BY **MIKE WOOD**

How do LEDs work?

A little physics; a little basic semiconductor theory

CHATTING WITH SOME COLLEAGUES at the USITT show in Cincinnati last week it occurred to me that, although we've dug into many LED topics in this column, one thing we've never talked about is how the darn things actually work. Most of the light sources we use in entertainment luminaires produce light using techniques we are familiar with from experience and natural phenomena. We understand that if you heat an object to a high enough temperature then it starts to glow red and emit light, so the light output from a filament in an incandescent lamp isn't at all surprising. Similarly we've all seen lightning streak across the sky and can make the mental connection between that and a discharge lamp. Fluorescent lamps are a little harder to explain, but again they rely upon effects seen in nature—a plasma discharge and fluorescence converting the ultra-violet emissions from that discharge into visible wavelengths. Similar fluorescence is seen in many natural organisms both in plants and in animals, being particularly common in ocean dwelling life forms. You don't have to go scuba diving to see examples of natural fluorescence though, many butterflies have fluorescent pigments and I'm sure everyone has noticed their finger nails glowing under UV or black light on stage or at Halloween. Although not quite as bright as finger nails, other keratin based substances such as wool and hair exhibit the effect as well.

All of those are readily understandable but what on earth is going on inside an LED to make it emit light? It isn't any of the phenomena we've just mentioned and doesn't involve heat (except as a by-product), an electric arc or fluorescence. Instead it's a very low level sub-atomic effect produced by the movement of electrons within energy bands inside the device. I'm not going to dig too deeply into the physics of this (even if I knew it) but it's worth taking a closer look at what's going on.

LEDs are more properly known as Light Emitting Diodes and, as the name suggests, normally consist of a single p-n junction diode. But, hang on a minute, what's a diode and what's it got to do with emitting light? A diode is the basic building block of solid state electronics and is the simplest possible semiconductor device. The fundamental electrical property of a semiconductor diode is that it only allows electric current to flow in one direction, but how does it do that? Most semiconductors are made of a poor conductor such as silicon and germanium that has had atoms of another material deliberately added to it. This process of adding these impurities is often called doping. The original pure material is electrically neutral and has exactly the right number of electrons associated with each atom, meaning there are neither too many nor too few electrons and so there are no free electrons available to carry electric current. However the doping process of adding extra atoms moves some of the electrons in the material and can leave a material with either more free electrons than it needs in some parts or with too few, thus leaving positively charged holes where electrons can fit. Both these changes make the material more able to conduct an electric current. In normal terminology the material with extra electrons is called N-type, since those extra electrons are negatively charged particles, and the material with a deficit of electrons (or surfeit of holes) is called P-type. Because of the electrostatic attraction between positive and negative particles free electrons are attracted towards the positively charged holes.

A diode is a very simple device which uses one piece of N-type material (with an excess of electrons) connected to another piece of P-type material (with an excess of holes). The area where the two materials meet is known as the junction. **Figure 1** shows a

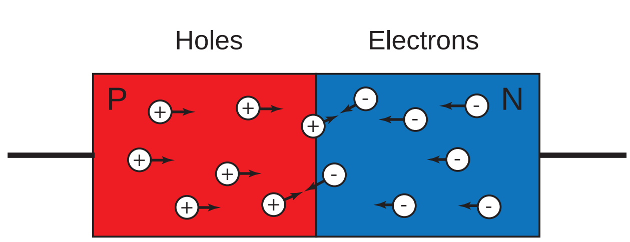

Figure 1 – Initial diode formation

schematic illustration of what this assembly might look like at the moment the junction is formed.

Initially the N-type material (shown in blue) on the right has too many electrons and the P-type material (shown in red) on the left has too few, this causes an imbalance and the electrons and holes will tend to move towards each other across the junction attracted by their opposing electrostatic charges. Where a hole and electron meet they will cancel out forming a neutral area of paired holes and electrons. This will continue until the situation shown in **Figure 2** is achieved with the formation of an area called the depletion zone (shown in yellow) on either side of the junction where everything is nicely balanced out and all the surplus holes and electrons are used up.

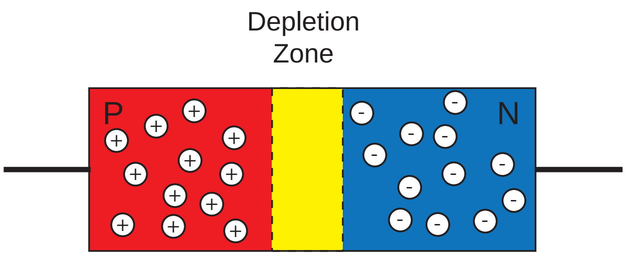

Figure 2 – Depletion zone

In the depletion zone the semiconductor material is essentially restored to its original, pre-doping, state where there are no free electrons to carry current so it behaves, once again, as an insulator. In this state, with no externally applied voltage, the diode is an insulator which would allow no current to pass. To get current flowing through the device you have to encourage the free electrons on the right in the N-type material to move towards the P-type material on the left and vice-versa and overcome the yellow depletion zone. By connecting the P-type material to the positive terminal of a power source and the N-type material to the negative terminal as shown in **Figure 3** an electric field can be created across the diode so that the free electrons will be attracted towards the positive electrode and repelled from the negative one. Similarly the holes will be attracted towards the negative electrode and repelled by the positive one. Get the applied voltage high enough and the electrons that are happily sitting in holes in the depletion zone will be shoved out, the depletion zone will be eliminated, and everything will start moving again.

> "… what on earth is going on inside an LED to make it emit light?"

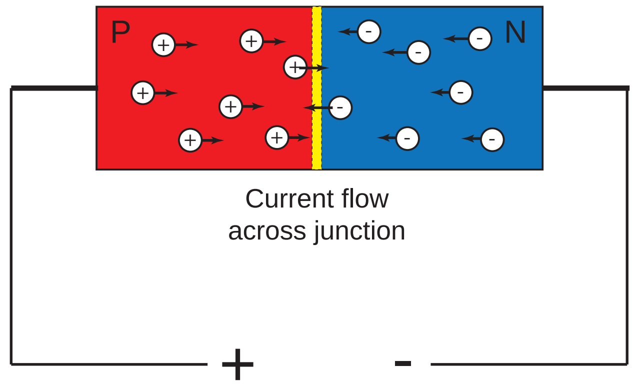

Figure 3 – Current flowing

If you connect the voltage the other way around with the positive terminal connected to the N-type material and the negative terminal to the P-type material then just the opposite happens—the electrons retreat even further towards the positive electrode and the holes towards the negative making the depletion zone even larger. In this state the diode becomes an even better insulator and won't conduct electricity at all.

Okay, you might say, this is all very interesting, but I'm not that interested in the physics. When do we get to the light emitting part of this particular diode? Don't worry. This is just about all the theory we need to understand the principles of the process but there's no avoiding a little delving in the bowels of basic semiconductor theory.

> **". . . there's no avoiding a little delving in the bowels of basic semiconductor theory."**

In a light emitting diode everything behaves exactly the same as in the diode illustrated here and, in fact, most diodes are *light emitting* to some extent, but the light might be invisible. LEDs are operated in the connection shown in **Figure 3** *(known as forward biased)* where the diode is connected such that current flows through the device and electrons and holes are continually moving and meeting at the junction and being replenished from the applied electric voltage. It's what happens when those electrons and holes meet up that actually generates the light.

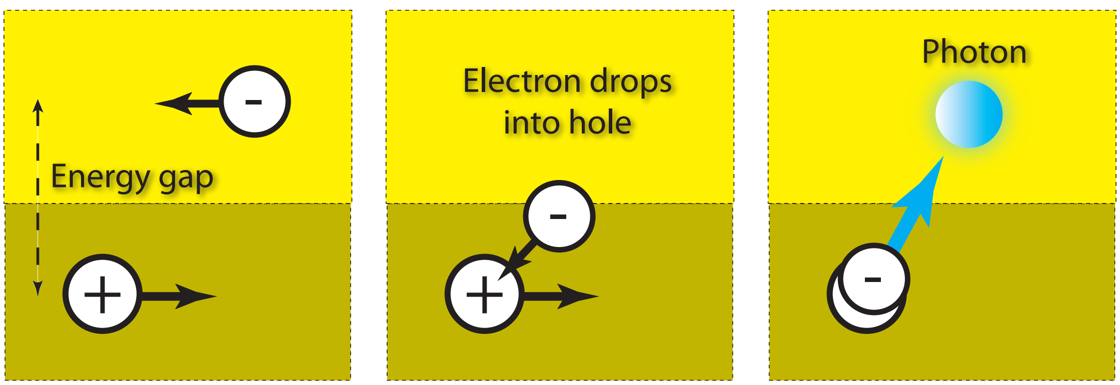

Figure 4 – Electron and hole combine

As shown diagrammatically in **Figure 4** a free electron in the conduction band of the semiconductor has an energy level higher than the energy level of the hole. When the high energy electron drops into a low energy orbital in the hole it has to lose that excess energy somehow and, in this case, the energy is emitted as a photon, the basic unit of light. The difference in the energy levels, or the height of the fall, will determine the energy of the photon and the higher the energy of that photon the higher the frequency of the light. As mentioned earlier many semiconductor diodes exhibit this effect, it's just that the band gap energy level in most materials is fairly low so the light emitted is of very low frequency, outside of the visible range down in the infra red. The fundamental difference with LEDs is that the semiconductor materials are chosen such that the energy drop is much higher and the photon emitted is high enough in frequency to be visible. The key again is that the higher the energy of the photon, the bluer the emitted light. Most semiconductor materials tend to exhibit a single size energy band gap, which means that all the photons are emitted with approximately the same energy level. This results in the narrow band of almost monochromatic light that we are all familiar with from LEDs.

When you look at an LED chip it looks like the whole thing is glowing and emitting light. However, from the description above you can see that actually photons are only emitted from the area where electrons and holes combine near to the junction of the LED where the two materials, the N-type and the P-type, join. In other words, it's the meat in the sandwich that produces the light. Unfortunately, this is not ideal, as for the light to exit and be useful it now has to pass through one or the other layers as well as whatever is used for an electrical connection. The photons also may hit another electron on the way out and be absorbed in the process of knocking it out of an orbital into a higher energy level. In non-LED diodes even if photons are produced most of them are absorbed by the semiconductor material in this way and end up as heat. However, in an LED the materials used for the semiconductor layers, connection layers, and packaging are carefully selected to be transparent and thin enough that many of the photons escape as usable light. The choice of these semiconductor materials is critical. To be a good LED material they have to possess the right energy gap for the light color you want and be transparent to that particular color of light. In the early days of LED research it proved relatively simple to find materials that moved the frequency up from the infra red into the visible red, so red LEDs appeared first with gallium arsenide (GaAs) based devices in the fifties. Research into complex materials with a high enough energy gap to produce greens and blues took a lot of research, and, as we know, it wasn't until the early nineties that Shuji Nakamura of Nichia (now on the Materials Department faculty at the University of California at Santa Barbara) demonstrated a gallium nitride (GaN) material that was capable of producing high output blue light. Strangely enough, although we now have materials that have the right height band gaps to generate long wavelength light in the reds and deep ambers, and others with larger band gaps that generate short wavelength light in blues and ultra violet, there is still a big gap in the middle around the yellows and greens where no efficient materials have yet been developed. Ironically, this is right in the region around 555 nm where the human eye is most sensitive and LEDs would be really useful. This gap extends to around 625 nm as, although amber LEDS are available, their performance and stability is poor. Considerable fame and fortune awaits the researcher who manages to plug this hole and patent the process! In the meantime developments in phosphor assisted LEDs where amber or yellow phosphors are excited by a deep blue or UV LED are helping fill the visible gap.

> **“. . . it’s the meat in the sandwich that produces the light.”**

Next time I’ll continue this tale and talk about how the semiconductor materials are packaged to control and maximize light output and the innovation that is going in to that and heat management. Strangely enough as we journey through photonic lattices we will end up back with a natural phenomena; butterfly wings. ■

Mike Wood is President of Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the Treasurer and Immediate Past President of ESTA. Mike can be reached at 512.288.4916.

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**!

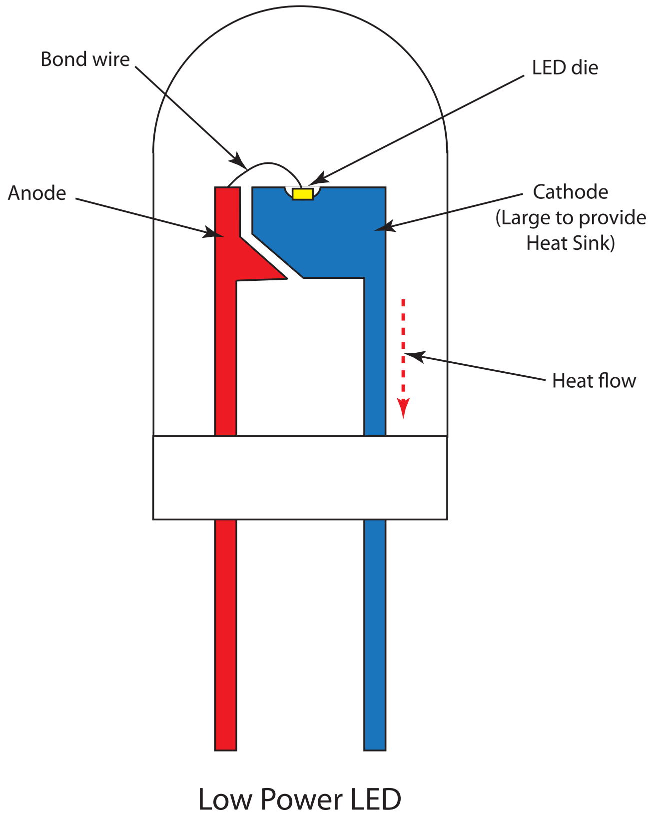

Figure 1 – Low power LED package

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.)*

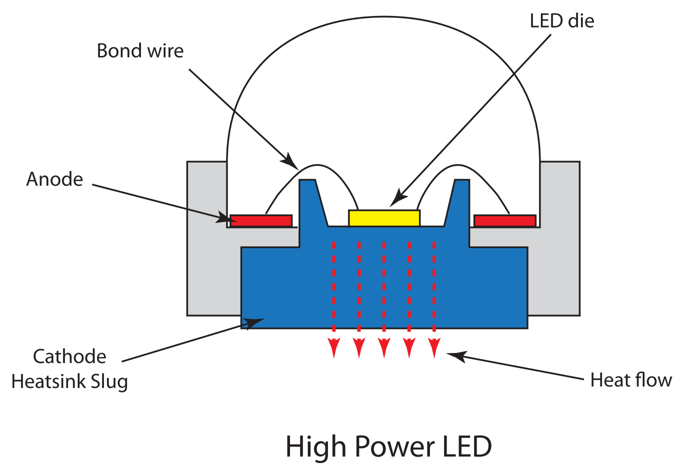

Figure 2 – High power LED package

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

“A thing accursed or consigned to damnation or destruction . . .”

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!

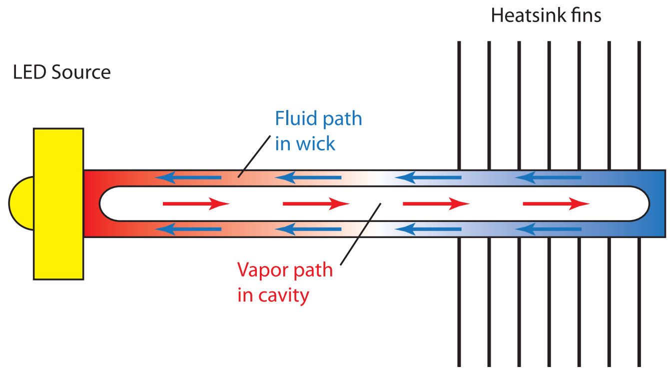

Figure 3 – Heat pipe

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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BY MIKE WOOD

How do LEDs work? Part 3

A look at the science and physics behind LEDs

IN THE LAST TWO ISSUES we covered the basic principles of operation of how an LED (Light Emitting Diode) produces light and how, even though the mechanism for producing light is completely different from other sources, some things never change, and heat is still public enemy number one. In this article I want to discuss how that light finally gets out of the LED die and the problems—and solutions—associated with that process.

As we discussed in the earlier articles, the light in an LED isn't produced on the surface of the LED die. Instead, it's emitted from the area where the P and N layers meet called the junction. This is very inconvenient, as the junction is right in the middle of the die, a bit like the meat in the sandwich, so how does the light actually get out of there? Firstly, it seems pretty clear that at least one of the layers making up the semiconductor has to be transparent to the wavelengths of light that the LED is producing! Without that, all you would have is a rather small heater. So now the light has to get out of the semiconductor, but that doesn't sound too bad if it's transparent does it? However, there's a huge "Gotcha" that can reduce the amount of light that escapes the die down to a tiny percentage of the original. That problem is TIR, Total Internal Reflection.

> **"… there's a huge 'Gotcha' which can reduce the amount of light that escapes the die down to a tiny percentage of the original."**

Total Internal Reflection

Sometimes TIR is our friend, sometimes it's our foe. Let's start off by explaining what it is. Total internal reflection is what can happen when light passes from an area of higher refractive index to one of a lower refractive index, such as when light passes from glass to air or water to air. If that light hits the boundary between the two media at right angles to the boundary, then it passes straight through and all is fine. As the angle between the light beam and the boundary increases the exiting light will be bent by refraction through a greater and greater angle until eventually it's bent so much that it refracts parallel with the boundary. Any increase in angle beyond that will result in the light being reflected back from the boundary as if it were a mirror. A very familiar example of this is the effect you get when snorkeling or scuba diving and you try and look up and out of the water as in **Figure 1.**

Figure 1 – Total Internal Reflection underwater (This is a photograph from a recent vacation in Mexico—little did the sea turtle know that he was going to be used as an example of TIR.)

Look above the sea turtle and notice that you cannot see much out of the water. Instead, you see clear reflections of the turtle from the boundary between the sea and the air caused by total internal reflection at that boundary. If the surface of the water were perfectly calm, then the mirror would be almost perfect. TIR is extremely efficient, and with clean flat surfaces you can expect almost 100% reflection. We take advantage of this in our optical technology. For example, TIR is how optical fiber communication systems contain light within the fiber. There's nothing special about the glass or plastic fiber itself, the light enters it at such an angle that it can't get out of the sides of the fiber; TIR keeps it bouncing back and forth as it travels along. Ironically, you also see extensive use of TIR lenses as the external optics on high power LEDs. Their high efficiency and immunity to chromatic aberration makes them perfect for the role.

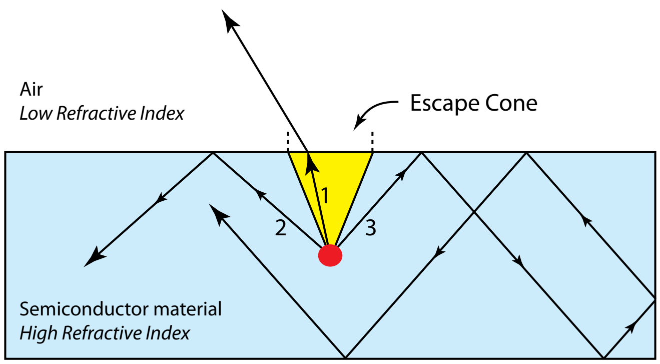

Figure 2 – TIR in a rectangular LED die

Back to LEDs – how does TIR impede the transmission of light out of an LED die? **Figure 2** shows a hypothetical LED die which is fabricated very simply as a rectangular block with the P-N junction horizontally across the center and its upper emitting face into air. In this figure the red dot shows an emitting point on the junction (in actuality the emitting region is an area, not a single point, but this simplifies the explanation). Looking first at light ray 1, you'll see it hits the boundary between the high refractive index

"... the light can never escape ..."

semiconductor material and the low refractive index air at an angle fairly close to the normal, or perpendicular, and so passes through the boundary with an angle of refraction bending the beam away from the normal just like any lens. This light ray is usable. Increase that angle, however, and very soon you reach the point where the light rays can't escape and instead get reflected back via TIR into the semiconductor. Ray 2 shows an example of that, while ray 3 continues the process and shows that once a ray has been reflected by TIR in a rectangular block, the light can never escape. It will hit every surface at an angle above the critical TIR angle and keep bouncing around forever, just like the light in an optical fiber. The yellow area in **Figure 2** shows the very small range of angles where a light beam can get through the boundary on that surface. In three dimensions, this region is cone shaped and often called the *escape cone.* In case you think I'm exaggerating how small that cone is in the figure, let's look at some real figures: for a gallium arsenide-based material (commonly used in red LEDs), which has a very high refractive index of 3.4, the escape cone has a half angle of only 17.1°, which means that only a little over 2% of the light can ever escape! Gallium nitride materials (blues and greens) are better, but still pretty poor; with a lower refractive index of 2.5, their escape cone has a half angle of 23.6° which equates to just over 4% output.

Early LEDs used for displays and indicators were like this with extremely poor outputs. Clearly, the TIR problem was a prime target for improvement, if they were ever going to be viable as light sources for illumination. All the work done in making the LED chemistry efficient would be a total waste of time, if only 2% of the light could actually get out! Fortunately, we can substantially improve on this by careful control of the die shape, encapsulation and other more advanced techniques.

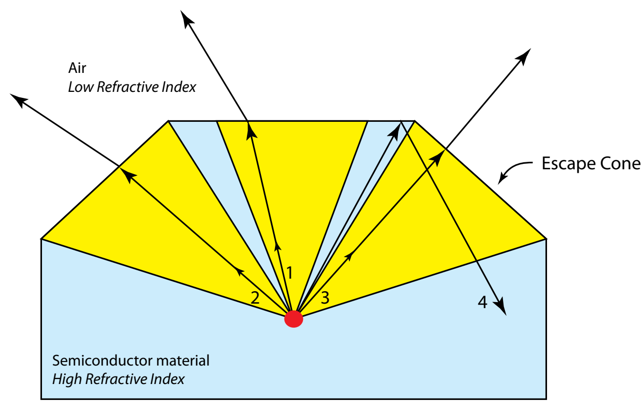

Figure 3 - TIR in a trapezoidal LED die

Figure 3 shows that a big improvement can be made just by cutting the top corners off the rectangular die. Now each of the facets at the top is angled so that the light rays hitting it are always at an angle much closer to the normal and so many more escape TIR. We now have a number of escape zones which add up to a much more efficient emitter, and, as you can see, rays 1, 2 and 3 all escape and become usable light. A simple trapezoidal shape like this is not perfect, though; ray 4 still hits an area where TIR bounces it back in again. It's also very much more complex to fabricate this shape of die. But let's not stop there, we can continue to make improvements by cutting the corners off again and again until we eventually end up with the hemispherical die shown in **Figure 4**.

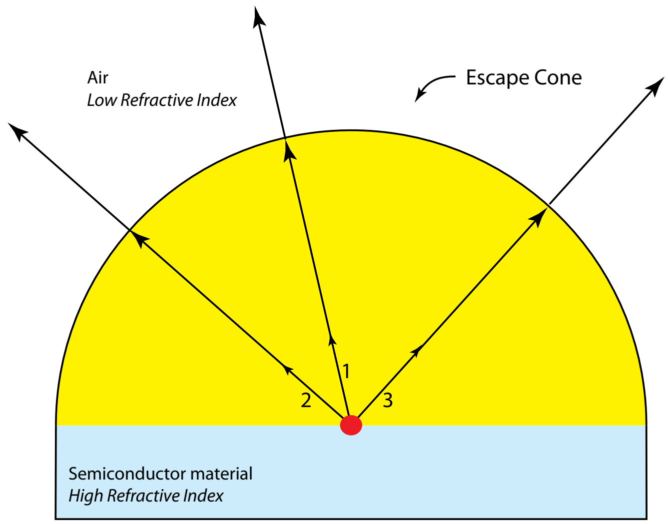

Figure 4 - TIR in a hemispherical LED die

Now all the light emitted in an upwards direction will hit the boundary at a normal angle and so will all escape with no TIR at all. Unfortunately, fabricating dies in hemispherical shapes would be extremely difficult and expensive. Semiconductor manufacture is essentially a laminar process, where you build up a series of flat layers by deposition or remove them by etching back, which doesn't suit these complex three-dimensional shapes. Is there nothing else that can be done?

Encapsulation

I'm sure you've noticed that many LED dies have a covering of transparent epoxy or silicon on top of the die. You may have thought this encapsulation was to protect the die. It does indeed provide protection, but it also can help with reducing TIR losses.

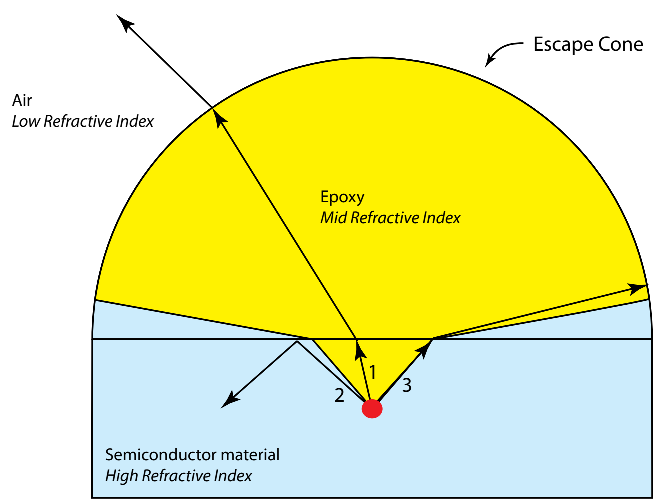

Figure 5 - TIR with epoxy encapsulation of the LED die

Figure 5 shows the same simple rectangular LED die shown in **Figure 2**, but with a hemispherical cap of an epoxy encapsulant on top of it. This encapsulant is chosen to have a refractive index that is between those of the semiconductor and the surrounding air. So, although we've doubled the number of boundaries from one to two, each one has a smaller difference in refractive index, and thus a larger escape cone. This is particularly helpful at the boundary between the semiconductor and the encapsulant. A simple encapsulant like this can improve the light extraction efficiency by a factor of 2x, taking our original 2% up to 4%. This is still not too good for light output, but is inexpensive and sufficient for many indicator style LEDs.

LED manufacturers have invested significant R&D dollars into improving light extraction figures, and much of the light output increase we've seen in the last few years from high power LEDs has come about because of this work. Different shapes and sizes of LED dies, different surface finishes, surface gratings using diffraction rather than refraction, anti-reflection coatings, and different encapsulants can all help. You may have seen dies that are inverted truncated pyramids, some described as flip chips and other strange names. These are all means of improving the light extraction.

Photonic lattices

One of the more recent improvements in light extraction has come from the inclusion of photonic lattices in the top layers of the junction. The idea was first proposed in 1987 by Eli Yablonovitch, now at the University of California at Berkeley, and has since spawned R&D efforts worldwide to expand and exploit the concept. The methods for manufacturing the crystals and the precise modes of operation are outside our scope (and my understanding!), but the interesting result is that long, thin, crystalline formations are embedded in the material, which to some extent act as diffractive waveguides and improve light extraction by redirecting and diffracting light out of the semiconductor.

Figure 6 shows a very simplified representation of the layout. The photonic lattice crystals in the upper part of the semiconductor sandwich tend to redirect the light along their length and thus much closer to the normal of the semiconductor/air boundary, avoiding TIR reflections back into the material. The very latest developments in this technology in real products from companies like Luminus Devices and Philips Lumileds are achieving light extraction efficiencies in excess of 70%—a far cry from the 2% efficiencies we started at!

In the last article I promised you butterfly wings—but how do we get from a discussion on extraction efficiencies of LEDs to the wings of Lepidoptera? Research in recent years has shown that

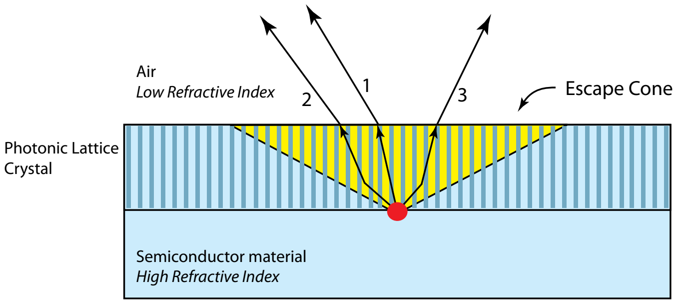

Figure 6 – Photonic lattice structure

the iridescent colors of various animals, including beetles and butterflies, are very often due to photonic crystals rather than any pigments. The size, shape, and pitch of these crystals, and their bumps and holes act to selectively absorb or reflect different wavelengths of light, and thus appear in different colors even though the crystals themselves are actually colorless. Additionally, because these photonic crystal arrays behave differently at different angles, just like the dichroic filters we are more familiar with, the resultant colors often iridesce and shift in a striking and alluring (at least to other butterflies) manner.

The science and physics behind LEDs is a fascinating and complex topic, and we've really only scratched the surface in this short series. It's also a rapidly changing topic, with regular significant breakthroughs in many areas. One thing's for sure: it's a topic we'll be returning to. ■

Bibliography:
Highly recommended but very technical book concerning the detailed operation of LEDs:

'Light-Emitting Diodes' by E. Fred Schubert published by Cambridge University Press (2nd Edition)

Mike Wood is President of Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the Treasurer and Immediate Past President of ESTA. Mike can be reached at 512.288.4916.