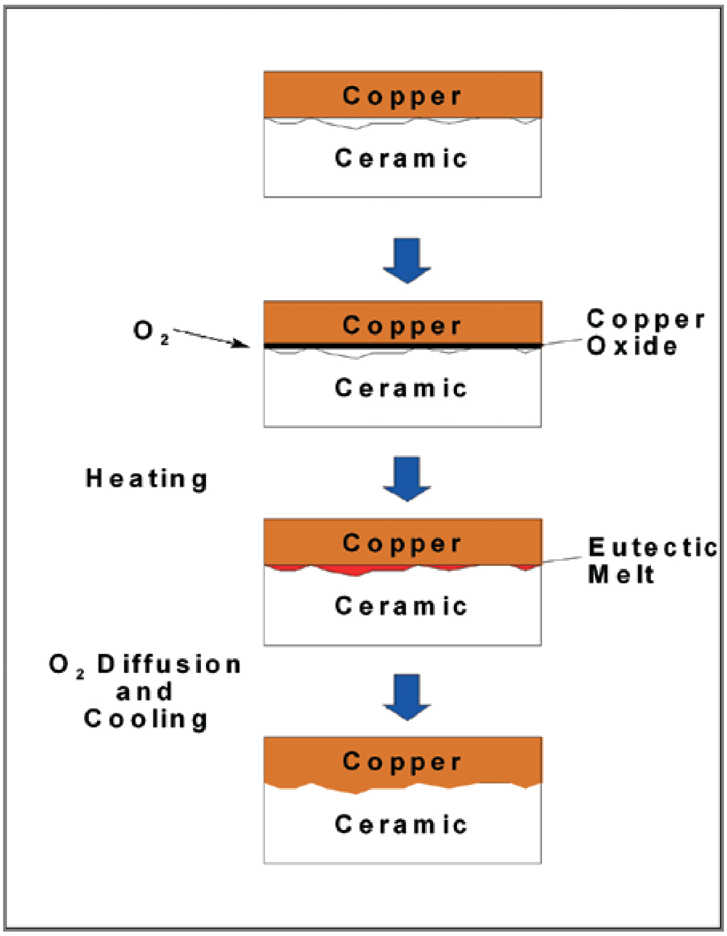

Figure 2: DCB-Process

A cross section of the substrate (Figure 3) shows the tight interface on both alumina (24 W/mK) and aluminiumnitride (180W/mK) substrates:

Figure 3: Interfaces on both alumina (left) and aluminiumnitride (right)

Motivation

The dependancy between expected catastrophic failure rates and junction temperature is a well known and documented fact and can be anticipated by the Arrhenius model [4]. Higher junction temperatures lead also to the degradation of lumen maintenance thus reducing projected module lifetime.

The key for higher quality LED modules is then to achieve lower junction temperatures through better packaging. With the proper material configuration of DCB substrates an increased lifetime of the assembled LED module and decreased cost per hour of lifetime can be achieved. Both AlN-based DCB substrates as well as thin alumina (0.25mm) DCB substrates pose economically and technologically viable solutions to the above challenge.

Considering a typical high power LED package of 5W and approximately 9 mm² of contact area (contact of slug to supporting substrate) it can easily be calculated, as listed in Table1, that even standard alumina ceramic substrates are quite sufficient thus avoiding the cost incurred by more exotic materials like Si3N4 or AlN. Thermal resistance for a given geometry decreases markedly by about 60% as compared to a conventional IMS substrate (75µm isolation thickness and 2.2 W/mK thermal conductivity).

Function	Thickness [mm]	Material	Specific Thermal Conductivity [W/mK]	Thermal Resistance [K/W]
Conductor	0.2	Copper	390	0.057
Isolator	0.25	Ceramic Al2O3	24	1.157
Conductor	0.2	Copper	390	0.057
				1.271

Table 1: Calculation of thermal resistance based on a 9mm² area and without heatspreading

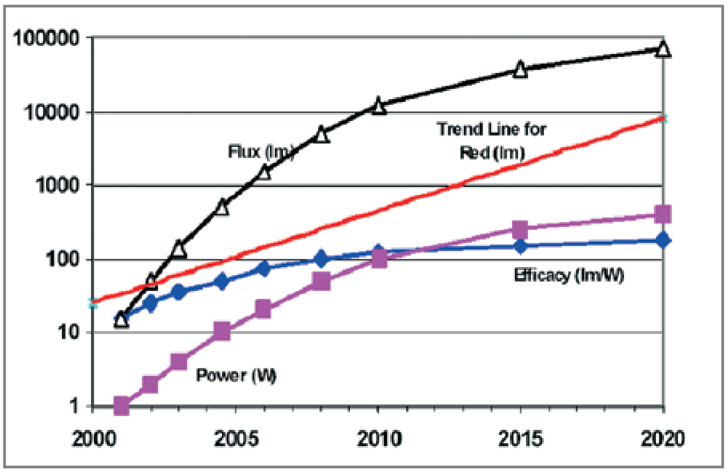

Figure 4: Expected development of LED power, Shatil [4]

Taking a closer look at the predicted development of power and therefore thermal resistance one can see (Figure 4) that by 2010 LEDs will reach the 100W boundary. It is important to understand that this issue that is the issue of packaging is not a completely new one. This requirement is shared with conventional power electronics. Therefore the same challenges result – and the same solutions apply.

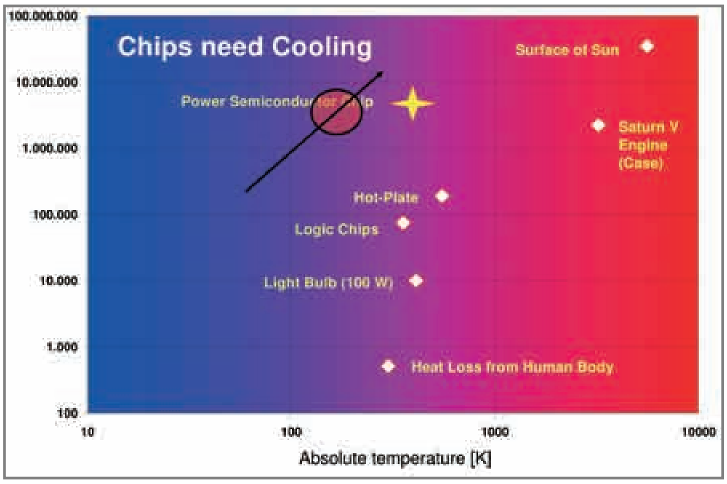

Figure 5: Power densities and temperatures, after U. Scheuermann, Semikron

As further motivation we took a look at the developmental trends for packaged high power LEDs of three major LED manufacturers (Figure 6).

As expected with higher power designers are pushed towards designing packages with decreased thermal resistance.

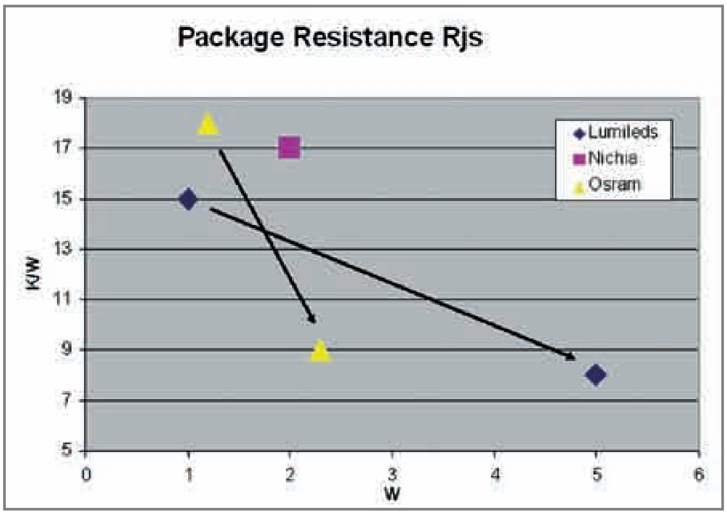

Figure 6: LED development trends for power and thermal resistance

By extrapolating this data it seems likely that further development will bring down the thermal resistance between junction and slug. Values of 4K/W for powers greater than 5W might be reached within the near future.

For Chip-On-Board Assemblies the substrate itself is already the bottleneck in thermal management. This trend mandates further improvement in the area of the substrate.

Thermal Characterisation of a LED assembly

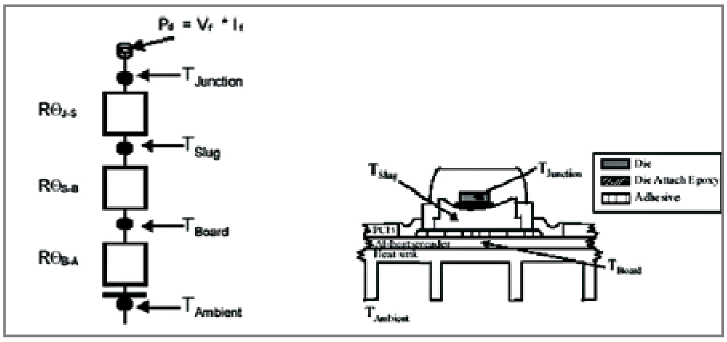

Figure 7: Modell of thermal resistance, Lumileds AB05

The above well know diagram (Figure 7) shows the thermal path of a power LED packages. Since the scope of this paper concentrates on substrates and the interaction with the light source we will neglect the heatsink and concentrate on:

RJ-B = RJ-S+RS-B

For our study on packaged LEDs we modelled a Lumileds Luxeon V (data taken from public datasheet) and examined the resulting heat distribution on a layout pattern optimized for thermal spreading.

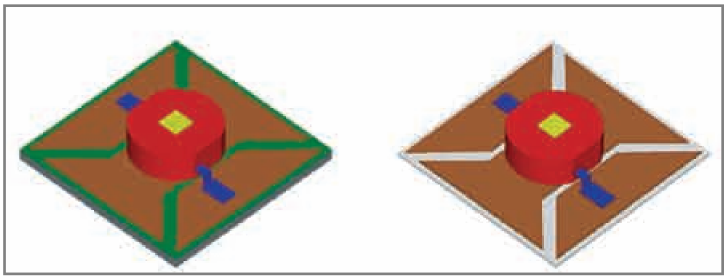

Figure 8: Geometric model

Basic benchmarks were done with an insulated metal substrate 1 mm Al / 75 µm dielectric / 70 µm Cu (dielectric: 2,2 W / mK). Thermal Power loss of the LED die was assumed to be 3 W, the boundary condition a heatsink fixed at 20°C. For Chip-On-Board simulations we used a rectangular body of GaAs of 2x2mm. Simulation software used was IcePack.

Simulation Results of packaged LEDs

The thermal resistance of the substrate materials RB shows the expected dependency on isolator thickness (Figure 9) . Minimum values measured for static thermal resistence of the substrate in conjunction with packaged LEDs were at 0.3 K/W.

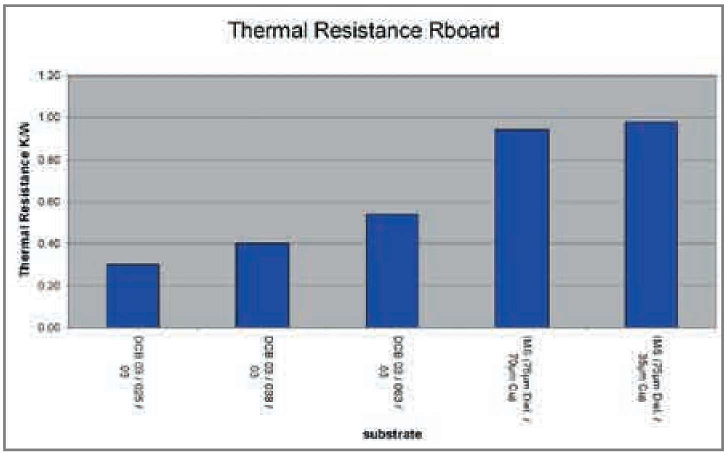

Figure 9: Simulated thermal resistance including heatspreading

The temperature distribituon within the packages shows that most of the temperature distribution takes place within the heat slug of the pacakge itself:

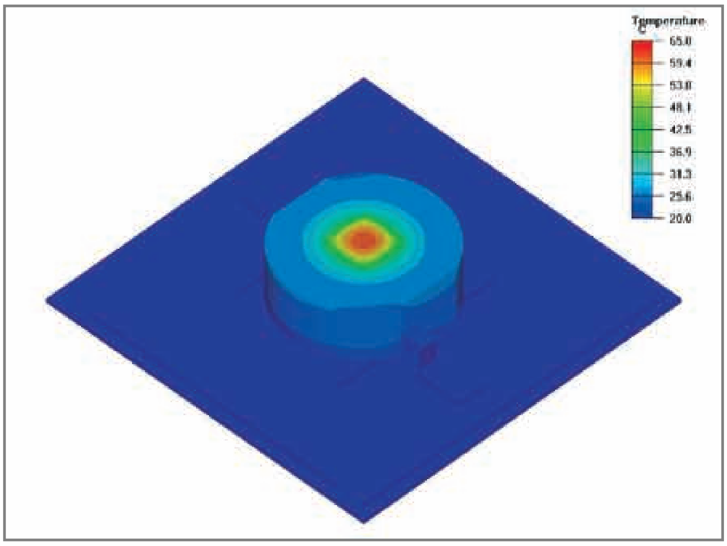

Figure 10: Overall thermal resistance junction to board (RJ-S+RS-B)

Therefore not surprising a look at the overall thermal resistance RJ-B shows that this did not transfer to the LED die itself. While there is a definitive decrease in temperature the overall drop in Rth is not well expressed. This is due to the fact that the thermal resistance of the package itself is to high for a drop in substrate thermal resistance to affect the overall outcome.

The situation for packaged LEDs needs to be reevaluated once the thermal resistance of the LED package itself drops further.

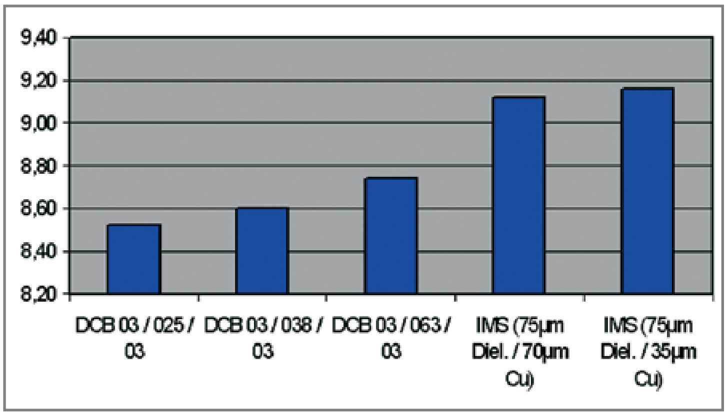

Figure 11: Overall thermal resistance junction to board (RJ-S+RS-B) in K/w

Simulation results for CoB

In comparison to the already packaged LEDs the chip-on-board approach shows distinct differences in thermal distribution depending on the substrate used:

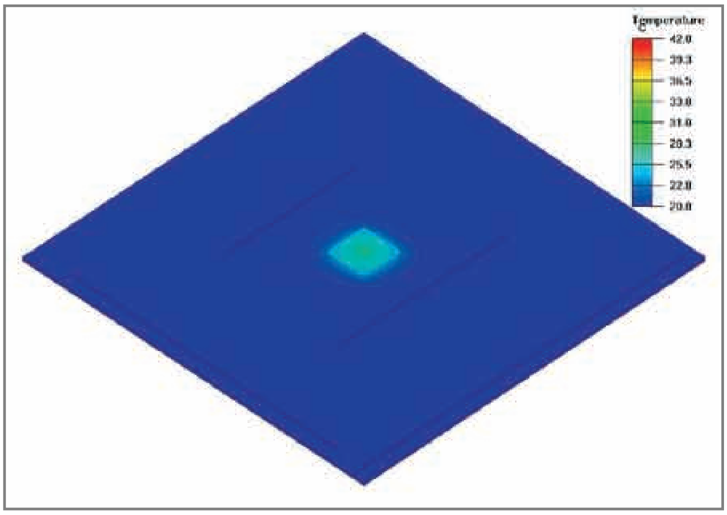

Figure 12: Simulation result of CoB with 200µm copper on 0.25mm Al2O3 (dTmax=7,4°C; thermal resistance junction to board 2.4 K/W)

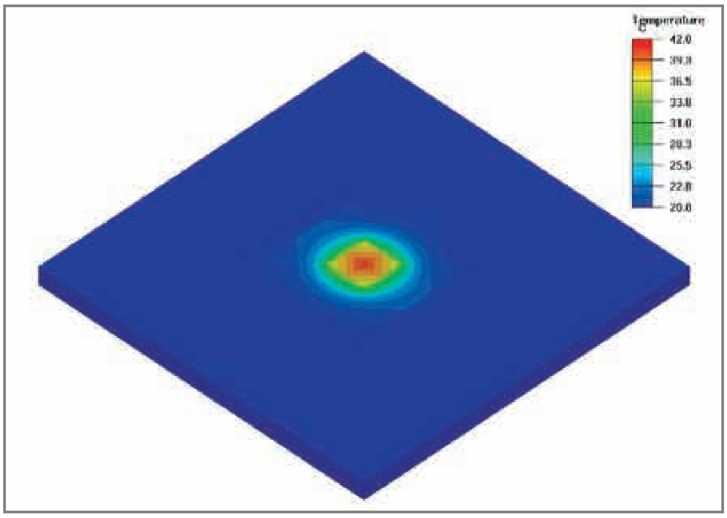

Figure 13: Simulation result of CoB with 75µm copper on IMS (dTmax=22,8°C; thermal resistance junction to board 7.6 K/W)

As seen from simulation results (Figures 12/13) DCB substrates offer the possibility to achieve low thermal resistances. The 2.4 K/W refer to an ideal solution with minium thermal resistance in an interconnection layer. In reality solder and or glue layers may yet add to this value.

Chip-On-Board-like approaches also enable tight placement of dies – unlike the packaged approach.

Heat Spreading and Dynamic Response

Since short life products like flashlights may overdrive the LEDs by three times the rated current, the added thermal capacity of DCB substrates may be an interesting property for those applications

Also the preferred and widespread method for dimming LEDs is some form of pulse width modulation (PWM- as shown in Figure 14). In this approach the LED is turned on and off within a prescribed duty cycle at a high frequency the eye perceives as dimmed and not cycled.

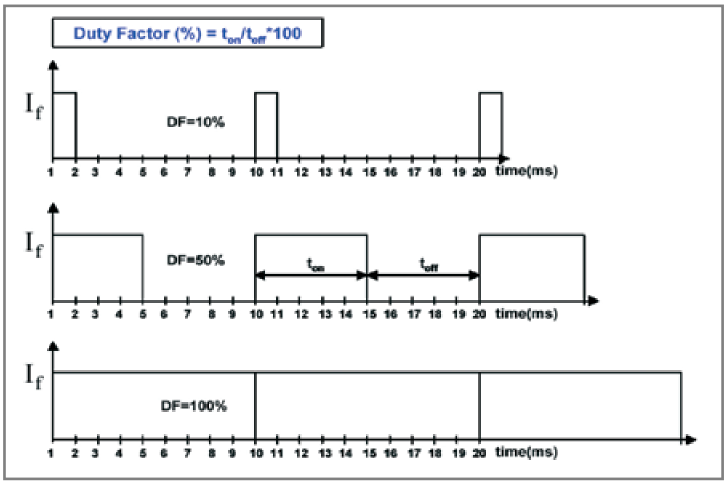

Figure 14: PWM as a method of dimming LEDs

This of course has implications for the thermal management needed. While packaged LEDs usually are supplied with a solid heat slug, Chip on Board assemblies need to provide sufficient thermal capacity for those modes of operation

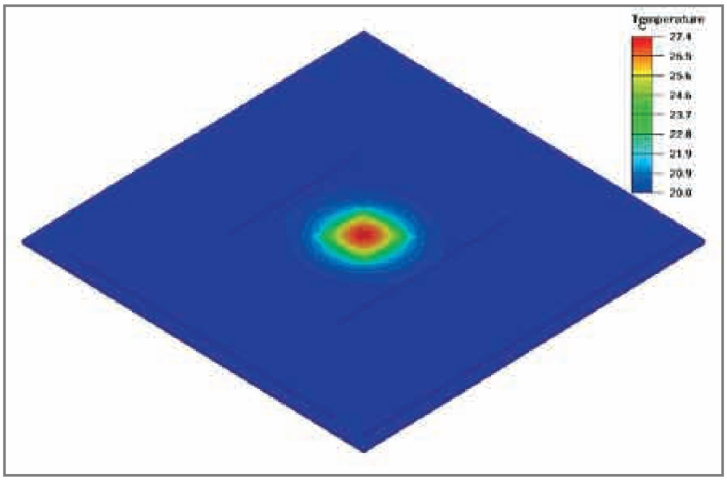

Figure 15: as figure 10 – normalized colour pattern

The heat spreading effect of the thick copper further improves static thermal behaviour but is best illustrated by in actual measurements and/or finite element simulations. The effect of the thicker DCB-copper can be seen quite clearly from the simulation. The effect of the heat-spreading appears as a concentric distribution around the placed die.

This spreading increases the area through which the thermal loss is dissipated. Certain alumina substrate/die configurations with thick copper may even compete with AIN for thermal performance.

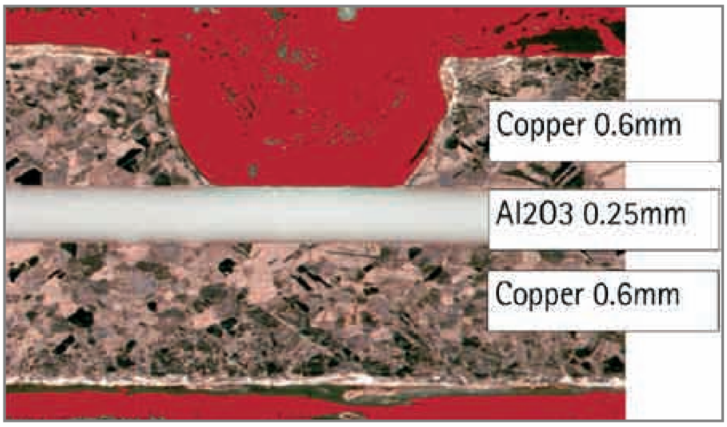

Figure 16 : Thin alumina substrate with thick copper

In numerical terms the static thermal resistance decreases compared to other substrate materials; dynamic thermal properties also show the effects of the increased thermal capacitance.

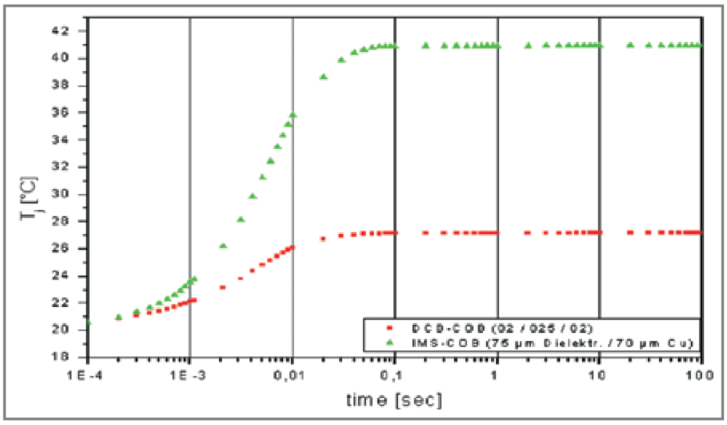

Figure 17: Dynamic behaviour of CoB die on both DCB and IMS

Further reliability considerations – rate of thermal expansion

While it is not a concern for packaged LEDs, a chip-on-board assembly needs to consider the need for thermo-mechanical compatibility. Different thermal expansion rates on both sides of any rigid interconnecting layer (e.g. solder) will result in stress in this layer. While the absolute reliability is also determined by the elasticity or rigidity of this material, the more stress must still reduce the relative reliability of the connection. [3]

With maximum permissible junction temperatures expected to rise this issue may become the same critical reliability issue it is in classical power electronics. An increase by 40°C and a difference of TCE of copper to GaAs (16.5-5.5) means a length mismatch of substrate to chip die of about 440ppm.

Material	TCE(ppm/°C)
Al	23.0
Cu	16.50
Cu/Mo/Cu	5.8
GaAs	5.5
GaN	5.6
GaP	4.65
SiC	3.7
AIN	4.4
Sapphire	7.9

This is a well known issue in power electronics. While beyond the scope of this paper there are three solutions possible:

- reduction of the difference in TCE by using matched materials
- reduction in overall temperature
- use of non-rigid interface materials

Alumina DCB as a composite material has a TCE of about 7.2 ppm/K depending on exact configuration. It thus can provide the matching transition material between a pure copper or aluminium heatsink and the semiconductor die.

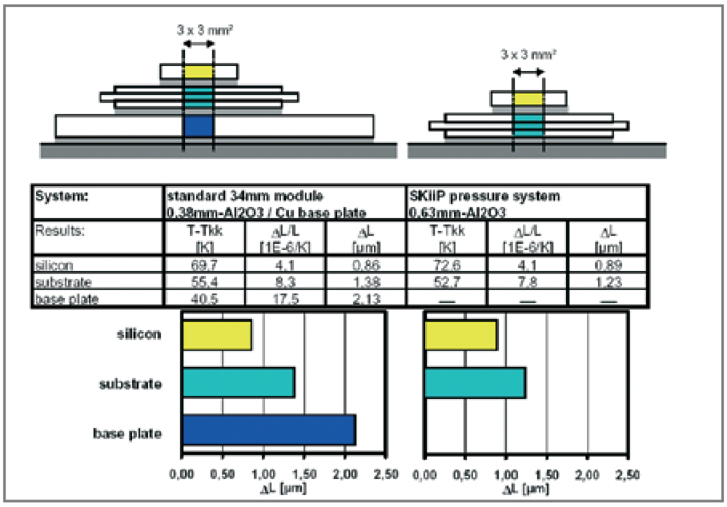

Figure 18: Effect of different expansion rates in power modules, taken from U.Scheuermann [3]

Adaption of DCB to power LED

Current pitch rates achievable on DCB are limited to 200-250µm. As some LED die manufacturers are relying on flip-chip-technology Chip-On-Board assemblies for DCB still need further development. First trials with alternative structuring technologies aim for isolation gaps in the range of 100µm.

Further development is also taking place for the issue of alignment of dies in exact geometrical alignment.

Figure 19: Justification marks on a copper surface

Conclusion

DCB substrates offer an attractive solution for future designs in the field of high power LEDs. While current packaged power LEDs with high thermal resistances will not significantly benefit from improved substrate thermal resistance, future LED packages as well Chip-On-Board approaches may benefit from the characteristic of DCB-substrates. ■

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Synthetic Jets for Active Cooling of LEDs

> Mick Wilcox and Lee Jones, Nuventix Inc.

Abstract

Synthetic jets allow LED designs with three times the light output of natural convection with no compromise on reliability or acoustics. One example of a synthetic jet module combined with a heat sink dissipates 350% more heat than natural convection and 50% more than a fan-driven flow. Existing SynJet™ cooling products designed for MR-16 and PAR-38 lamps use less than 750mW and have the MR-16 product producing less than 20 dBA – inaudible at a distance of two feet. Reliability exceeds even the longest-life LED products - L10 reliability for SynJets is 300,000 hours at 60°C. SynJets have been tested to 10,000 on-off cycles at temperatures up to 85°C without failure. A synthetic jet's low flow is not susceptible to dust and particle contamination. Its form factor is flexible, allowing any variation in design.

Introduction

As product designers develop higher-lumen LEDs for the lighting, medical and home entertainment product markets, thermal management increasingly becomes a design limitation. Proper thermal design is critical for these products to achieve high lumen output and long life. Without effective thermal management and heat sinking, the junction temperature of a LED rises, causing it to lose efficiency and diminishing light output. Thermal stress can also lead to failure of the LED wire bond, delamination, detached internal solder joints, and die-bond epoxy damage. For every 17°C above 90°C a LED's life expectancy is cut in half. An active cooling solution is often necessary for applications that use many tightly packed LEDs, have a small volume or surface area where natural convection is inadequate, or that are located where the ambient temperature is high. Active cooling allows the lumen output of individual LEDs to increase without the repercussion of thermal damage or lower life expectancies.

Several characteristics of traditional active cooling (i.e. fans) have prevented widespread adoption of LEDs in high-lumen applications. These include:

- Lifetime: The long life of LEDs, up to 100,000 hours, requires a long-life cooling solution.
- Noise: Consumers are unlikely to accept a solution that increases environmental noise. Lights should be seen and not heard.
- Power consumption: A power-hungry cooling solution would negate the advantage of the LED's high lumen-per-watt performance.

Some applications may also require resistance to dust and particle contamination or unusual geometries to accommodate innovative aesthetics.

Fans or blowers are the typical solution for cooling electronics, but in LED applications the poor reliability and noise level of fans are tremendous disadvantages. In some applications, such as light bulbs, high airflow is also undesirable. Synthetic jet technology is ideal for active LED cooling because of its high reliability, low power consumption, quiet operation and almost undetectable airflow. It allows two to three times the light output compared to passive LED thermal management designs.

Synthetic Jet Ejectors

A synthetic jet (SynJet™) is formed by periodic suction and ejection of fluid out of an opening (a nozzle) in a cavity by the time-periodic motion of a diaphragm that is built into a cavity. Several types of technology can create the time-periodic motion of the diaphragm, and the most common actuators are piezoelectric and electromagnetic. Figure 1 shows the way the air is ejected from the cavity, and the jet is formed. As the diaphragm compresses the air in the cavity, a strong pulse of air is pushed out of the nozzle. The first three frames in Figure 1 show the ejection phase. A vortex and jet are created and convected downstream from the jet exit. This pulse of air has very high velocity and travels far from the nozzle – notice how in frame five only the tail is visible. Ambient fluid from the vicinity of the nozzle is pulled into the housing. (last two frames of Figure 1). Much of the air is entrained downstream of the nozzle, while quiescent air from around the nozzle is sucked into the housing, this is known as the jet ejector effect

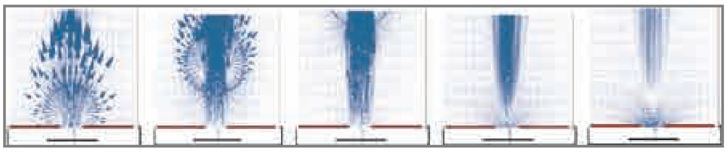

Figure 1: Particle image data showing the formation of a synthetic jet

These pulses of air, which are generated at a rate of 50 times per second, swirl along the walls of a heat sink and scrub the thermal boundary layer away, this "thermal scrubbing" results in extremely high heat transfer coefficients that allow more heat to be removed with less air.

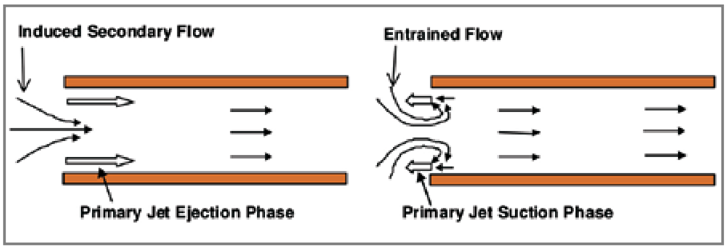

Figure 2: Operation of synthetic jet ejector

Efficacy of Synthetic Jet Ejectors vs. Fans and Natural Convection

Research over the past several years has shown that synthetic jets are significantly better at transferring heat compared to fan-type air flows. The reason is that a synthetic jet directs unsteady, turbulent, highly efficient airflow precisely along a heated surface in a confined environment and induces small-scale mixing. It is ideally suited for active cooling of heat sinks.

Early experiments uncovered the tremendous heat transfer abilities of synthetic jets. In a channel cooling experiment, Mahalingan et al. 1 showed that synthetic jet-driven channel flows exhibit higher Nusselt numbers– six to eight times higher - than for comparable conventional turbulent flow. (The Nusselt number is a parameter that is used to calculate the heat transfer coefficient – the higher the better.)

When a synthetic jet ejector was added to a heat sink for high-power microprocessors, testing revealed that this configuration dissipated 350% more heat than natural convection. In a comparison with a fan-driven flow through the same heat sink, the synthetic jet ejector dissipated 50% more heat than a fan (Figure 3).

In a configuration using synthetic jet ejectors and a channel heat sink, Mahalingan et al. 2 found that the thermal resistance through the heat sink via natural convection was 4.63°C/W. When the synthetic jets were utilized, the system had a thermal resistance of 0.83°C/W, which is more than a 450% improvement over natural convection. Figure 4 shows the variation in power dissipated by natural and synthetic jet convection as a function of case temperature.

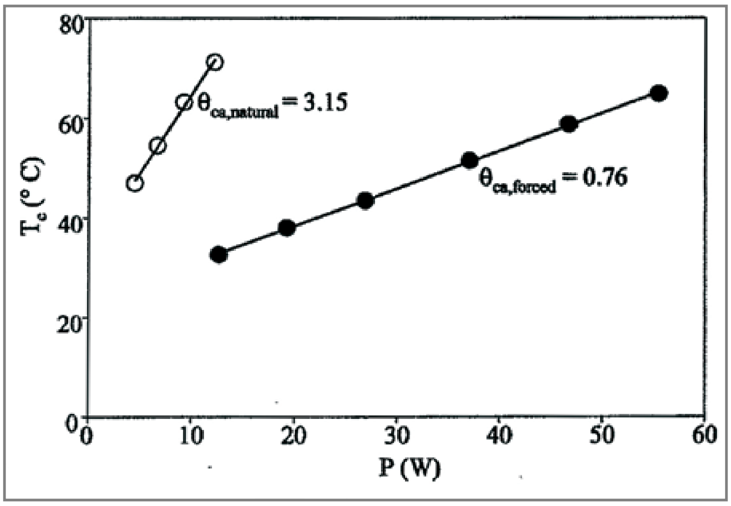

Figure 4: Comparison of power dissipated by synthetic jet (O) and natural convection (•)

What all this means for LED product designers is that SynJets are extremely efficient coolers in a small size. These features make applications such as high-lumen lighting to replace halogen and incandescent bulbs feasible even in enclosed or hot areas such as recessed lighting cans, theater spots and floods, and high-lumen LED projectors as well as large-array lamps.

Power Consumption

Synthetic jets consume very little power, and align strongly with the energy efficiency value proposition of LED lighting. An ANSI standard size MR-16 lamp dissipates 5 to 6W through natural convection. With a SynJet cooler that is currently available, it dissipates 15 to 20W while using only 750mW. In a PAR-38 lamp, natural convection might dissipate up to 20W under ideal conditions and less in applications such as recessed lighting. With a SynJet cooler, it can dissipate more than 40W while consuming fewer than 2W.

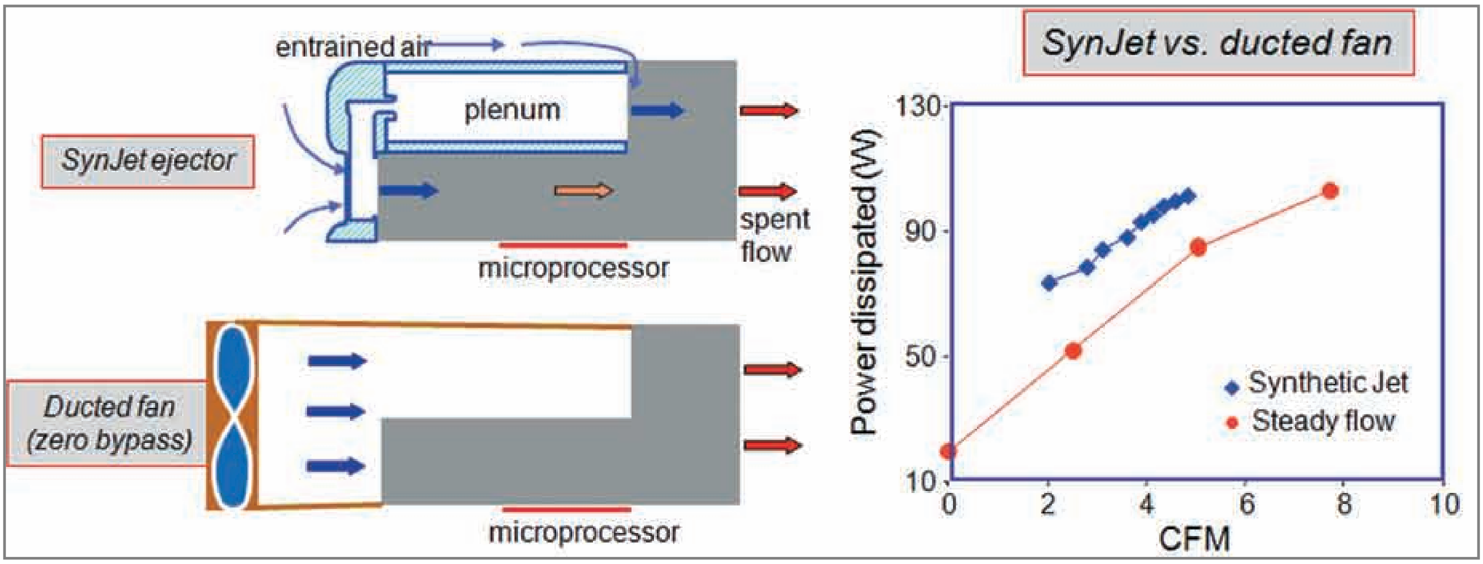

Figure 3. Comparison of a synthetic jet ejector and steady fan-driven flow on the same heat sink

Lifetime

Synthetic jet modules are inherently reliable because they have no frictional parts to rub or wear. There are no bearings, brushes, or motors to wear out and cause failures, whether those failures manifests themselves as mechanical or acoustic failures. Although fan manufacturers have no agreed-upon standard for measuring reliability, L10 life has been proposed as a means of accurate comparison. In reliability measurements the L10 life is the length of time that 90% of the devices tested continue to operate , under given conditions.

Nuventix testing of SynJets has shown that their L10 lifetime is 300,000 hours at 60°C. The best reliability for similar sized fans at 60°C hovers around the 50,000-hour mark (Figure 5) and most are much lower than that, near 20,000 hours.

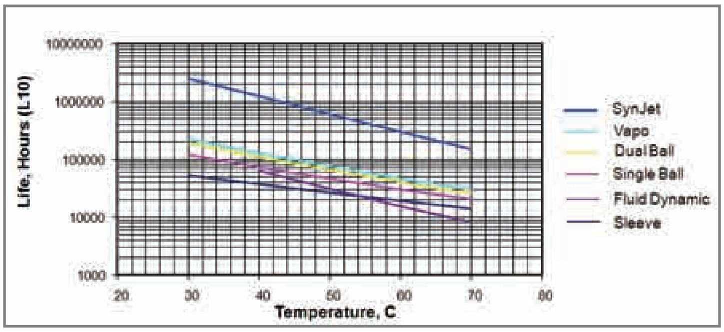

Figure 5. Comparison of L10 reliability for synthetic jet modules and other leading air movers.

The industry standard for LED reliability is B10 life, the time until 10% of the lamps are expected to fail, or B50, the time until half fail. However, since LEDs rarely fail completely but instead lose light intensity over time, this number is not useful in applications where light output is critical. Research has shown that a 30% reduction in lumens is approximately the limit of human perception, so the time to 70% or 50% lumen maintenance (L70 or L50) has been proposed as another standard for rating lifetime.

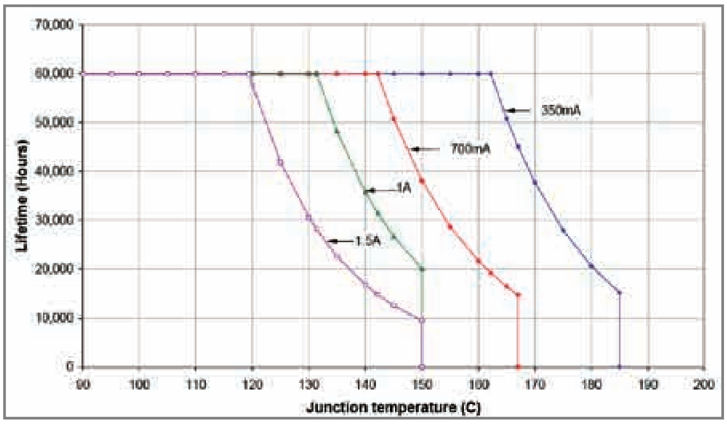

Figure 6: Lifetimes across current and temperature variables.

Current and temperature of the junction greatly affect the life of LEDs. Figure 6 shows B50 and L70 data for a Luxeon K2 LED rated at 60,000 hours. 3 up to 120°C, the rated reliability is assured at all currents. However, the dropoff is rapid at temperatures higher than 120°C for all current levels. One conclusion is that 60,000 hours is all that designers can be assured for LEDs at this time, even though some sources claim lifetimes of up to 100,000 hours. In either case, the 300,000-hour L10 lifetime of SynJets surpasses even the most optimistic estimates of LED life. The L70 values also underscore the need for reliable active cooling to extend the life of LED lamps.

Noise Level

The volume of airflow needed by a SynJet to cool LEDs is very low because synthetic jets are so thermally efficient. Low flow rate translates to low acoustic emissions. In addition, the absence of frictional parts eliminates friction noise. Synthetic jets of a size suitable for cooling LED lamps are virtually silent. MR-16 and PAR-38 LED lamps currently available have a sound pressure level of 25-28 dBA at one meter or less. This is equivalent to the sound of someone breathing one meter away; that is, undetectable in ordinary environments.

Other Considerations

Some applications have further requirements that synthetic jets can meet. Systems with moving parts may require that the cooling system stir up little dust. Systems that operate in a dusty environment may require lighting that is unaffected by dust and foreign contamination. Existing standards for light bulbs and other products may dictate the shape and size of an active cooling system.

Dust or Particle Contamination

Synthetic jet flows move very little dust in a system because the airflow volume is low and narrowly directed. Synthetic jets are not susceptible to failure due to dust contamination because of the low airflow and small quantity of air taken in by the actual module. Also there are no frictional moving parts to wear out or deteriorate due to dust contamination.

Form Factor

Synthetic jets can be positioned in any orientation, and their form factor is completely flexible. In the LED cooling application in Figure 7, two concentric circles of flow travel down the ID and OD of a cylindrical heat sink used in a LED application. Figures 7 and 8 show currently available implementations of a cooling module using a SynJet with a heat sink for MR-16 and PAR-38 lamps.

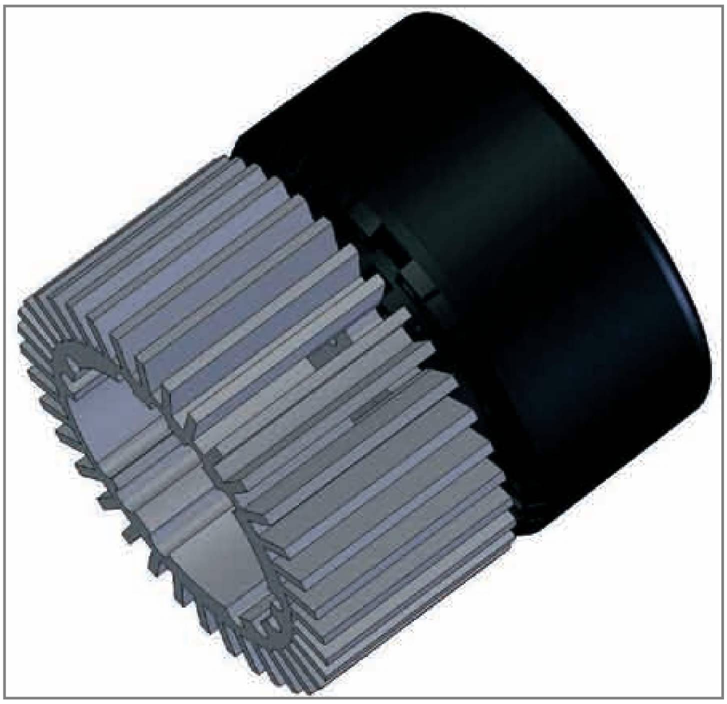

Figure 7. MR-16 SynJet Cooler

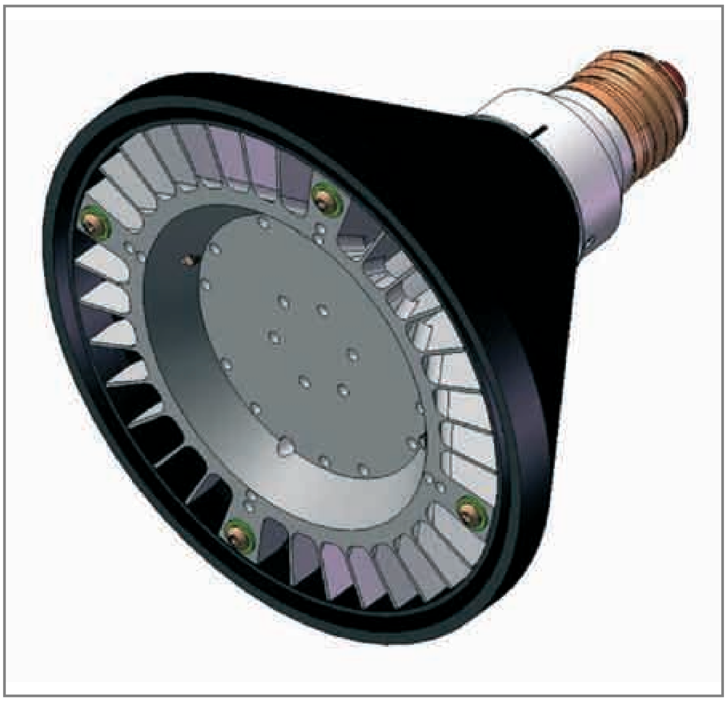

Figure 8. PAR-38 SynJet Cooler

Small form factor LED projectors are currently limited by producing relatively low lumens. An active cooling option is to add one or more synthetic jet modules. Because a synthetic jet can be manufactured into any shape, retaining the small size, high reliability and energy efficiency of current LED projectors is possible.

Imagining farther into the future, LED lamps will replace theater lighting or standard fluorescent lighting. For performance purposes, LED spot and flood beam projection lamps could provide color-changing effects and cut down on the electricity required for a performance, or reduce the heat load on air conditioning systems. Where LEDs might first replace fluorescent lighting is in areas where the cost of maintenance or safety from mercury emissions is an issue that compensates for higher initial cost, such as clean rooms and surgical theaters. As costs come down, LED lamps will be attractive for replacing fluorescent lamps in stores, offices and schools, particularly as the US Environmental Protection Agency (EPA) pushes for lower mercury emissions, a concern for landfills and municipal incineration plants. Again, synthetic jet electors can be a part of these solutions for all of the reasons stated in this article.

Conclusion

The efficient, quiet cooling that synthetic jet ejectors provide will undoubtedly be integral to the future of higher-lumen LED applications. Having the option of a cooling system that matches or exceeds the LED in long life, energy efficiency and the synthetic jet module's complete flexibility of form gives designers a powerful tool and unlimited possibilities for combining with any heat sink design. ■

References:

1) Mahalingam, R. et al., Thermal Management Using Synthetic Jet Ejectors, IEEE Transactions on Components and Packaging Technologies. Vol. 27, No. 3 (Sept. 2004), pp. 439-444.

2) Mahalingam, R. et al., Design and Thermal Characteristics of a Synthetic Jet Ejector Heat Sink, Transactions of the ASME. Vol. 127, June 2005, pp. 172-177.

3) http://www.lumileds.com/pdfs/WP12.pdf. Accessed on 11/07/07.

Insulated Metal Substrate for Maximum Brightness and Lifetime

> Nico Bruijnis, The Bergquist Company

When designing lighting systems using high-brightness LEDs, effective thermal management is essential to optimise both optical output and durability. At the device level, an efficient thermal path away from the LED chip through the package is usually provided. This typically culminates in a heat slug of relatively high thermal capacity.

Proper design of the surrounding system elements should ensure continuation of thermal flux, through the heat slug to eventually dissipate into the surrounding atmosphere. The PCB substrate can present a barrier to this flux, since the thermal conductivity of standard FR4 is low compared with the LED package, metallic pads and the heatsink. Designers need solutions that improve the thermal performance of the substrate, if they are to design the system to operate the LED at an acceptable steady-state temperature.

Die Temperature and LED Performance

An HB-LED die has several temperature dependent properties. For example, as the temperature of the die increases so, too, does the emitted wavelength, leading to a shift in colour. This is particularly important with white LEDs, as the human eye is able to detect very small colour changes in white light. Some colour variance is unavoidable between multiple LEDs in an array, due to slight manufacturing variances in junction-to-case thermal resistance. However, the effects of poor thermal conductivity in surrounding components such as the PCB substrate can accentuate these variations, so that the effects can be visible to the human eye.

There is also an appreciable loss of luminous efficiency with increasing die temperature. Hence, assemblies that are sensitive to changes in ambient temperature may display a noticeable reduction in light output. Outdoor signage such as traffic signals, for example, may become dimmer as temperatures increase during the day. Effective thermal design is necessary to minimise or eliminate this effect.

Finally, the die temperature has an important influence on the useful lifetime of the LED. LEDs do not fail catastrophically in the same way as a tungsten filament lamp. Instead, the optical output reduces steadily over time, with the rate of decay closely related to the temperature at the junction. The lifetime of an HB-LED is usually considered in terms of "lumen maintenance failure", or the point at which the light output has fallen below an agreed useful threshold. This can be application dependent, and is also a subjective measure. The Alliance for Solid-State Illumination Systems and Technologies (ASSIST), e.g. proposes that a 30% reduction in light output is close to the threshold detectable by the human eye, and is therefore a good metric for general lighting applications. Other applications may be more or less tolerant of reductions in light output.

The Thermal Management Imperative

When designing a lighting array or fixture using HB-LEDs, designers will determine the optimum forward current to obtain the desired optical power output at the intended operating temperature of the die. The design of the lighting control circuit is predicated on supplying the required forward current to the LED junction.

Considering that LED operation is fundamentally a process of converting the electrical energy supplied into optical energy, the need for thermal management stems from the unavoidable inefficiencies in this conversion. A proportion of the electrical energy, for example, is not converted to light. In addition, a proportion of the light energy produced at the LED junction cannot be effectively expelled from the package. This lost energy produces heat, which must be extracted from the package. Inefficient thermal management will cause the temperature of the die to increase, leading to colour shift, reduction in light output and reduced lifetime, as described. In the extreme, the die temperature can exceed the maximum sustainable temperature and cause catastrophic failure of the device.

Thermal Modelling and Design

In order to ensure adequate provision for the removal of heat, it is important to consider the mechanisms by which the unwanted thermal energy is extracted from the die. This is typically conducted through the package to the PCB substrate and into the heatsink, from where it is transferred into the ambient environment by convection.

In the case of a typical HB-LED application, several elements of thermal resistance are present. Figure 1 shows a thermal model comprising the individual thermal resistances of each component in the assembly, arranged in series, culminating in the thermal junction between the assembly and ambient.

Clearly, although the thermal resistance of the package, from die to case ($R\theta$-C), is determined by the LED vendor, design decisions taken by the lighting designer will critically influence the actual thermal performance of the assembly. In turn, this governs the light-output characteristics and in-service lifetime that can be expected.

Hence the LED manufacturer's best efforts at ensuring effective removal of heat from the die to the edge of the package should be continued throughout the remainder of the thermal pathway to ambient, in order to ensure consistent, reliable, long-lasting performance of the end product.

Continuing the Efficient Thermal Path

Of the elements that comprise the thermal stack illustrated in figure 1, the PCB potentially has the highest thermal resistance. The performance of the PCB is a function of the thermal properties of the dielectric and the component pad sizes. For example, the thermal resistance for a standard FR4 glass-epoxy dielectric can be over 30°C/W, depending on its thickness. This high thermal resistance impairs heat transfer from the edge of the package to the attached heatsink. Implementing large pad dimensions reduces the total thermal resistance. However, perennial pressure to minimise overall product dimensions limits the extent to which pads can be enlarged. This places greater emphasis on the thermal properties of the dielectric.

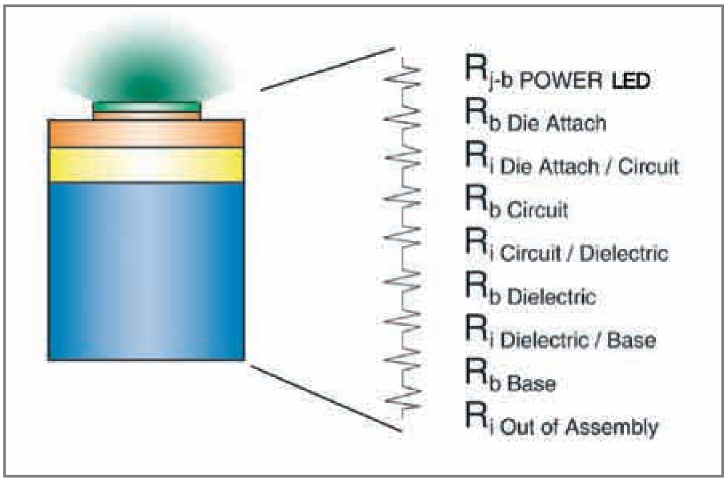

Figure 1: Thermal resistances in a HB-LED lighting assembly.

To minimise the thermal resistance of the substrate a thin board is desirable, although the resulting lack of rigidity may challenge other aspects of the system's overall performance. Another technique to improve the thermal resistance of standard FR4 is to implement an array of plated-through vias around the LED. This may be an effective solution where small numbers of LEDs are mounted and other system design constraints may require the use of standard FR4. On the other hand, implementing large numbers of vias adds to the processing overhead - and therefore the cost – of PCB fabrication.

A thermally enhanced substrate such as The Bergquist Company's Thermal Clad Insulated Metal Substrate (IMS) comprises a thin, thermally conductive layer bonded to a metallic substrate to maximise heat dissipation, as shown in figure 2.

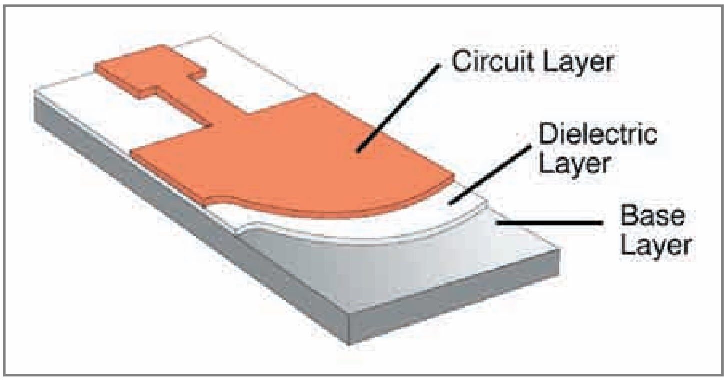

Figure 2: An Insulated Metal Substrate provides electrical isolation and reduced thermal resistance.

The substrate may be aluminium or copper of varying thickness, depending on the chosen specification. Thermal Clad circuit board materials are available in various thermal performances ratings, whereby the right material depends on the power density of the design. As the available conductor area for mounting the LED diminishes in successive product generations, the contribution of thermally enhanced materials such as IMS become more valuable. The following thermal simulation and practical test results compare the performance of two different dielectric layers with that of standard FR4 is a reference assembly using an HB-LED supplied as a bare die.

Design for Optical Performance

Three test assemblies were constructed using a bare die, which was mounted on Thermal Clad substrates with MP and LTI dielectric, as well as a standard FR4 PCB of comparable dimensions. Figure 3 illustrates the results produced by a thermal simulation, showing the temperature of each die when a constant current is applied.

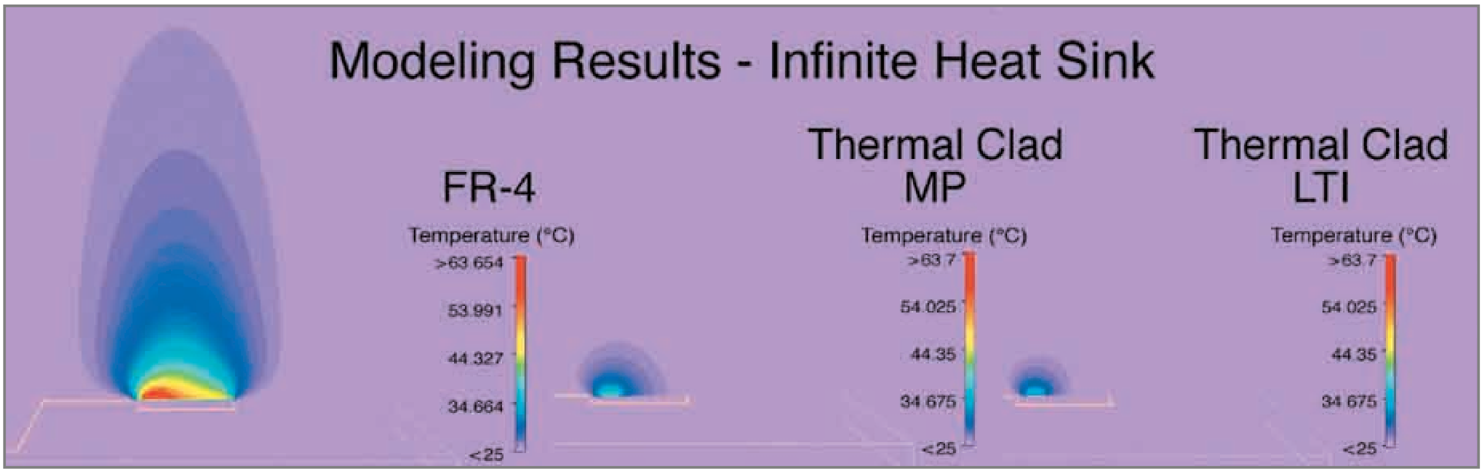

Figure 3: Temperature simulations using IMS and standard FR4 PCBs.

The die is modelled on 70 micron circuit foil, 0.020" square. The die-attach medium is a tin-gold eutectic alloy, and gold wire bonds are used to complete the circuit. Power dissipation was set at one Watt. The resulting die temperature for the FR-4 is 63.7°C, MP is 36.9°C and LTI is 34.2°C. Clearly, for a given forward current the IMS substrates allow the die temperature to be maintained closer to ambient, indicating advantages in terms of LED colour-shift, luminous efficiency and long-term lumen maintenance.

Design for Life

Alternatively, if designing for a desired die temperature to meet a target for useful lifetime, such as a stipulated relamping interval for a municipal lighting solution, the enhanced thermal performance of an IMS allows a higher forward current for increased light output. Figure 4 illustrates the result of a bench test carried out using the bare die mounted on FR4, Thermal Clad MP and Thermal Clad LT substrates. The forward current is adjusted to maintain the die at a constant 50°C in each case. The differences in light output are significant, and clearly show the advantages of using an IMS in place of standard FR4 to achieve the highest light output, reliability and longevity. This can enable lighting designers to meet a requirement for total luminous flux using a smaller array of LEDs, and thereby access the numerous benefits to be gained by reducing part count.

Figure 4: Bench test results carried out at constant 50°C die temperature.

Another dielectric material, BondPly TCP-1000 now expands the Thermal Clad range and is specifically developed to satisfy the cooling needs of High-Brightness LEDs. An IMS incorporating this new dielectric is able to deliver an enhanced cost-performance ratio for efficient, long-lasting LED illuminations.

Conclusion

Market interest in HB-LED illuminations is currently high, as owners seek greater energy efficiency, longer lifetime and lower ownership costs, and also the greater variety of operating modes and effects that can be achieved. To maximise the optical output of HB-LED arrays, and therefore challenge traditional light sources in all aspects of performance, effective thermal management throughout the assembly is critical. IMS technologies offer significant advantages over standard PCB materials. ■

Thermal Simulations for LED Applications

> Dr. Johannes Adam, Flomerics Ltd.

Readers of this journal are well aware that the junction temperature TJ of LEDs plays a key-role for their performance; not only for light output (efficacy) but also for wavelength stability. The cooler the LED, the better will be the performance. However, the temperature of the LED is not only a function of its own termal power loss, but also depends on the other heating components on the board and the cooling and heating paths due to ambient conditions, i.e. the mechanical and thermal environment in the final application. These ambient conditions might be quite harsh e.g. in car entertainment systems where high ambient air temperatures can occur, other heat sources are near-by and space for cooling is precarious.

It is not only necessary to find a good solution for the temperature problem but, also to find it as early as possible, so that any necessary heat control measures can be implemented in good time and at a reasonable cost. Modifications to the finished design are always the most expensive solution. Also, one would like to know the answer with reasonable accuracy. Frequently found rules of thumb (for example simple temperature estimates with thermal resistance calculations) only hold true for specific geometrical configurations or physical assumptions and yesterday's empirical values probably cannot be extrapolated to today's situation. Experimental mock-ups (heating resistors and "shoeboxes") are not precise enough. Flomerics advocates numerical simulation as still the most precise way to get realistic early temperature predictions (without hardware prototypes). It is flexible, provides insight into the heat flow paths and it can be used in early phases of the product development. As development proceeds, early estimates for model parameters and geometry can then be increasingly replaced with hard and fast values. .

Thermal calculations

All three software packages mentioned above analyse the system, calculating airflow, infrared radiation, and heat conduction on a 3D calculation mesh. The algorithms are similar to those used to forecast the weather but much of the work is automated by the program, making them much easier than weather forecasting. For example, the user doesn't have to worry about the heat transfer between the surface of the components and the air, and the mesh generation is fast and intuitive. The degree of detail in the virtual model is controlled by the engineer and the project status. FLO/PCB is focusing on the thermal scene on and around a PCB. It is simple to use and very intuitive: components, layer patches and thermal vias can be defined by drag and drop, by numbers or by extracting from libraries or partially from IDF files or electronics layout software. The calculation process is fully automated and therby suitable for an electrical engineer. FLOTHERM goes beyond the PCB level where the user (usually a mechanical engineer with more background knowledge about electronics cooling) is creating a geometrical model of the device by selecting and placing objects (enclosures, circuit boards, perforated sheeting, fans, heat sinks etc.) and assigns the physical parameters (power dissipation, materials etc.) to the parts. The calculation and meshing can be controlled in various ways. PCB geometry from FLO/PCB can be imported in a FLOTHERM model. While FLOTHERM can be used stand alone and is strongest, most effective and very fast with rectangular cartesian geometries (one might say in prototyping a thermal model), EFD is embedded – really embedded - in CAD Systems such as Solid Works, ProEnginneer or Catia V5. According to the Flomerics philosophy, the burden of complicated meshing or numerical analysis expert knowledge is taken away from the user. A volume model of a CAD geometry can be turned quickly into a calculation model. EFD is adressed to mechanical designers who have to use pre-defined CAD parts from a company wide library and whos geometry is far from beeing rectangular. All in common to all simulation tools is that only good input gives good output. This holds especially for thermal power loss, spatial dimensions (area and thickness) and material properties (thermal conductivity). Geometrical shape is a form factor of 2nd-level importance - more or less - mostly. In the following sections we will describe some examples to illustrate the simulation approach for LED applications.

Light-emitting diodes

In terms of its inner structure the LED is still one of the simplest electronic components but it is still neither possible nor desirable to include all the details in a model. You need a good (!) data sheet with clearly-defined conditions for the thermal resistance between the chip and the circuit board, which effectively translates the inner structure into the thermal resistance between the chip and the heat spreader. For an example we use an Osram TOPLED LA E67F with a thermal resistance junction to board of Rth JB=130 K/W given in the data sheet and in the application note. The simulation model of the LED consists of no more than a 2-resistor network of size 3 x 3.4 x 2.1 mm and a FR 4 substrate mounted on an aluminium base plate with adhesive. The recommended soldering pad is of size 4*16 mm^2 = 64 mm^2 and thickness 35 θm. The other resistor, junction-top, can be set to a very high number, as the heat flow is designed to be unidirectional towards the board. The first step in modelling is to create a test model using the data sheet conditions (circuit board, soldering pad, setup conditions, and environment) and try to reproduce the values from the data sheet, esp. the junction-ambient condition. Note that Rj-a is influenced by heat spreading and heat transfer outside the component and thus depends on the board layout and air flow conditions.

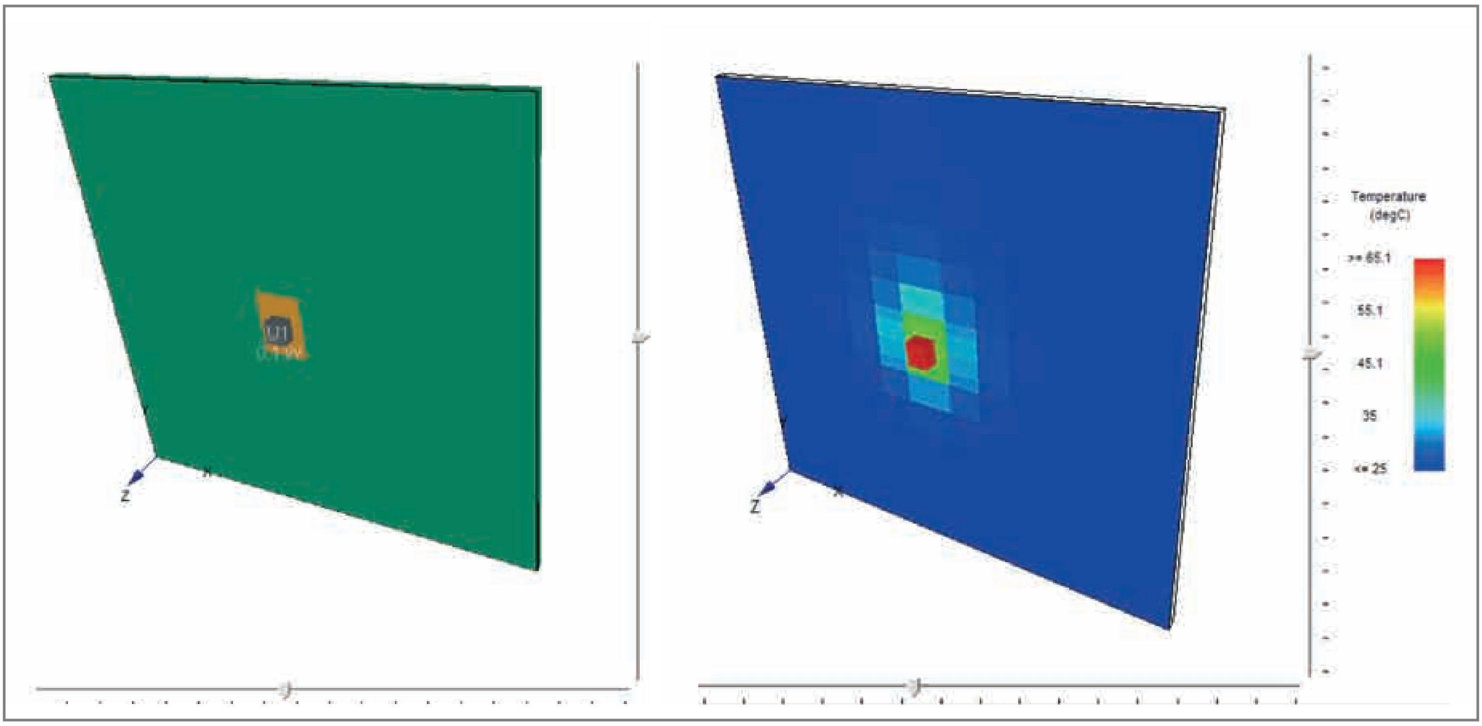

Figure 1: Results of the verification model for an Osram LA E63F deliberately calculated with FLO/PCB. A 2-resistor model of the LED is placed on a soldering pad - on a FR4 test board. The model input data are RJB=130 K/W and PV=0.1 W. The desired output according to data sheet is about Rja=350 K/W. The calculated junction temperature of the 2R model is 65 °C. The testboard is placed in "still air", i.e. free convetion with radiation. If the area of the solder pad were doubled, the junction temperature would drop to 56 °C.

From a prototype model to an advanced model

Once we have confirmed the LED model, we may then proceede to a prototype of the actual application model. Suppose we should have 8 TOPLEDs with thermal loss of 0.2 W each on a PCB of size 76 mm x 76 mm.

- First we try with just a 1.6 mm thick FR4 board. The junction temperature rises to 100 °C.
- What, if we laminate a 0.2 mm thin isolation foil on an aluminium plate (insulated metal substrate)? The result is 66 °C.

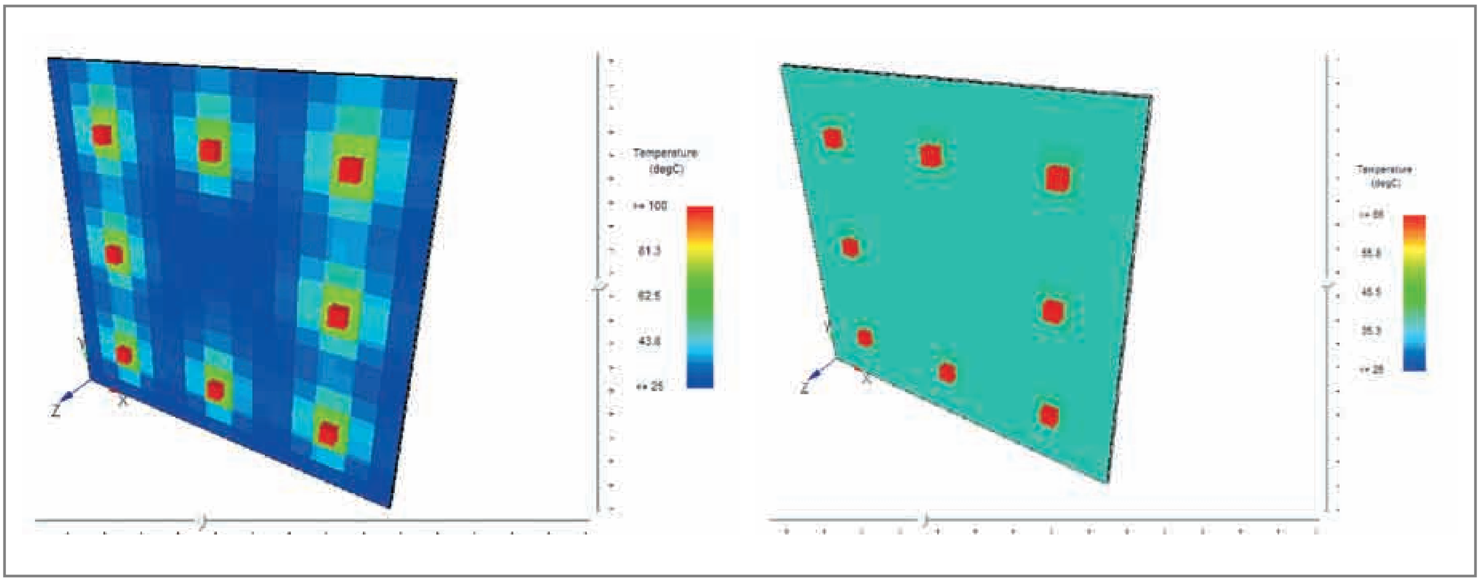

Figure 2: Calculated result of 8 LEDs each of 0.2 W of thermal loss (left) on a FR4 board (TJ =100 °C) and (right) on an IMS board (TJ=66 °C)

In order to reduce the temperature we might have the idea to add some cooling fins to the aluminium plate. We choose a staggered pin fin array to allow for more directional independence.

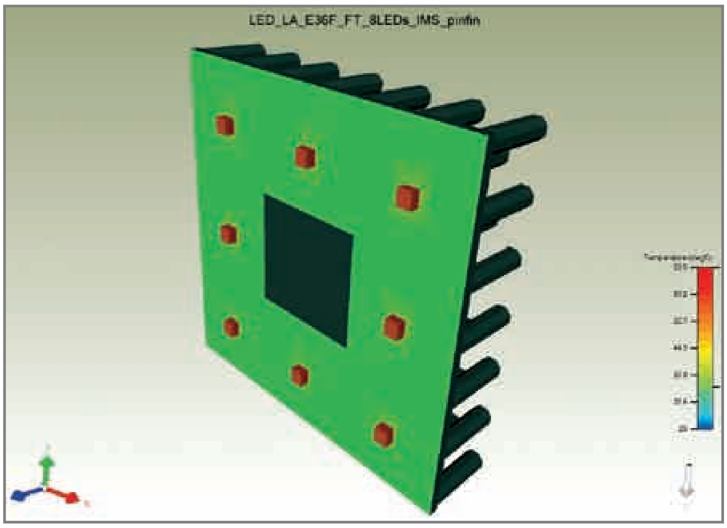

Figure 3: Calculated surface temperatures for an ambient temperature of 25°C with 7x7 staggered pin fins each 15 mm high in free convection ("still air"). Temperature drops to TJ= 63 °C, only. If this doesn't seem to be sufficient, FLOTHERM can look for a better solution by Design of Experiments (DOE) and subsequent optimization steps.

What would be an optimum number and diameter of the fins, or if the optimum would lead to a very heavy heat sink, what could be a good compromise? This question is perfectly posed to numerical simulations as no hardware prototypes have to be prepared and the relative accuracy of comparable models is very good. The graph shows the results of a "Design of Experiments" in a given parameter space defined by the number of pins in x and y and the diameter of a pin. The temperature of the hottest component is given as function of the corresponding mass of the heat sink. The result looks disappointing on the first glance. The reason why using no pins (i.e. just mounting on the board) is not substantially worse than using pins is because the heat flux can be transported already in the copper patches, the aluminium plate by heat spreading and radiation from the surfaces. The best configuration calculated is 7x8 fins with 3 mm diameter each (61 gramms) .The study also shows, that too much of pins are bad for cooling, because denser packing is inhibiting good air flow in the remaining channels. So, this calculation would have saved a lot of time and money.

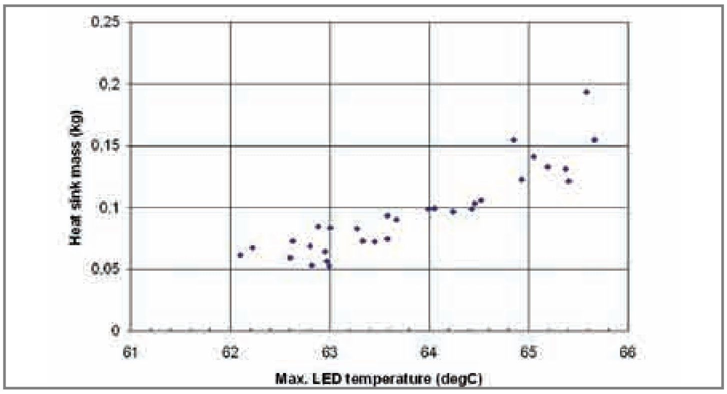

Figure 4: Results of a Design of Experiment study on heat sink parameters for the 8 LED model shown in the previous figure. The more fins, the worse the result because air flow in the pin channels is inhibited.

Funny geometries

When non-rectangular geometries have to be calculated, e.g. in automobile lighting applications, EFD is the software of best choice. Just as an example, the figure shows the calculated surface temperatures and the airflow on some LED lamp. LED models are placed on a thin spherical shell made in IMS technology which is mounted on a plastic handle. The lamp model is calculated for free convection with thermal radiation to the ambient. For the LED model the silicon chips are glued on a copper slug and protected by a thin hemi-spherical plastic cover. The results show that the generated heat flows mostly to the aluminium ball, so that the tiny plastic domes stay cool.

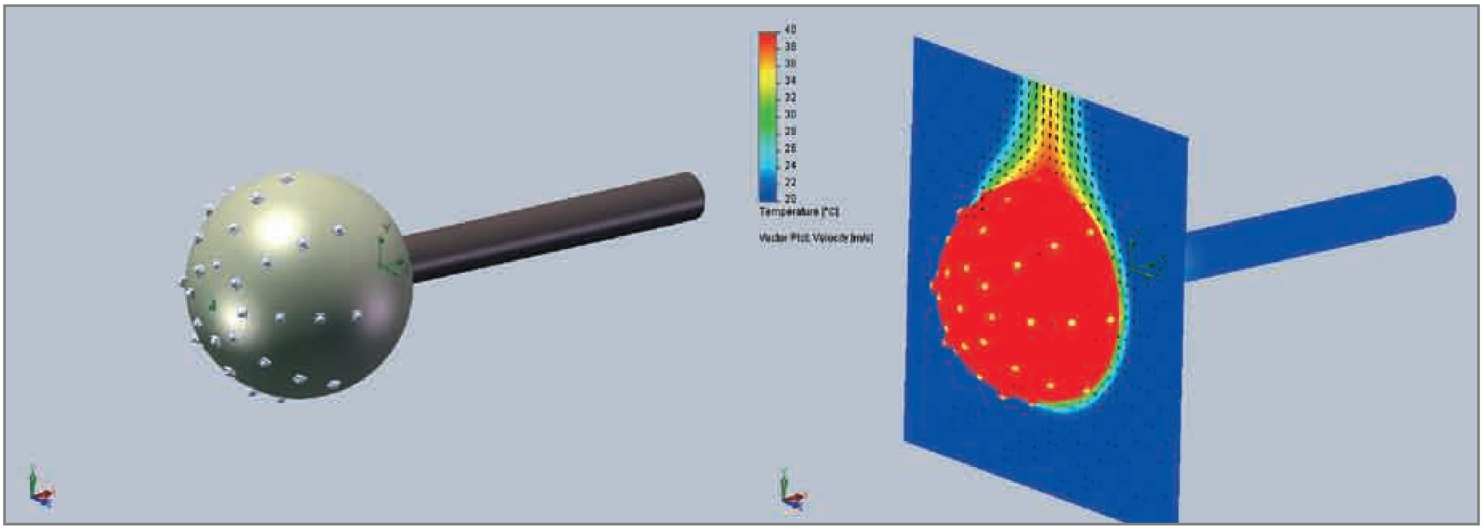

Figure 5: 33 LEDs on a spherical shell of aluminum with FR4 isolation. Internal, external airflow and heat transfer is calculated.

Experimental thermal and radiometric properties of LEDs

The better the thermal models of a LED the better the temperature predictions. Data sheets are not always telling the complete truth. Either the thermal properties are too optimistic in order to outrival competitors, or they are too conservative in order to allow for a wide margin of production tolerances.

TERALED provides combined thermal and radiometric/photometric characterization of high-power LEDs. The system can be used as a stand-alone optical measurement system for LEDs, or as an add-on to MicReD's T3Ster® equipment. TERALED has been developed specifically in response to demand from leading LED manufacturers and provides a unique, complete solution for LED testing. The system is scalable with low initial investment. You can start with just a plain radiometric detector and later upgrade the system to measure luminous flux as well as chromacity coordinates. Combining TERALED and T3Ster® thermal transient measurements produces highly accurate "structure functions" which provide detailed internal thermal resistance information for power-LED packages. The results can be used not only for calculation purpose, but also for quality control in looking for die-attach failures and other structural integrity problems. ■

Figure 6: The TERALED extension for the T3ster thermal transient tester provides high accuracy experimental radiometric and thermal data of LEDs