BY MIKE WOOD

How do LEDs work? – Patterned sapphire substrates

THIS ISSUE I'M CONTINUING MY IRREGULAR SERIES of articles talking about various aspects of the inner workings of LEDs with a discussion on patterned sapphire substrates (PSS). This topic links on nicely to some of those prior articles, particularly the Out of the Wood columns from *Protocol*'s 2009 Spring, Summer, and Fall issues. It also touches on my ongoing discussion of etendue, and why you can never win when dealing with the second law of thermodynamics. Karl Ruling suggested the topic, and I thank him for that.

So, what the heck is a patterned sapphire substrate, and why should I care? Well, let's start with the same figure I used in 2009, which demonstrated a fundamental problem in LED design: that of actually getting the light out from the middle of the high-refractive index material it's made out of into the air.

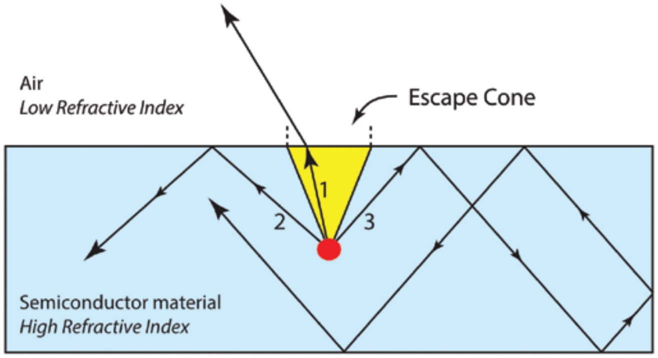

Figure 1 – Light escape cone

In **Figure 1** 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 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 total internal reflection (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.

Figure 2 expands that simplistic diagram a little to show some more detail. The emission area is actually a planar area within the semiconductor sandwich known as the depletion zone, so this emission and reflection is going on everywhere over the surface of the die. At the base of the semiconductor is a substrate, or base, on which the semiconductor layers that make up the LED are grown. Most commonly used for this substrate is sapphire.

Note: Sapphire sounds exotic because we know it as a gem stone, but it's actually quite a simple substance. Sapphire is aluminum oxide (Al_2O_3) also known as corundum. You've likely come across corundum used as an abrasive as Al_2O_3 is extremely hard, nearly as hard as diamond. It's used in this application as a semiconductor substrate because, as well as being hard, strong, easy to machine flat, and a good electrical insulator, it's also an excellent thermal conductor. A great mix of properties. Transparent when produced synthetically, the blue color in naturally occurring sapphires (and the red in rubies, which are another form of corundum) comes from impurities in the crystal lattice, not the corundum itself.

This sapphire substrate layer forms part of the structure and can also reflect light rays. In **Figure 2** the substrate is shown as flat, as it always was with semiconductors including LEDs.

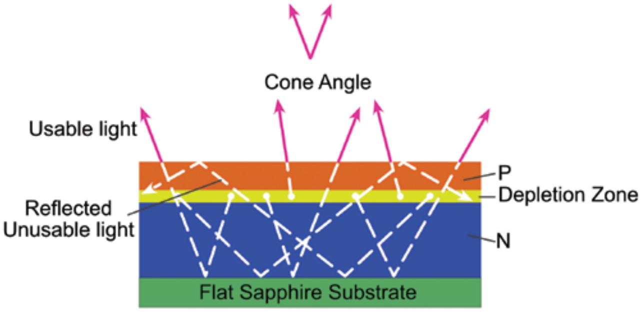

Figure 2 – Escape from flat substrate

> "What the heck is a patterned sapphire substrate, and why should I care?"

The cone angle of light that can escape can be very small in these circumstances, perhaps only around 20° or so, which means that most of the light never gets out.

One way of improving this situation is by roughing up that flat sapphire surface so it disperses light at various angles. This breaks the endless loop of TIR reflections and allows much more light to escape. **Figure 3** shows an example, the light may have to bounce around a few times but eventually escapes the grip of the TIR and escapes. The pre-textured substrate used to aid light extraction is known as a patterned sapphire substrate, or PSS.

The shape of the PSS also improves the growth of GaN crystals on top of it by reducing the imperfections or dislocations in those crystals caused by the mismatch between the GaN and substrate. This makes for better, and quicker, GaN layer growth. However, that's outside the scope of this article. For now, I'm just considering the reduction of TIR losses as that's a topic close to our lighting hearts, but you should know that PSS brings other advantages to LEDs.

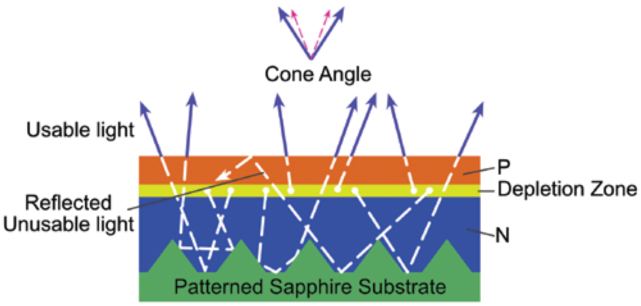

Figure 3 – Escape from patterned substrate

The good thing is that this technique can increase the usable light output from the LED by as much as 30% - 40%. The bad thing is that, as the second law of thermodynamics tells us, nothing in engineering or physics comes for free. Yes, we get more light out, but the overall cone angle of that light, and thus the etendue of the light source, increases. If all you need is light and you don't care what direction it goes in, then you can use all that extra 40%, however, if you have downstream optics or lenses, then it is likely that some of that extra light will be wasted because of its greater cone angle. Etendue always wins.

A lot of LEDs are produced as flip-chips where the entire structure is inverted after semiconductor growth and the light comes out through the substrate. Texturing can help here as well. **Figure 4** shows the basic structure of a flip-chip die. In this case after the semiconductor layers are grown onto the substrate the entire assembly is flipped upside down for use and the substrate ends up on top. Compare **Figure 4** with **Figure 3** which is a conventional, unflipped, design. Transparent sapphire is used as the substrate so it lets the light escape. However, it's still a much higher refractive index than the surrounding air, so the problem of TIR and an escape cone still exists. I haven't shown all the internal light rays here as it gets confusing, but the texture on the sapphire helps in the same way as before. Light will bounce around the structure and escape.

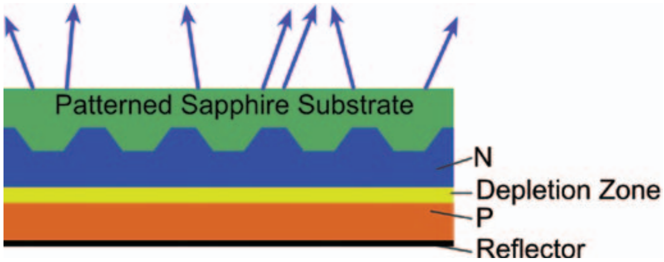

Figure 4 – Flip-chip structure

Note that the mount underneath the bottom semiconductor layer must be reflective material so that any light going in that direction is reflected back.

> "One obvious disadvantage is that silicon is not transparent . . ."

Before the advent of PSS, structures like **Figure 4** used to be manufactured by first depositing the semiconductor material and flipping the chip, then removing all the sapphire substrate by ablating it with a laser. The final step was to roughen the exposed N surface layer using an etch process to provide a textured reflection surface. This gave the desired 40% improvement in light output, but with a very complex and expensive process. You will see products manufactured using this technique referred to as TFFC, or Thin-Film Flip-Chip and it was the most efficient technique four or five years ago (which is an eternity in LED development). The introduction of PSS where the sapphire is textured before any layers are put down is much simpler and cheaper to manufacture and the overall cone angle of that light, and thus the etendue of the light source, increases. If all you need is light and you don't care what direction it goes in, then you can use all that extra 40%, however, if you have downstream optics or lenses, then it is likely that some

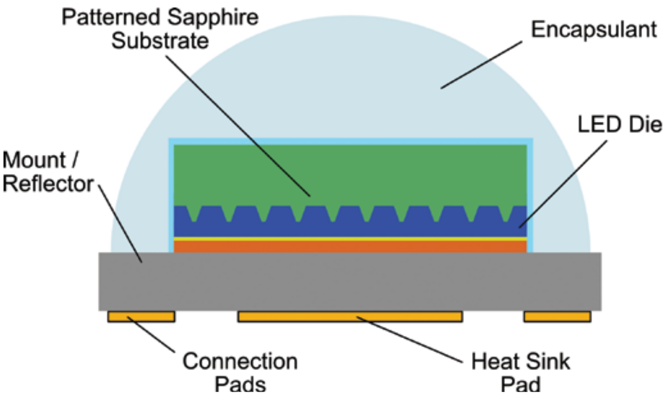

Figure 5 – Packaged flip-chip PSS LED

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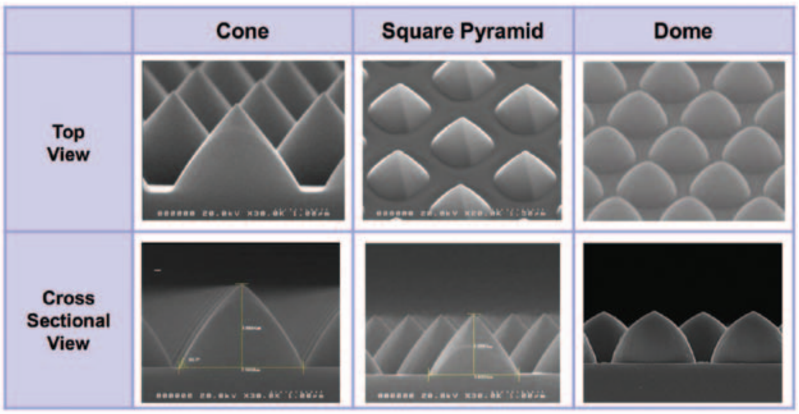

Figure 6 – PSS patterns

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Figure 5 shows the end result when a flip-chip PSS die is packaged.

You get all the advantages of flip-chip with easy connections and good heat transfer straight out of the semiconductor layer with the additional benefit of PSS proving significant improvement in light output. Most of the LEDs you are using today will be constructed like this as LEDs built on PSS now represent over 80% of production.

The PSS technique has a further advantage over the prior etching technique in that leaving the sapphire substrate in place makes for a much stronger die that can be used directly in a chip-on-board (COB) application without any mount at all.

All my figures wildly exaggerate the size of the patterns in the sapphire so that you can see what's going on. In reality, these structures are tiny with each of the textured shapes rising only a micrometer or so from the surface. **Figure 6** shows some electron micrographs of examples from Rubicon Technology of the shapes and geometries that are being used. Pyramids, cones, hemispheres, and many combination shapes are being tried. The spacing and size is critical, both to their effectiveness (particularly to the promotion of good GaN crystal growth and the reduction of dislocations or cracks), and to how difficult they are to manufacture.

This isn't the end of it. As I said, the structures in common use in PSS today are one or two micrometers high, but work is also going on with more complex nanometer sized patterns that have additional advantages. Just in case I haven't been clear about how small these structures are and thus how far out of scale the figures in this article are, think about the wavelength of the light they are reflecting. Green light has a wavelength around 500 nm, or half a micrometer, so these "large" structures are only three or four wavelengths in height. The smaller nanometer sized structures are much less than the wavelength of the light the LED is producing and thus produce their scattering by diffraction rather than reflection.

There are also potential advantages in applying the pattern to both sides of the substrate. More expensive to manufacture, but might be worth it. **Figure 7** shows the concept. Yes, even higher etendue, but higher output to match!

Unfortunately, the properties that make sapphire a good material for this task, its strength and hardness, also make it hard to machine. Sapphire is resistant to many chemical etchants and is very difficult to process. Various techniques are used to produce these patterns including plasma dry etching or depositing nanoparticles, but it still isn't easy. The LED manufacturers would much prefer to use silicon instead of sapphire, it's much cheaper to produce, easy to etch, and can be made in larger wafers—300 mm diameter is common as opposed to the 75 mm of sapphire. It would also have the advantage of making it much easier to integrate CMOS circuits and LEDs on the same chip. One obvious disadvantage is that silicon is not transparent, at least not to visible wavelengths, so can't be left in place as a flip-chip substrate for an LED.

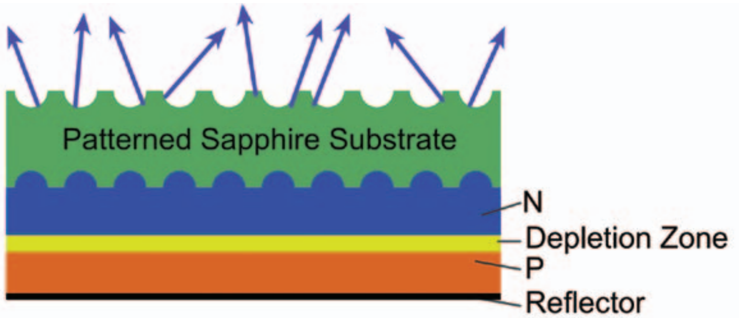

Figure 7 – Double Sided PSS

Finally, you might also remember another technique that was used to achieve a similar result which made some inroads into our industry. Luminus Devices had some success with their PhlatLight LEDs with a number of entertainment lighting manufacturers using them in their products. Luminus Devices products grew out of research done at MIT using crystal photonic lattices on the top of LED chips to control TIR and improve light extraction. Effectively their methodology created numerous tiny waveguides perpendicular to the LED that led the light out of the surface through diffraction. This was an effective technique, better than PSS as I understand it, and it also didn't increase the etendue as much. However, unfortunately, the cost of producing these photonic crystal lattices was too high to justify the improvement in light extraction. PSS may not be quite as good, but it's much less expensive. ■

Mike Wood runs Mike Wood Consulting LLC, which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 40-year veteran of the entertainment technology industry, Mike is a past President of ESTA and Co-Chair of the Technical Standards Council. Mike can be reached at mike@mikewoodconsulting.com.