BY MIKE WOOD

# How do LEDs work? Part 2

## Understanding the challenges of heat management

IN THE LAST ISSUE we covered, while hopefully not getting bogged down too much into the physics, some of the basic principles of how an LED (Light Emitting Diode) produces light without glowing red hot or using an arc. We talked about PN junctions and how the light is produced at that junction as electrons fall from a high energy level down into a lower energy one and give off that excess energy as a photon of light. However producing the light is only a very small part of the tale. Getting that light out and keeping everything cool and comfortable is of equal—if not more—importance to producing a useful and usable light source.

> **“Everything you do eventually ends up as heat and there’s not a darn thing you can do about it.”**

I’ll continue this tale and talk about how the semiconductor materials are packaged to control heat and maximize light output and the innovation that is going in to that and heat management.

Although in almost every other way an LED is significantly different from other more familiar light sources, it shares one fundamental problem with all the others—too much heat. Heat management is the single biggest problem we have to deal with when designing a luminaire to use LED light sources. The perception might be that, because it’s a semiconductor-based emitter with high efficacy—a high ability to turn energy into light with a perceived brightness—heat emission is minimal. Unfortunately that’s not at all true and heat is still a huge problem. Current efficacies of commercially available LEDs are approaching 100 lum/W for a white LED and perhaps 80 lum/W for single colors such as green. Those figures sound and are very good compared to conventional light sources, but still fall a long way short of what is theoretically possible.

The maximum possible efficiency for a white source is not an easy number to pin down as it depends on the color temperature we want as well as the CRI we are prepared to live with, and you also have to integrate under the photopic curve to allow for the eye’s different sensitivity to different colors. However, very roughly, the maximum possible efficacy is about 260 lum/W for 3200 K black-body white light. Let’s compare that with the efficacies of real light sources. The very best incandescent lamps have efficacies approaching 30 lum/W which is about 11% of this theoretical maximum. *(Luminous efficiency is usually expressed as a percentage of the theoretical maximum. For our incandescent lamp that is 30 / 260 = 11%.)*

On the same basis a 100 lum/W white LED will be about 38% efficient—much better than the incandescent, but it still means that over 60% of the supplied energy is being emitted as heat. Our green LED is even worse; the theoretical maximum output for a monochromatic green light right at the peak of the photopic curve at 555 nm is 683 lum/W so our 80 lum/W green LED is actually less than 10% efficient and very similar to our incandescent lamp with 90% of the supplied energy appearing as heat.

Heat is always where energy ends up. It’s the end of the line for energy and a fundamental of thermodynamics. You can pretty much paraphrase the first two laws of thermodynamics as “Everything you do eventually ends up as heat and there’s not a darn thing you can do about it.” Or, as Sting and The Police almost put it:

> Every breath you take
> And every move you make
> Every bond you break, every step you take
> . . . ends up as **heat**!

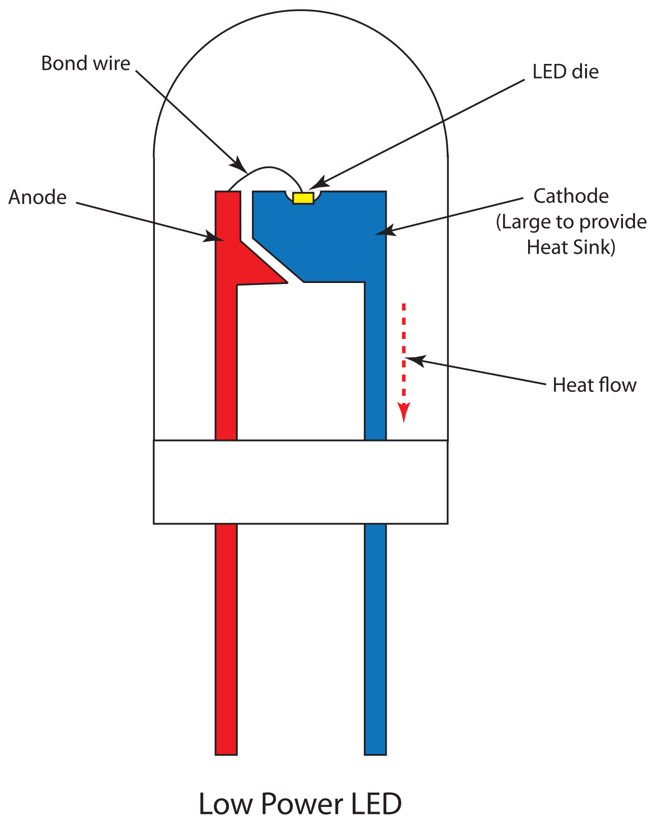


Figure 1 – Low power LED package

Efficient thermal management of the luminaire and the enclosed LED package present the most fundamental design challenges for anyone involved in LED product design and decisions made here affect the efficiencies and success of the entire project.

Apart from $I^2R$ losses in leads and connections, the majority of the heat generated is produced within the junction of the LED, just where it's the most difficult to get out. As is often the case with engineering design there are two conflicting requirements: to maximize light output we want to leave the LED die as open and unrestricted as possible, whereas for maximal heat transfer we want to surround and connect it with efficient thermal conductors. We clearly need to leave the top of the device as open as possible for light to exit so, in most cases, heat only has one path out of the LED; via a heat slug to the bottom of the LED package to the PCB. The top of the package is sealed, often with optical materials that are poor thermal conductors, trapping the LED die itself in a sealed package like a small oven.

An awful lot of R&D and design goes in to reconciling these conflicts to produce the brightest and most efficient products. Fundamentally the goal is to get the heat out of the bottom of the package as rapidly as you can while simultaneously collecting and controlling the light output from the top.

A low power LED such as that illustrated in **Figure 1** produces a small amount of heat and the large cathode and lead wires are sufficient to conduct that heat away from the die.

If you take a look at one of these familiar low power 5mm package LEDs through a magnifying glass you'll see that the cathode lead wire is much larger than the anode so that it can provide a heatsink to the die and assist with that heat conduction. The LED die is bonded directly to the cathode lead wire, often with a silver-loaded epoxy which is a good conductor for both heat and electricity. As long as the lead wires, particularly the cathode, are soldered to a good heat conductor such as the copper traces on a circuit board then there is enough heat flow to keep everything cool. The thermal resistance of such a heatsink and its connections is about 250 °C/W which means that for every watt of heat that is dissipated the temperature at one end of the heatsink will be 250°C higher than the other. At 100 mW or 0.1 W this represents a 25 °C temperature difference between the LED die and the circuit board which is fine—but what about 1W and 5W packages? Now we have 50x the amount of heat to get rid of and a simple 250 °C/W lead wire requiring 1,250 °C temperature gradients won't do the job anymore!

**Figure 2** shows a stylized diagram of the basic arrangement in high power LED packages. *(The actual die and connections are often much more complex than this but this shows the basic heat flow.)*

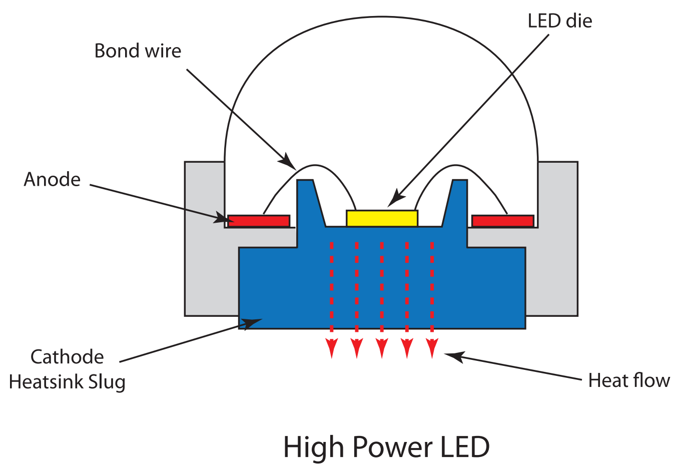


Figure 2 – High power LED package

Here the LED die is mounted to the large cathode heatsink slug *(often through a submount that provides electrostatic discharge protection)*. High powered surface-mount LED lamps are completely reliant on the thermal efficiency of this slug, which has to be bonded to an underlying circuit board to provide an efficient heat path from the LED. The circuit board itself may have much thicker than usual copper pads or may be a thin layer of insulating epoxy material on top of an aluminum core; it could even be some composite material such as a heat conducting ceramic or other esoteric material. Whatever it is, the goal is minimal thermal resistance while providing a stable substrate for providing the electrical connections and mounting the package. The heat dissipation problem doesn't stop there though; the heat has to be

> **"A thing accursed or consigned to damnation or destruction . . ."**

led away from the circuit board, usually to a connected heatsink.

We are also starting to see real innovation in what happens next to that heat energy. We need to get it as far away from our LEDs as we can. The easiest way to do that is through fans, but those are anathema to our industry. *(Anathema is the perfect word—it's defined as "a person or thing accursed or consigned to damnation or destruction," which I think describes pretty well the reaction of many lighting designers to noisy fans!)* That means either large passive heatsinks or some other quieter method of active cooling. A couple of manufacturers have experimented with Peltier cooling systems, which are semiconductor heat pumps, while others are looking at heat pipes such as those used in many computers to keep the main processor chilled. **Figure 3** shows the basic principle of a heat pipe—it uses exactly the same principle as a refrigerator or HVAC system where a volatile fluid is evaporated taking up heat from its surroundings to do so and then condenses back to a liquid again in another location giving up that heat. In the case of a heat pipe there is no pump or compressor involved to move the liquid and it instead relies upon capillary action in a wick or pipe to move the fluid. The heat comes from the LED slug and is transferred via the evaporated vapor to a large heatsink where it condenses back to a liquid again. I expect we'll see many other innovations in this area as time goes on—should be interesting!

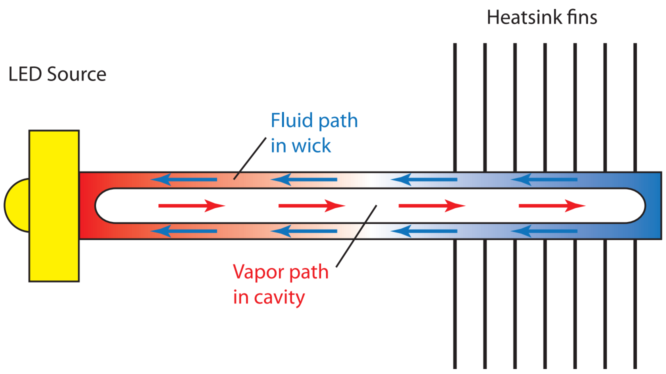


**Figure 3 – Heat pipe**

But why the big fuss about heat in the first place? When an incandescent or discharge lamp runs too hot the result is usually a shortened life, but the effects of too much heat in an LED system can be subtler and more insidious. As well as also losing life with increased temperature, the quantum efficiency of LEDs is temperature sensitive so that, as the temperature rises, the output drops. The effect is relatively small with blue and green LEDs, but can be very significant with ambers and reds. In fact an amber LED can easily lose 50% or more of its initial output as it warms up from room temperature to an operating point around 80°C. Just to compound the problem the color of the LED moves with temperature as well. If you recall from the last article the wavelength of the light emitted is determined by the width of the energy band gap that the electron drops across. The width of this band gap is affected by temperature and shrinks as the temperature rises. This shrinkage means that the energy emitted by the electron as it drops across the gap also shrinks, which results in a lower energy, or redder, photon being emitted. I discussed the results of this red-shift effect in the Summer 2008 issue of *Protocol* in an article entitled "When white light isn't white—Part 2" and the loss of output with temperature in "It's not easy being green" in the Winter 2009 issue of *Protocol*. We've now worked full circle from those end results to explain the physics of why this happens.

This is all really just scratching the surface of the problem. It seems that just about every day a manufacturer finds a new way of packaging an LED die to improve the heat transfer. This might be by the materials used, or the way the die is shaped, or the method of connecting the die to the substrate, or any of a thousand other small tweaks. Whatever the method the goal is simple: the more heat you can get out of the package the more power you can put into it.

Well, that's about it for heat management. In the next issue we'll talk about light extraction and how you actually get that light out of the middle of the semiconductor sandwich. Strangely enough, as we journey through surface textures, total internal reflection and photonic lattices we will end up back with a natural phenomena: butterfly wings. ■

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