LEDs and Heat: Managed or Micromanaged?

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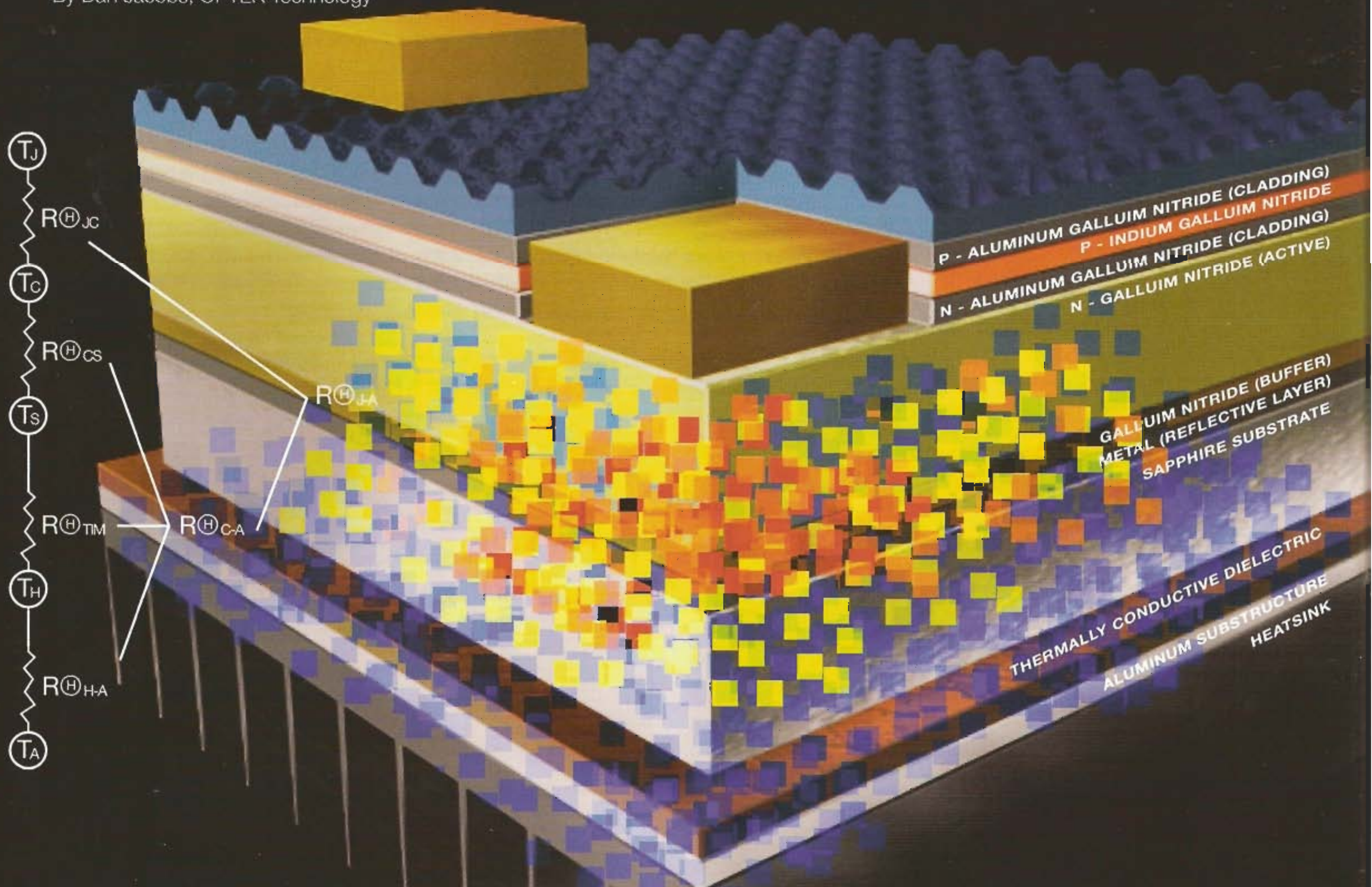

All of the focus on thermal management of light emitting diodes raises the question: is it always worth the cost? For LEDs, every penny must be applied efficiently. The benefits of lower junction temperature are well known, but there is a tipping point between investing additional product cost in thermal management and getting a return on that investment. Good thermal management starts with clear product and application definition. Mechanical and electrical elements exclusive, of thermal management materials, may have a strong, unexpected impact on junction temperature. It is often possible to direct added cost to other parts of the product design to accomplish equal reduction in junction temperature, while gaining performance in these other areas. Smart design and sound product development decisions will rightly relegate thermal management materials to secondary status in products. Given a choice, the best place to invest is in the LEDs themselves.

Justifying good thermal management

In case you have not heard, reliability is the calling card for LED products. Long life and lumen maintenance depend on junction temperature more than any other factor; thus thermal management indirectly supports the most significant, marketable aspect of this technology. This connection makes it easy to tout the importance of thermal management.

Beyond reliability, LED performance is inextricably linked to junction temperature with efficacy, forward voltage, chromaticity, and product life directly dependent on this characteristic. Consider functional changes in LED performance for every 10°C change in junction temperature. Luminous efficacy (lm/W) decreases by 2-5% depending on color. The design must compensate for these losses either by providing more input power—and further straining the thermal performance of the system—or by adding more components. Forward voltage decreases by roughly 30 mV. If a linear regulator circuit is on-board with the LEDs to maintain forward current, the regulator must dissipate extra heat from the extra voltage. As the LEDs net forward voltage decreases, its functionality or reliability can be compromised. Wavelength shifts by about 1-2 nm; consequently, the color temperatures of white LEDs are impacted as their blue sources change. Chromaticity affects the aesthetics of lighting solutions—if the junction temperatures of LEDs in the same room or area are not consistent throughout, there may be apparent differences in color temperature.

Application Considerations

Let's consider application criteria before delving into aspects of LED product design intended to reduce junction temperature. Thermal management tends to be handled as a reaction to the rest of the design, but it should be considered from the outset—when the application is first assessed. Environmental conditions need to be suitable for LEDs. Lighting within an enclosed environment will make thermal management difficult to impossible. LEDs in environments with large temperature changes force designers to add elements that meet the requirements of the extreme worst-case scenario. When conditions are mild, those aspects of the product are extraneous. If high temperatures will be present, common sense should be applied before proceeding with LEDs. Fortunately, LEDs fit some applications particularly well because they produce less heat and operate well in low temperatures. For example, elevator lights tend to heat the cab significantly enough to make the environment uncomfortable for passengers; LEDs in elevator cabs provide a means to dramatically reduce this effect. Another good example is placing light fixtures in places that may be regularly touched by people, particularly in retail stores and at home. Since LEDs produce less heat and operate at low voltages, these applications move from desirable to possible.

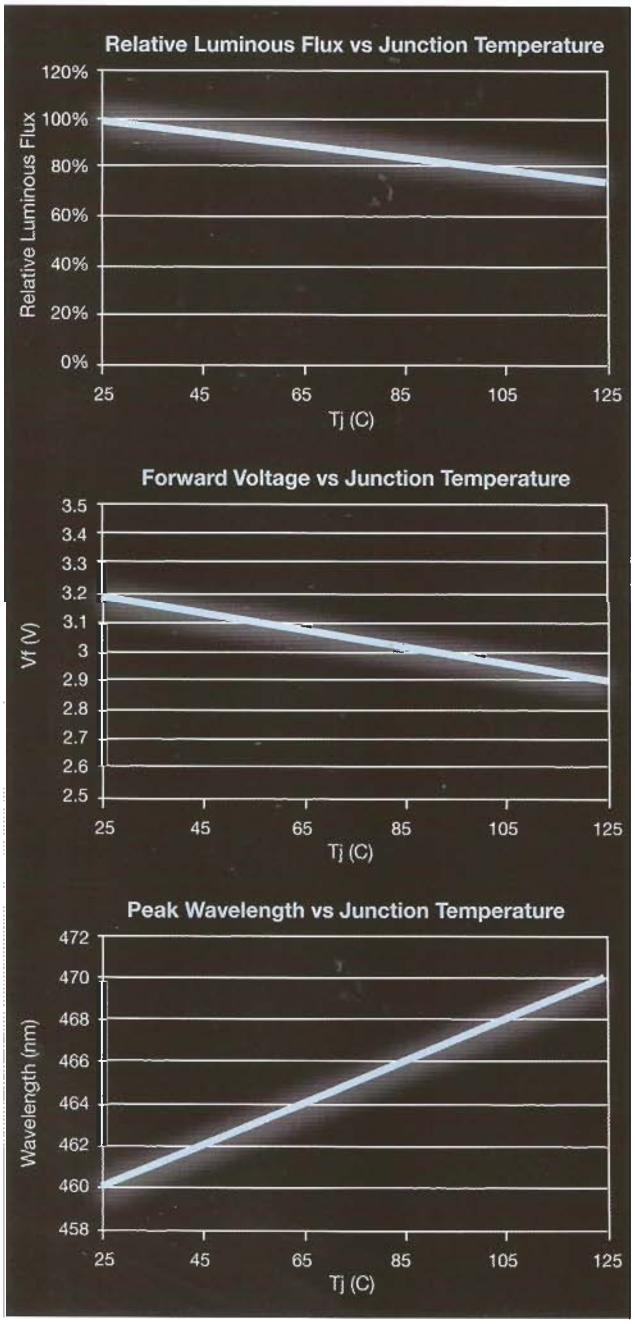

Figure 1: Effects of T_J on LED characteristics

To reduce the impact of heat, let's rethink the way an application need is addressed. For example, replacing incandescent and compact fluorescent bulbs with LED bulbs doesn't make much sense in many cases. This product path is chosen to shortcut the process of replacing fixtures, but it makes thermal management difficult to impossible. As a result, the LED bulbs are not bright enough for most of the applications requiring bulbs. It is not just the physical constraint of removing heat from the bulb itself; much of the time, bulbs are installed in enclosed spaces such as can lights or in ceiling and wall fixtures. Designing products that rely on the end-user for proper thermal management leaves much to be desired.

New fixtures and lighting expectations may be necessary to best manage and apply LEDs. The conversion to LED lighting will be slower than many hope or claim. Better to accept that idea than to attempt to force change. Let LEDs be a part of lighting evolution, without a revolution. The LED industry does not want to create a stigma about its technology through misuse and wait years for a recovery. Consider the early impressions of fluorescent lights, for example.

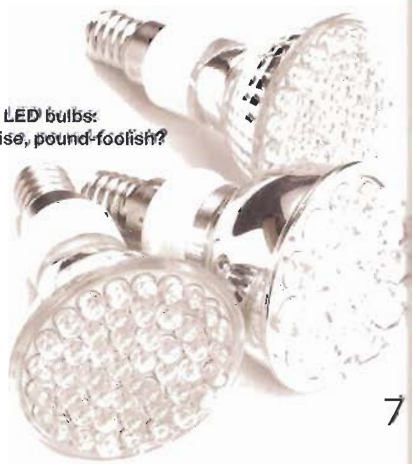

Figure 2: LED bulbs: penny-wise, pound-foolish?

Cool Design

The purpose of thermal management is straightforward: decrease the difference in temperature between the junctions of the LEDs and the ambient environment, ΔT_{JA}. Conventionally, reductions are achieved by increasing the net thermal transmission of all thermal paths from junction to ambient, in other words, increasing W/m·K. However, that's half of the process—reducing the total thermal watts is equally effective at cutting down junction temperature. Aspects of optical, electrical, and mechanical design not normally associated with thermal management are explored here. In each case, approximate effects on ΔT_{JA} or ΔT_{CA} (case to ambient temperatures) are considered.

Higher efficacy components offer gains in performance that significantly reduce thermal strain. A premium paid here directly accomplishes the most obvious changes: reduce the heat generated per watt and cut the number of watts applied. For example, 10% greater efficacy reduces ΔT_{JA} by 13%. It seems like a no-brainer to not pay a hypothetical 20% premium to increase efficacy by only 10%, but the net cost may actually be reduced in the long run by starting with higher efficacy components, even when they seem cost-prohibitive. Keep in mind that this premium exists at the time of design, but will diminish relatively quickly within the product life cycle. Having higher efficacy components from the beginning allows for a more streamlined design, cutting some cost out of the mechanical and electrical aspects, as well as reducing form and easing fit. In the long run, even more efficient components will become available, making thermal components less and less critical.

Adding LEDs can have the same impact as increased efficacy. Though it generally seems cost-prohibitive, adding components relieves the thermal load for each emitter and improves efficacy for the system overall. When 10% more components are used to produce the same number of lumens, ΔT_{JA} decreases by 5% because of the change in efficacy.

Rethinking the way light is currently delivered offers the opportunity to spread LEDs away from each other—here's the mistake made by cramming LEDs into bulbs or tubes. If the design is already limited by these old lighting conventions, thermal management will be challenging. Figuratively speaking, LEDs placed on thermal islands rather than one continent will have far less apparent thermal load. A nifty example would be streetlights. When you shift the streetlight from a concentrated source in the cobra head to isolated sources along the arm, concerns about thermal management are eliminated. The streetlight no longer needs to support the large cobra head, so the form it takes is reduced and simplified. Depending on how far apart the LEDs can be, the differences in ΔT_{JA} vary greatly, but a nominal reduction would be 10% for designs that shift the light source from the form of a light bulb to the form of a reflector housing or fixture for that particular light bulb (i.e. spread the LEDs from a 2-3" diameter spheroid to a 5-6" diameter spheroid).

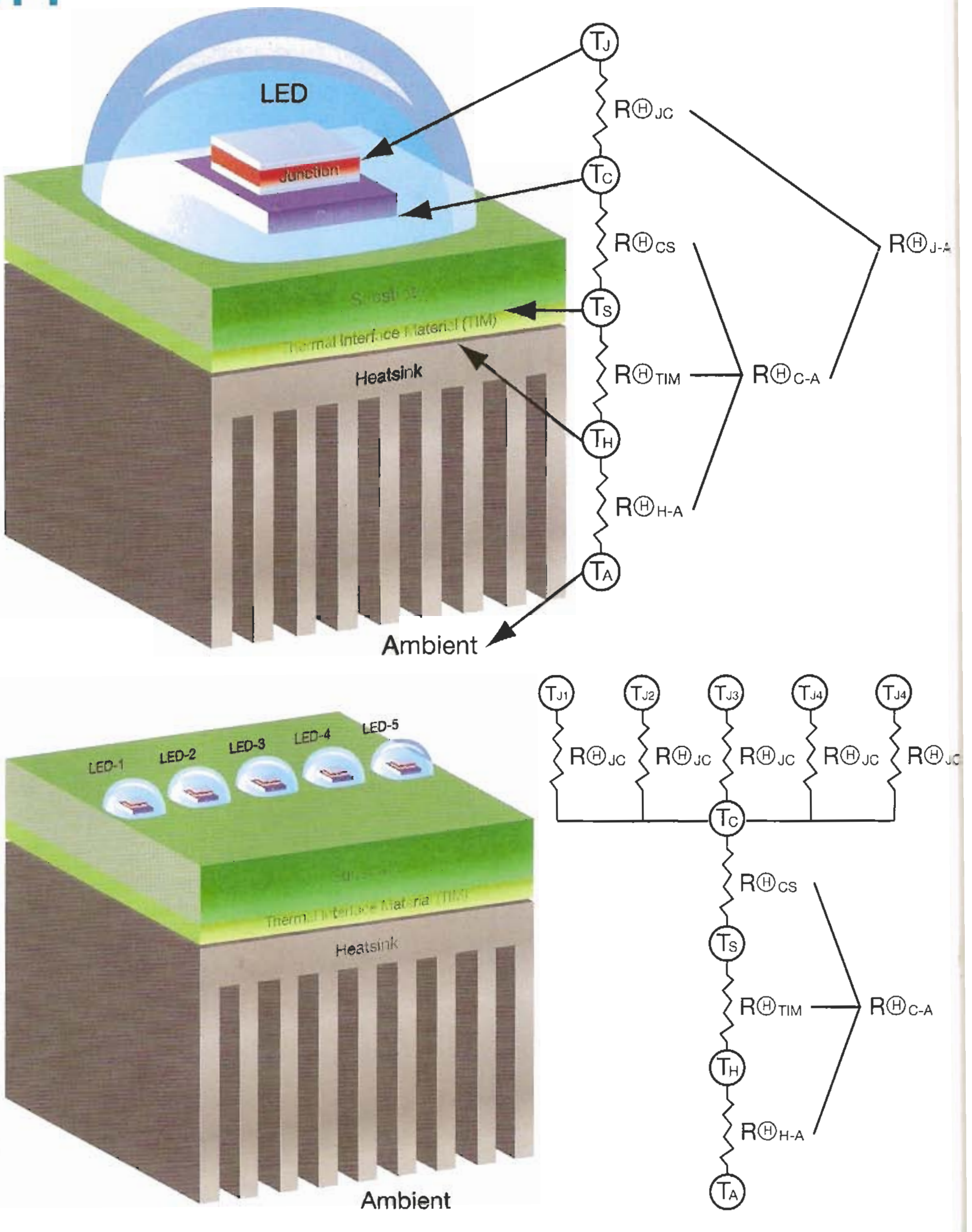

Figure 3. Simplified models of LEDs and their thermal management materials. Spreading the heat among more LEDs with lower ΔT_{JC} acts to reduce the total ΔT_{JA}. Heat produced at the junction must pass through all of the "resistors" along the path to the ambient environment. Removing resistors or creating parallel "circuits" can be equally or more effective than reducing the values of the resistors.

LEDs offer the unique ability to incorporate secondary optics and achieve high transmission efficiency within reasonable space. The easy potential choices too often selected are to not bother with optics at all or use commercially available, off-the-shelf lenses. Paying a premium for a custom lens seems prohibitive, but the marginal gains in optical efficiency can also provide a net reduction in manufacturing cost over a product's life cycle. A 10% gain in efficiency—and consequently 10% lower ΔT_{JA}—is generally possible by implementing custom secondary lenses and higher-transmitting diffusers compared to standard optics. In applications where light can be specifically targeted for tasks, custom optics may achieve 30% higher or better efficiency by flattening intensity over the target area and sharpening the edges. Excess brightness in the target area and stray light outside of it waste electricity and add to the thermal management demand.

Virtually all LED products must convert or regulate input voltage and current to deliver the proper current to the components. The regulation circuit is too often located on-board with the LEDs. In this case, any heat dissipated by the regulator is managed by the same thermal system. Moving the regulation circuits away from the LEDs or using a separate power supply with constant current directly input to the LED board, reduces junction temperature depending on how much heat is dissipated by the regulators. For a 12V system, it is not uncommon for 15-20% of the power applied to the circuit to be consumed by the regulator and converted entirely to heat instead of light. If half of that heat is isolated from the LEDs, ΔT_{JA} is reduced by 10%.

The most common regulation circuits used are linear in design. They do not increase or decrease the input voltage used by the circuit to drive the LEDs. If 2.0V of voltage overhead need to be provided to the regulator and the input voltage is 12V, the efficiency of this regulation circuit is only 83%. Switching to a buck (output voltage less than input voltage) and/or boost (output voltage greater than input voltage) switching circuit may add 5% to the overall product cost but will achieve 93-95% efficiency. That difference accounts for a 10-15% reduction in ΔT_{JA}.

If switching circuits are cost-prohibitive or cannot be used for other reasons (such as magnetic interference), using higher input voltage with linear regulation achieves similar gains. A good example would be comparing LEDs run with 12V input and 36V input. In both cases, 2V are needed for the linear regulator. With 10V left, 12V allows a single circuit of three LEDs and 36V supports 10 LEDs per circuit. If all LEDs are driven with equal current, the 36V system uses 11% less power, which equates to almost 9% lower ΔT_{JA}. ΔT_{JC} (LED junction to LED case) is not affected by the regulation efficiency, only ΔT_{CA}. As a result, slightly less thermal improvement is observed compared to the electrical efficiency gain.

Redesigning lighting fixtures to better use LEDs opens the door to another improvement. The enclosure of the fixture itself will be the heatsink. This aspect may appear to be part of the thermal design, but it fits better into the category of mechanical elements that facilitate thermal design. Direct LED integration eliminates thermal interfaces and impediments. Since air is one of the better insulators, particularly when it is stagnant within an enclosed environment, removing spaces between the LEDs and the outside environment is a critical step. The impact on ΔT_{JA} cannot be specifically pinpointed, but it is larger than the effects of other design changes proposed above.

Various design changes incrementally improve thermal performance though they have nothing to do with selecting substrates, heatsinks, active cooling devices, or interface materials. Though each impact is small alone, as more of these changes are added the net improvement is profound, and the benefit of more expensive or larger thermal materials is reduced. Here are those changes and their nominal impacts on ΔT_{JA}:

- 10% higher efficacy LEDs, 13%
- Adding 10% more emitters, 5%
- Spreading the emitters apart, 10%
- Custom, high-efficiency secondary optics, 10%
- Switching from 12V and linear regulation to 36V or switching regulation, 10%
- Direct integration of LEDs to the enclosure or chassis, 10%

None of the changes seem large, but multiply them all together and ΔT_{JA} sees a net reduction of more than 45% and a net efficacy improvement of nearly 50%. The changes add 30% to the production cost and additional design time and tooling cost up front. However, similar junction temperature results are not possible by adding that r cost in thermal materials alone, and the ancillary efficacy improvement is mostly to improved LEDs and optics. It is nearl impossible to reduce ΔT_{JA} this much by the thermal materials and design alone. premiums necessary to squeeze extra W out of substrates, interface materials, an passive or active cooling devices often e the costs of most of these changes. Sm efficient functional design enables develc to avoid the pitfalls of overemphasizing tl management.

Conclusion

Thermal management is a fundamental p designing effective LED products, but pre thermal materials and components serve band-aid the problem rather than address as best as possible. If applications are we defined and products are developed with open mind that ignores prevailing convent junction temperatures will not stand in the of successful LED implementation. When h is a problem, the options necessary to rec the predicament are not limited to applying extra cost to more thermally conductive materials or designs. Added cost can be directed to additional, better LEDs with sim effect. Non-recurring investments in optical enclosure design are effective without addir new production costs. Extra attention paid electrical design options such as regulation circuits, driver placement, and input voltage pays dividends in reduced LED temperature Each of these improvements has ancillary benefits beyond thermal performance—increased electrical efficiency and optical performance most particularly—that cannot be similarly achieved through investment in increased W/K alone. If, despite all efforts to maximize the functional design, premium thermal materials are still necessary to meet application's needs with LEDs, it's likely that application is on the fringe of LED applicabili and should wait for better LEDs tomorrow.

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