LIGHTING THE WAY

To manage heat removal for LED lights, DuPont engineers used ANSYS CFD simulation to accurately predict temperatures within their proprietary substrate — information that could not be gained without simulation. This information is employed in guidelines to develop reliable CooLam® substrates for lighting manufacturers that require a broad range of configurations.

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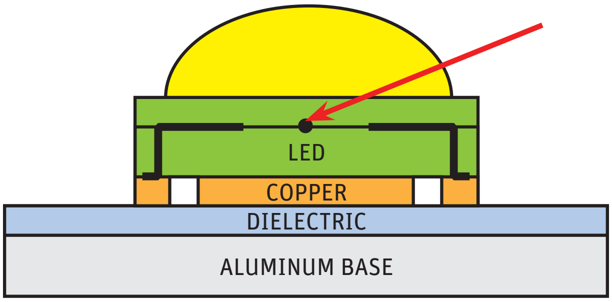
Light-emitting diodes (LEDs) are an increasingly popular source of lighting because they are very efficient, long-lasting and controllable. The global commercial LED lighting sector was expected to reach $26.7 billion in 2015 [1] and $42.7 billion by 2020 [2].

Because they are cool to the touch, LEDs are often considered to be thermally efficient compared to incandescent lighting. Thirty percent of the energy passing through an LED chip is converted to light, while 70 percent is converted to heat. (In incandescent bulbs, 90 percent of the energy escapes as heat [3]). Energy is dissipated as heat reduces the energy available for light output. If allowed to build up, the heat would eventually destroy the LED chip, but it can be easily removed using a thermally conductive material such as copper. Unfortunately, most thermal conductors are also electrical conductors, so the LED chip must be electrically insulated to avoid shorting out the device. Heat is often removed with a thermal substrate composed of a sandwich containing thermally conductive metals and a thin dielectric material to transfer heat as efficiently as possible while providing the necessary electrical insulation.

Developed specially for cooling LEDs, DuPont CooLam® thermal substrates consist of a sandwich of (moving from the LED outwards) copper foil, polyimide dielectric, and an aluminum heat sink or base. As lighting manufacturers have increasingly adopted this product, questions have arisen about the optimal configuration for specific applications. For example, what are the cost and performance trade-offs involved in using a larger or smaller base, different aluminum alloys, etc.? The challenge for DuPont engineers tasked with answering these questions is that the junction temperature — the point in the chip where

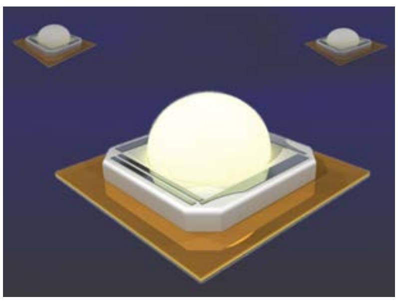


▲ CooLam® thermal substrates consist of copper foil, polyimide dielectric and aluminum base. The arrow shows the center of the thermal pad, which cannot be measured under operating conditions.

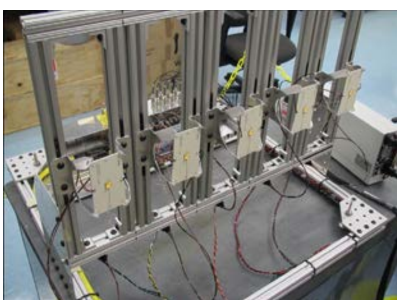
temperature is most important — can't be physically measured because it is deep inside the chip. DuPont engineers overcame this challenge by using ANSYS CFD software to simulate heat transfer of a typical LED with a wide range of thermal substrate configurations. They developed application guidelines that help determine the best configuration for nearly every application.

LED COOLING CHALLENGE

The junction temperature at the heart of the LED chip must be kept at 75 C to 85 C to provide optimal light output and service life. The traditional approach



▲ DuPont CooLam® thermal substrate improves thermal management of LEDs.



▲ Test setup in laboratory with yellow LED mounted on thermal substrate hidden behind LED and thermal substrate mounted on gray board

used to cool LEDs (thermal substrates made of aluminum-based FR-4 glass-reinforced and epoxy-based materials) is limited by relatively low thermal conductivity. More recently, the industry moved to metal-core printed circuit boards (MCPCB) made of sandwiches in which each component is designed to optimally conduct heat through the board, where it can be dissipated by convection and radiation. The thermal properties and geometry of each material in the sandwich are all important parameters that determine the junction temperature and ultimately the LED performance.

DuPont engineers set out to quantify the impact of the specific thermal substrate construction and design on the junction temperature of the chip. They performed lab measurements on an LED chip cooled by a number of different thermal substrates. They measured the temperature on the thermal pad of the LED chip as close as possible to the solder pad and also on the back side of the aluminum heat sink. The LEDs were powered with a constant voltage/current DC power supply; the heat sinks were cooled in a natural-convection air-conditioned room environment. A high-power LED lamp was tested over a range of power levels from 5 to 17 watts. The LEDs were cooled with CooLam thermal substrates having:

- two different copper foil thermal pad thicknesses of 35 µm and 140 µm
- two different polyimide dielectrics with thermal conductivities of 0.7 W/mK and 0.24 W/mK
- two different aluminum heat sinks with thicknesses of 1 mm and 2.5 mm made of two different alloys. The alloys have thermal conductivities of 138 W/mK and 205 W/mK

Four different test board layouts were also evaluated:

- One LED and a thermal pad with the same footprint
- One LED with an extended thermal pad
- One LED and a thermal pad covering the full 3.5-inch by 2-inch test board
- An array of three LEDs with heat sinks having the same footprint.

CFD MODEL ACCURATELY PREDICTS JUNCTION TEMPERATURE

The next step was creating an ANSYS CFD model to match the test setup. ANSYS Fluent was the best tool for this simulation challenge for several reasons. The Boussinesq approximation for natural convection with parameter-fitting included in Fluent helped to easily map the model to physical measurements. The product's discrete ordinate radiation model was used to model the heat leaving the LED through radiation from the lens. The software also made it easy to apply different thermal conductivities to the multiple materials in the model. This was accomplished easily via the ANSYS Workbench parametric capability.

DuPont engineers obtained aluminum and copper material properties from the literature and dielectric properties from in-house measurements. LED and solder-mask properties were estimated based on data provided by their manufacturers. The heat dissipation of the LED was based on rated wall-plug efficiency — the energy conversion efficiency with which the system converts electrical power into optical power. Engineers ran transient conjugate thermal simulations and compared the results with the time histories of the thermocouples and dynamic IR thermal imaging. The simulations were tuned by carefully matching the gentle laboratory room air flow in the CFD model. Adding the discrete ordinates model to track radiation losses through the lens and from warm surfaces was the final model element needed to refine the simulations. The result was a near perfect match between the CFD predictions and thermocouple measurements.

It's not possible to measure the junction temperature of the LED, or even the temperature in the center of the thermal pad directly under the center of the LED. So LED design engineers typically take a measurement on the solder pad located on the outside edge of the LED and use that as an estimate of the temperature at the center of the thermal pad. Then they use the thermal resistance specification provided by the LED manufacturer to estimate junction temperature. With the CFD results validated, DuPont engineers were, for the first time, able to determine

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the temperature at any point in the LED and thermal substrate. They discovered that the temperature at the solder pad was 15 C less than the actual temperature at the center of the thermal pad. The simulation demonstrated that the previous method had substantially underestimated the junction temperature under actual operating conditions.

DEVELOPING APPLICATION GUIDELINES FOR A WIDE RANGE OF APPLICATIONS

The simulation results provided useful guidelines to help DuPont engineers configure CooLam thermal substrates for specific customer applications. The results show that using a thicker aluminum base has the biggest impact, providing a 12.4 C to 12.7 C reduction in junction temperature depending on the power of LED and type of dielectric used. With this major insight, engineers now consider increasing the base thickness as a first step in difficult thermal management problems. Using an aluminum alloy with higher thermal conductivity from 138 W/mK to 205 W/mK, regardless of other parameters, also assists in temperature reduction. And the high-performance dielectric of 0.7 W/mK provided a significant junction temperature reduction, from 5.4 C to 5.7 C depending on the power level and type of heat sink.

The simulation results provided the first validated measurements of the impact of CooLam substrate design variables on the junction temperature of an LED. This could not have been determined using any method other than simulation. DuPont engineers demonstrated the value of high-performance configurations and made it possible to quantify their impact under various operating conditions. As a result, the DuPont application engineering team can confidently supply lighting manufacturers with thermal substrates that ensure high LED performance, reduced power consumption and long life.

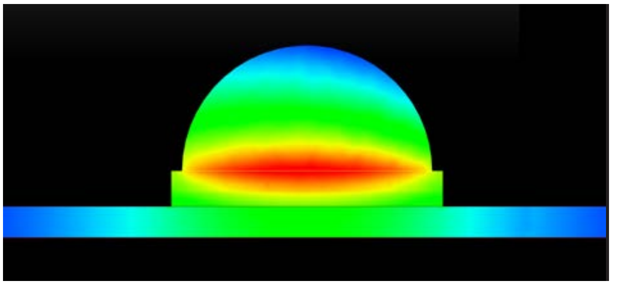
References

[1] Yu, H. *LED Journal*. Global LED Lighting Trends Reveal Significant Growth and Product Development. ledjournal.com/main/blogs/global-led-lighting-trends-reveal-significant-growth-and-product-development (10/21/2015).

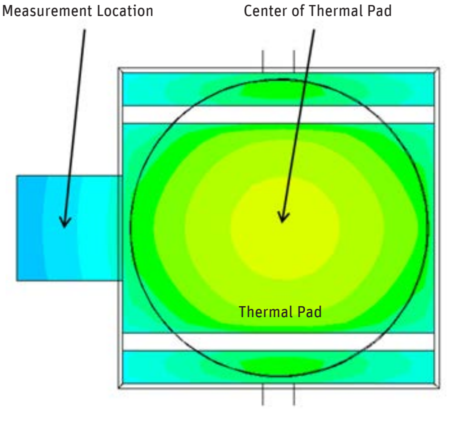
[2] Breslin, M. *Electrical Contractor*. Global LED Market Expected to Reach $42.7 Billion by 2020. ecmag.com/section/your-business/global-led-market-expected-reach-427-billion-2020 (10/21/2015).

[3] Lighting Technologies: A Guide to Energy-Efficient Illumination. energystar.gov/ia/partners/promotions/change_light/downloads/Fact%20Sheet_Lighting%20Technologies.pdf (11/18/2015).

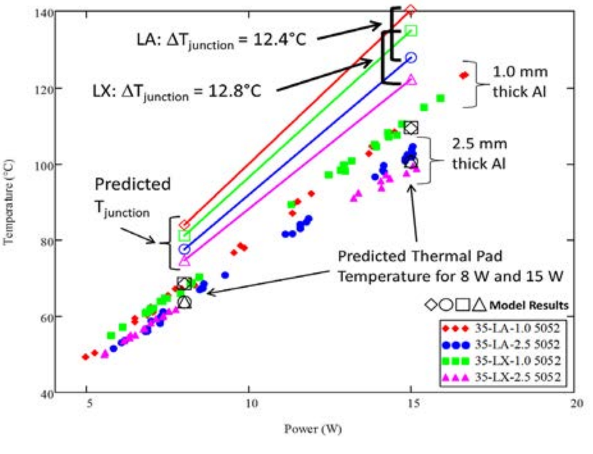
Heat causes reduced light output and would eventually destroy the chip.



Simulation results show temperature plotted on LED, thermal substrate and board.



Simulation showed a 15 C temperature difference between the solder pad and the center of the thermal pad.



Effect of aluminum thickness on junction temperature for two power levels and two types of dielectric material (LA and LX)