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.

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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.

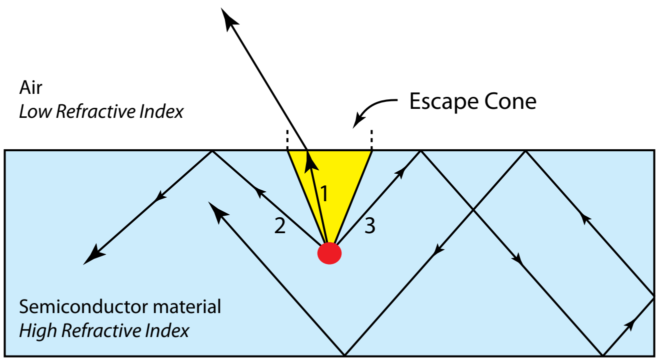

Figure 2 – TIR in a rectangular LED die

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.

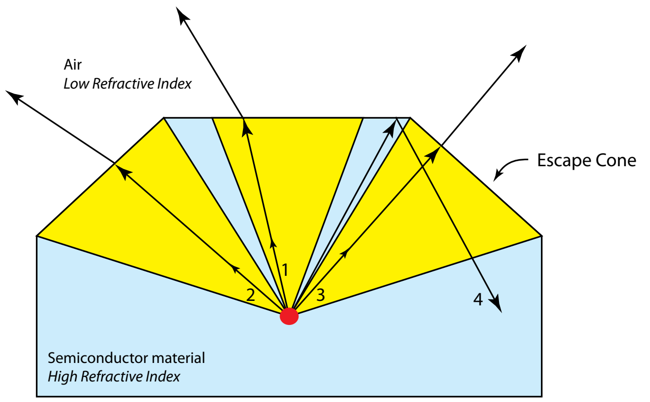

Figure 3 - TIR in a trapezoidal LED die

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**.

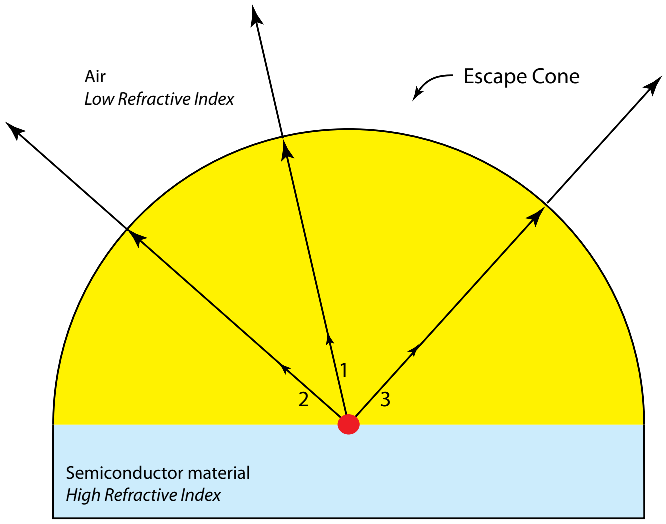

Figure 4 - TIR in a hemispherical LED die

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.

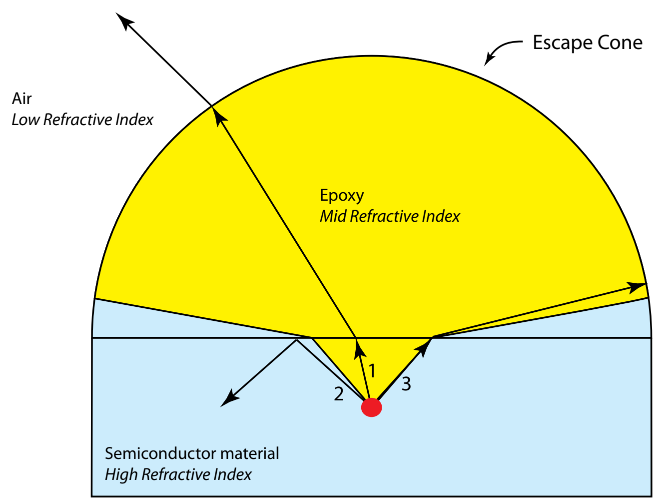

Figure 5 - TIR with epoxy encapsulation of the LED die

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

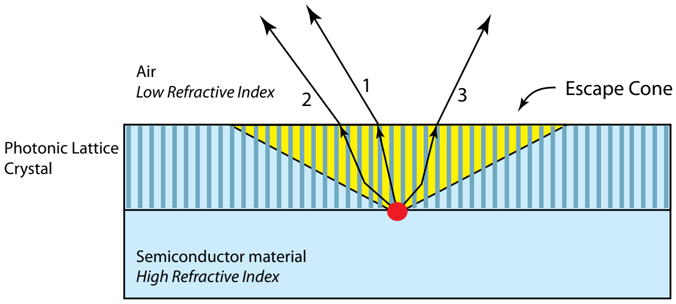

Figure 6 – Photonic lattice structure

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)

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