

## **HBLED Reality Check**

*High-Brightness LEDs, Incandescent Lamps And Mark Twain  
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It's been quite a while since something besides nanotechnology has created Wall Street buzz for electronics components, but that's changed over the past couple of years with the introduction of high-brightness light emitting diodes (HBLEDs). They have captured the fancy of the engineering community as well as the consumer.

The Internet is being flooded with hundreds of rapturous press releases from HBLED makers all explaining how their new devices will render Thomas Edison's 140-year-old invention obsolete. These companies have become very adept at employing HBLED jargon: lumens; lux; candela; footcandles; color temperature; wavelength; lambertian distribution; scotopic and photopic vision... even if they are not quite clear on what it all means.

What becomes apparent is that companies often use or put emphasis on quite different specifications to describe the merits of their products. It's sort of like Ford giving mileage in miles per gallon but Toyota using meters per liter and Audi using wheel revolutions per tank full of gas, and leaving it to you to do the math to determine if product A is really better than product B. By themselves these technicalities are not the issue. The real problem is that in many cases the technology is being promoted in end-user consumer products in ways not much different from the marketing of women's cosmetic products for "eternal beauty." That is, there are probably some facts buried in there somewhere.

Compounding the confusion is the fact that there are actually very few sales or marketing people in this arena who really understand anything beyond a superficial level. Consequently it's not surprising that customers are often confused, whipsawed and otherwise befuddled by the various claims being made by the half dozen or so big HBLED vendors.

Putting the hype aside, there is indeed extraordinary potential for energy savings, new functionality, longer product life and greater reliability. But the pace at which HBLEDs, and their associated benefits, enter the mainstream may or may not be anywhere close to the enthusiastic predictions we're hearing today. In order to separate "the steak from the sizzle," we need to look at some of the lesser-known physical principles and manufacturing technologies that make HBLEDs possible.

Hopefully we will put a few developments in perspective and give you a feel for some of the aspects of the market that are not usually evident. It may even help the poor salesman of HBLEDs who's been given a sales quota of a zillion dollars for the next year by helping him to refine his sales pitch so that he/she will sound halfway knowledgeable to the chief engineer he may be talking to.

## The Lighting Market: A Two-Part Equation

In a discussion of the lighting market and the potential for HBLEDs, it is important to make some fundamental distinctions. They will not apply to all market categories but can safely apply to over 95% of the areas of opportunity. First of all, we can divide the market into its two principal areas: Illumination and Indication.

Illumination is that kind of light which helps us view our surroundings or perform tasks better. Indication is that kind of light which informs or alerts us relative to the status of something, or otherwise provides us with information. They are as different as night and day and it is critically important to appreciate that.

Within the area of illumination, there are two subcategories:

- general area lighting
- directed lighting

The area of indication includes:

- panel indicators
- messaging

Table 1 provides a roadmap for looking at the HBLED market in a little more detail. The underlined items show where HBLEDs are having their principal successes. It's interesting to note that there has not been much change in this makeup over the last 18 months and there is no obvious major imminent shift.

### **Illumination**

General Lighting:

Incandescent room lighting  
Ceiling fluorescents for offices, factories, stores  
HID lamps for factories, warehouses, streetlights, ballparks  
Portable lanterns

Directed Lighting:

Track lights  
Floodlights  
Headlights  
Flashlights  
Pulsed/strobe illumination

### **Indication**

Panel Indicators:

Equipment status  
Operator guidance

High Awareness Messaging:

Highway and railway traffic lights  
Brake lights  
Hotel/theater marquee signs  
Commercial & highway message signs  
Giant color graphic displays  
Warning/safety notification

**Table 1**

Each of these subcategories has its own unique performance, cost, and reliability expectations. It's also worth noting that in some cases there are additional physiological and psychological nuances that have to be considered in the marketing of such items.

Up to now the lighting industry has been represented by thousands of different types of lamps, developed over a hundred years in response to evolving market needs. Those needs are extraordinarily diverse and one might suggest that the chances for replacement of all these by a single super-efficient LED technology would be slim to none. It does mean, however, that an increased appreciation of all the nuances of these categories can lead to more effective leveraging of HBLEED technology by companies with new and exciting value-add technologies which are market and application driven.

In this wild and wooly pioneering market, the HBLEED makers are saying: "Here's my fantastic new LED...please find a way to use it!" It's also not unusual to hear the same manufacturer also saying "And if you wouldn't mind, please let us know how you got around the various limitations you found ( because we haven't figured that out ourselves yet!)"

One must be careful in extrapolating the early success of HBLEEDs in a very few markets toward inevitable success in most other possible markets. Success in traffic lights (the most publicized HBLEED story) has been no surprise because of the dramatically better lamp longevity (eliminating the very high cost of highway department lamp replacement labor costs) and elimination of the need for the red, green and yellow colored lenses which reduce light efficiency. This is a real functionality and ROI success story. High-end automotive brake lighting has also been a success but that has been more marketing-sizzle and style driven and does not represent a mainstream application. Another early market success has been the large moving-color graphic displays found in Las Vegas hotels, arenas and other high-traffic, high-dollar venues.

The contrast between Indication and Illumination is striking, with far fewer home-run applications in the latter category. The fact that there are some products being offered in every single category including Illumination simply confirms that there are some early technophile buyers for almost any high-tech product, whether it's a Segway or GPS-enabled golf balls. At this stage of a developing market, it's usually not clear whether an innovation is simply a solution in search of a problem or really the next big thing, but it is important to appreciate that it could be either.

A good example of the time lag between a technology's introduction and its finding a home in the mainstream market is the energy-saving compact fluorescent lamp (CFL). Some major lighting companies were making and promoting their first CFLs in 1983 but that did not mean either were ready for prime time. In fact, it took 15 years for them to get market traction. Gas/electric hybrid vehicles are also following a similar long adoption curve. Despite this caveat it's also useful to note that the mistakes, or off-the-mark assumptions of the earliest product innovators, are often a textbook for the next individuals or companies to "get it right" from a pragmatic business standpoint.

## Understanding Popular Light Sources

Before we look at HBLEDs it's probably a good idea to understand the competition. We'll begin with a quick overview of two well-established technologies which cover most of our current lighting needs -- incandescent and gaseous discharge -- before we take a look at newer solid state solutions.

### Incandescent

Incandescent lamps are the types we're most familiar with. Whether they're regular lamps, or their higher-performance halogen brethren, all such lamps operate on the basic principle of heating a wire within an atmosphere of selected gases such as argon and krypton, until that wire is white hot. In a very predictable time period the material of the filament "boils off" just like boiling water in a pot. Halogen lamps have additional specialized gases, under greater pressure, to allow the filament to burn hotter/brighter, without boiling off. The principle is exactly the same as in grandma's pressure cooker.

The filament gets thinner and then and finally breaks, at which time it acts like a fuse opening up. There is always a momentary surge of current at turn-on, a surge that is always harmless except that one time when the lamp filament is as thin as it can get and it blows it like a fuse, typically doing a brilliant, fraction-of-a-second, "flameout."

The basic design of these lamps has not changed much over the last 75 years, and neither has one of the primary design trade-offs which balances lamp temperature (how fast it boils off) against output color (whiteness). A lamp can be made more energy efficient (more light, or lumens per watt) but its lifetime would be reduced drastically. Its life could be extended dramatically by reducing the lamp voltage 15 - 20% but the whiteness might be compromised slightly.

It took nearly 50 years after Edison's early work in the 1870s for the incandescent lamp to really become widely popular, and even then most of lighting applications which now exist were not even imagined. In the 1930s most families had only a few lamps in the home; electricity was very cheap and the few lamp types needed could be bought at the general store. In fact, for nearly 50 years, the 40 W, 60 W or 100 W lamp went a long way toward meeting 90% of America's needs and lamp manufacturers justifiably created a set of design guidelines as a common denominator for all needs. Today all those factors are quite different, but the lamp has remained the same.

### Gaseous Discharge Lamps

Gaseous discharge covers both low-pressure neon, sodium and fluorescent and high-intensity discharge (HID) lamps. Within the HID category there are Mercury vapor, metal halide and high-pressure.

*Sodium types* For the sake of simplicity we'll bypass a discussion of neon (known best for signs) and low-pressure sodium (which has fallen out of favor because of its extremely poor color rendering (it makes everything look brown). All gaseous discharge

lamps operate on the principle that a controlled "arc-over" must be created across the length of the gas-filled tube. This "ignition" is facilitated by a ballast (which may be of either the autotransformer or electronic type) to create a momentarily-high starting voltage. (Consider a gaseous-discharge lamp to be a fancy version of a sparkplug in a vacuum bottle.)

The fluorescent lamp principles were discovered in the 1800s but not refined into commercially-useful form until the 1930s and, early on, by GE. The fluorescent lamp is noted for its exceptional energy efficiency and long life. Generally having 5 - 6 times more lumens per watt than an incandescent, the fluorescent also can last 10 - 15 times longer. Unlike an incandescent, fluorescent lifetime is degraded by very frequent on/off switching and the attendant physical deterioration of the electrodes caused by that switching. A simplified explanation is that every time it is switched on, a microscopic amount of material gets knocked off the electrode.

Finally, fluorescent lamp lumen output is quite sensitive to temperature and even requires a higher ignition voltage to come on at all when temperatures drop substantially. But, despite their shortcomings, the popular 4-foot fluorescent tube remains an extraordinarily cost effective, energy-efficient light source for larger indoor areas.

The high-pressure mercury-vapor lamp was an extension of the basic fluorescent lamp. A much smaller arc, under higher pressure and temperature, allowed a much more compact, higher-power lamp to be created. Fifty years ago, the mercury-vapor streetlight became commonplace. Like the fluorescent it provided over 5 times the energy efficiency and 15 times the life of an equivalent incandescent bulb. Consequently It's no surprise that many municipalities and factories moved toward these lamps.

But, unlike fluorescents, mercury-vapor lamps have a 5 minute or more warm-up period and when turned off must first cool down before being receptive to turn-on again. That delay, called the "restrike" time, is caused by the very hot gas requiring a far higher ignition voltage than the ballast has been designed for. After some cooling, the required ignition voltage drops to where the lamp can operate. The inconvenience caused by long warm-up and restrike delays have dogged the HID industry for decades and has prevented these extraordinarily efficient, compact, long-life lamps from being used in far more places. The mercury-vapor lamp has also carried the baggage of having a bluish tint which has been an issue when perfect color rendering has been desired.

Metal-halide lamps are an extension of the mercury-vapor lamps and have a gas mixture to create emission more resembling daylight. These lamps have more complex chemistry in how the light is created and how the ballast must control the arc. Nevertheless, the metal-halide lamp has essentially replaced the mercury-vapor lamp today wherever good color rendition is appropriate, as in a large new car lot or "big box" store environment where it is desired to accurately show clothing colors.

The high-pressure sodium lamp has become king of the hill for streetlights, sports complexes, warehouses, parking lots, etc. They exhibit unmatched energy efficiency (up

to 10 times that of incandescent and longevity up to 20 times more They are available with up to 1000 W ratings and have been improved over the years so that the yellow tint is much less noticeable and certainly not even remotely as color unfriendly as low-pressure or neon light sources.

As with all HIDs, however, these lamps have a restrike issue so they can only be used where they are always on or, as a street light, only get one cycle per day.

Over the years some firms, such as Westinghouse, developed "instant restrike" HID lamps whereby special ballasts and unique designs could allow extremely-high voltage to strike the lamp even when the gas was very hot, as just after turn-off. Today some low-power (under 75 W) versions are available with special electronic ballasts in order to turn the lamp back on -- not instantly -- but to near full brightness in a fraction of a minute...obviously still not fast enough for room lighting.

### Solid-State Lighting

There are several types of solid-state lamps in use with electroluminescent (EL) and light emitting diodes (LEDs) being most familiar, and the new structures called Organic LEDs (OLEDs). We will focus on the LED and, more specifically, semiconductor chip-based technology but it's worth at least noting the other two because they fill some special market niches which their solid-state cousins may be less well-suited for.

EL light sources have been around for well over 40 years but are related to special-purpose indicators where power consumption is important but light intensity is usually not. Suffice it to say that the EL lamp is a kind of capacitor that has its surface light up in proportion to the amplitude and frequency of a voltage impressed across it. OLEDs are created with a kind of thick film printing of crystalline substances. These devices are limited to low power but nevertheless destined for major success in low-to-moderate brightness graphic displays.

### Light From Chips

The concept behind the LED was known early in the 20<sup>th</sup>-century and it is ironic that the first light-emitting structures were created with Silicon Carbide (SiC), the same material that in the late 1990s became the "new" material making possible some of the first new blue LEDs. Work was done on light emission with SiC throughout the 50s and 60s. However, materials such as Gallium Arsenide (GaAs), Gallium Nitride (GaN) and, very recently, Indium Gallium Nitride (InGaN), took over and continued to the present for both infrared and visible emitters.

In the simplest manner, we can say the LED is a signal diode which emits light at the junction of its two positive and negative layers, in proportion to the current passing through that junction. It differs from the incandescent and gaseous discharge lamps in that it has no filament or electrodes to wear out but, like the other two, it does indeed need to factor in temperature. It must be treated in almost all respects just like any other diode, in terms of heat removal, breakdown voltage, dynamic impedance and assembly/package techniques.

Unlike the other light sources, the LED is monochromatic, ie it emits light at only one wavelength. Unlike an incandescent lamp putting a colored lens in front of an LED will not provide another color. To get something that looks more like the full spectrum associated with daylight one must mix light from multiple LEDs. Alternatively, a UV- or blue-emitting chip can be co-packaged with a phosphor coating. The result is what is called "secondary emission" as the phosphor emits a multi-wavelength light when stimulated with the LED's single wavelength. Because it costs much less than packaging several LEDs together, many so-called "white" LEDs use phosphor-based secondary emission technology.

It's interesting to note that this is exactly how a fluorescent lamp has operated all these years. The arc inside the fluorescent tube generates ultraviolet light, which excites the phosphors coated on the inside of the tube to produce secondary emissions in the visible spectrum. The various fluorescent lamps called "cool white" "warm white" etc simply mean different mixes of phosphor. The chemistry of achieving the proper phosphors' secondary emission characteristics reflects serious science. That's why white LED manufacturers are also obliged to become masters of phosphors.

But there are additional complications in making a properly-functioning HBLED. Managing the light, after it has left the chip, is one of the largest challenges of the HBLED maker. Many problems arise because light traveling from the quantum junction of that tiny chip (which is typically no larger than 40 thousandths of an inch square) must travel through a coating and then through additional clear encapsulant material to the viewer. Because different wavelengths are refracted differently as they pass through different materials a prism effect can occur. This means that the beam of light from of a white HBLED can have "fringes" of light that may not be the same color as in the center of the beam. This is caused by slight "frequency shifting" of the original light as it refracts while passing from one material into another.

### **Intensity Vs Illumination**

Perhaps the most misunderstood aspect of light source comparison is the meaning of lumens per watt and its application to HBLEDs versus other sources. The confusion arises from the different ways that light from each source is measured. When we talk about a 60 W incandescent lamp having a 750 lumen output we mean all the light emitted as might be collectively measured inside of a sphere, with the bulb suspended in the center. On the other hand all HBLED lumen output references are based on measurement of the light which lands in an area at that far end of a conical light beam. Indeed the HBLED, especially if it has the right lens or plastic package dome, can have more lumens per watt at a specific point but overall, the total lumen output, if measured in that sphere, would be a fraction of the incandescent light.

So when it is said that an incandescent gives 10 - 12 lumens per watt, but an HB LED gives 20 or 50 lumens per watt, we must be careful. Even if we were to develop an HBLED which exhibits the theoretical maximum lumens per watt (often claimed to be

100, 200 or even 300), it still may not be dramatically more than an incandescent in terms of total non-direction light emission. In fact we often do not necessarily know the conditions under which the HBLED maker has derived the lumen number.

One way to bring home the point is to compare the concept of illumination with intensity. If we stare at a 1 W white HBLED from 10 feet away, we will be blinded by the intensity of the "spot" (high lumens per watt as measured by our eye) but the rest of the room will be dark. If we stare at a 40 W incandescent from the same distance our eye will observe dramatically less intensity (much lower lumens per watt as observed by our eye) and we can stare at the bulb for a good while and in fact the room will be illuminated. Since very few people have actually participated in such a simple experiment, the true meaning of lumens per watt has escaped them.

### **A Simple Experiment**

It's nice to talk theory, but a little practical experience goes a long way to getting a real feel for a technology. So, if you are more of the empirical type who prefers direct experience, you can try this simple experiment:

Take some operating incandescent lamps rated at 7, 11, 25, 60 and 150 W and put them 10 feet from a daylight-sensing photo detector or regular light meter (a calibrated equivalent of your eye). Also 10 feet away, place a flashlight, a 70° angle white HBLED ( not collimated or "reflectorized"), a 5-W MR11 halogen lamp, and an HBLED with a 10° lens

If you don't have the time to run the experiment yourself, here's roughly what the photo detector will register in terms of brightness

<b>Light Source</b>	<b>Relative brightness</b>
Small high intensity flashlight (reflector removed)	2
11-W incandescent	4
Small high intensity flashlight (set to wide beam)	6
25-W incandescent	6
HBLED (at 300 mA) 70° viewing angle	6
5-W MR 11 halogen lamp (integral reflector)	12
60-W incandescent	15
100-W incandescent	20
HBLED (at 300 mA) with 10° collimator	25
Regular 2 D cell flashlight	100
Small high intensity flashlight (set to narrow beam)	100

Besides the relative brightness of each source notice that the 60 W and 100 W bare lamps are easily seen to light up the room, while the two flashlights and the collimated HBLED exhibit proportionately bright circles on the wall with the rest of the room being nearly

dark. It becomes obvious that reflectors and collimators, or just the domed lens of the LED itself, can provide dramatically superior lumens per watt figures over a bare lamp.

What's happening here is that we are seeing, when light is collimated, a very bright *indicator* and, when light is near-spherically emitted, a bright *illuminator*. Understanding this differentiation is the first step in intelligently and creatively applying the new LED technologies. A LED reading light, as in an aircraft, where almost 100% of the light is used only where wanted, can indeed be more energy efficient than an incandescent source lighting the same page. It is not that the LED is actually more efficient but rather that the more productive manner of directing the light creates the legitimate equivalent of more energy efficiency.

### **LED Industry Evolution**

In the late 60s and early 70s technologists were focused on developing infrared emitters for optocouplers, and IR sensing in general, as well as visible-red indicators for simple applications.

In the 80s development of green, amber, and other colors beside red gave visible emitters a little more attention, but it was not until blue LEDs became available in the mid 90s that the press-release machinery went into high gear. White LEDs became feasible with what is called the RGB LED. With any RGB device, red, blue and a green emitting chips were combined to generate white light. The RGB LED today is a major contributor to high-end color displays of all kinds.

With those developments the equipment industry could replace just about any incandescent panel lamp with an LED and the days of the colored lens were ending. Today, the LED has dominated the panel indicator market. The SMD compatibility, longevity, and immunity to vibration are tough to beat for an incandescent.

The progress of HBLEDs is not the result of some single breakthrough but rather numerous factors. Once the white RGB LED was introduced there was immediately attention given to possibilities other than simple white light panel indicators or simple color mixing. These possibilities demand not just indication but high brightness so as to be seen from a good distance. The result has been the refinement of substrate materials, phosphors for secondary emission and recognition that chip sizes needed to get larger and assembly methods needed to change for the first time in over 30 years. LED chips for indicators and optocouplers have historically been no larger than 10 to 15 mils (thousandths of an inch) on a side. But larger illumination-oriented applications they will require fabrication of higher-output chips that are 40 x 40 mils or larger. As we'll see this is a technical feat that is of "giant" proportions for most LED companies.

For over 30 years LEDs found applications as indicators and couplers, tasks which used 20 mA - 30 mA of current and required little thought about thermal resistance or heat sinking. Likewise, the "ballast" used to regulate the current flowing through the LED can

be implemented using a resistor in these low-power applications. HBLEDs, on the other hand, need special circuits to maintain the proper current if all of the efficiency advantages of the LED is to be realized. Analog IC makers have stepped up to the plate with current-controlled driver chips.

The HBLED market is also maturing as lens and reflector companies introduce new products to enhance the LED light output effectiveness. Meanwhile heat sink manufacturers are also rolling out their specialized products for thermal management solutions that deal with the unique thermal issues that arise in high-powered LEDs. We'll take a closer look at this.

So while LED development used to mean just coming up with a few new IR or visible emitter chips, and perhaps a couple of new packages from time to time, the HBLED chip itself is now just one piece of the product puzzle just as the maker of a microprocessor must become expert in the ways of software and the nuances of the end market.

### **HBLED Design And Manufacturing Issues**

Much is heard about the physics of the LED chip and the projections for dramatic increases in quantum efficiency. That is the kind of thing which gets the most attention at conferences, in scientific technical papers, not to mention being the stuff that gets federal research program funding.

In reality a better part of the challenge is actually in areas other than the chip physics itself.

These other areas require multidisciplinary skills: a mixture of mechanical, optical and thermal engineering, electronic-drive-circuit engineering, all of which historically have not been part of the LED makers' primary skill set.

### **Thermal Resistance & Other Hot Issues**

It was earlier noted that most LED chips have been no larger than 15 mils on a side (the smaller the better in terms of manufacturing cost). At 20 mA - 30 mA this is of no consequence but at 300 mA, or more (typical HBLED operating levels), it is a big deal. All semiconductors have what is called thermal resistance, ie how hard it is to transport heat from the principal dissipation-creating junction, usually specified in °C/W. In other words, it's a measure of how much the chip-junction's internal temperature will rise above the mounting surface for every watt of power in the device. Once heat gets to the case or other mounting surface it then has to travel further to a heat sink or encapsulant before it's finally dissipated into the surrounding air.

There are three things that are critical to keeping an LED junction from melting down. The ability of the heat to get out of the chip at this first barrier is determined by:

- how far the heat has to travel (even a few thousandths of an inch is not a good thing)
- the heat conduction properties of the LED material itself
- how large the chip is (the larger the surface touching the metallic mounting surface of the case the more easily heat is drawn away)

HBLED makers strive to have the dissipative p-n junction as close to the case or substrate as possible. This has not been an easy job due to the many tradeoffs and processing limitations involved, but there have been substantial improvements over conventional, historical, lower-current LEDs. Manufacturers also face the material challenge, but there is less to be done here. Materials such as InGaN are substantially worse than silicon as heat conductors so that built-in penalty will exist for the foreseeable future.

The LEDs typically used as panel indicators and optocouplers are usually no more than 15 mils on a side and have very high thermal resistances, well over  $150^{\circ}\text{C}/\text{Watt}$ . This prevents them from being driven with much more than 30 mA - 40 mA. To operate above 300 mA (and as much as an ampere), HBLED makers have had to more than quadruple the area of the die and relocate the actual junction location closer to where the chip meets the heat sink. Today's chips, which can be as large as 40 mils per side, have essentially hit the wall in terms of thermal resistance and power capability for a single device. Thermal resistances of  $12 - 15^{\circ}\text{C}/\text{W}$  are about the best which can be achieved today for the raw die, plus another  $3^{\circ}\text{C}/\text{W}$  between the package and its heat sink.

There is an unfortunate (and common) misperception in the HBLED industry that one can simply add a finned heat sink and the sum of the areas of the fins will act greatly magnify the cooling ability: nothing is further from the truth. Unless it's exposed to moving air a heat sink with fins is only marginally better than a block of metal of the same volume. And it's also important to remember that a heat sink with very tightly spaced fins, even with air flow, will have little effectiveness unless the air is forced through the fins.

The dynamics of cooling with fins is an extremely nuanced area and even very experienced power semiconductor people are continually surprised when computer modeled heatsink designs result in less than expected results. For example, some LED literature suggests that the customer use a " $5^{\circ}\text{C}/\text{W}$  heat sink." Little does she know that there is no such fixed number. The thermal resistance of a heat sink is a function of its physical design, coupled with the rate of air flow across its surface (this can range from no flow all the way up to 400 or 600 linear feet per minute). The heatsink maker often says in the fine print that there is such-and-such a figure but only certain air flow conditions.

To get a better feel for how all this works, let's take a typical HBLED in a typical mounting. When you push a forward current of 700 mA through it the device will produce around 3 W worth of heat to get rid of. This means that even with a heat sink the

size of a barn and a cooling fan just as large 3 W is about the maximum if one wants any kind of lumen maintenance or LED longevity. In the real world folks don't use such gigantic heat sinks or fans, nor even mount the packages perfectly; so achieving anything close to 3 W is problematic.

In the world of silicon semiconductors this issue has been met by producing much larger die, and using much larger wafers to keep the per-chip processing costs at a reasonable level. Unfortunately, while silicon chips are now produced on wafers as large as 10 - 12 inches, the crystalline properties of the sapphire and nitride materials used for the substrates of LED chips limit the size of the wafers to 2 - 3 inches (as silicon still was in 1965). We'll take a closer look at this issue.

## **Optics**

After heat, the next issue is making sure that chip-generated light (which is blue to start with) is properly emitted from the package as white light in a manner which is most efficient and of minimal degradation over time. This involves a highly complex collection of issues requiring a thorough understanding of reflection and refraction mechanisms associated with various wavelengths.

Various mechanical techniques have been developed, particularly that known as a flip-chip design, to allow light to exit with minimal attenuation as it first travels through the solid chip structure. Going to the more recent flip-chip designs also allows connectivity to the chip without having wire bonds in the line of sight of light transmission.

As mentioned earlier, a white LED chip is usually a blue/UV chip that's coated with a phosphor-filled epoxy or silicone to produce a secondary emission of white light. The principles of such secondary emission were well known and demonstrated over a century ago. However, understanding the theory and reducing it to commercial usefulness are two different things. It took until the late 1930s for the technology to show up in regular fluorescent lighting.

The phosphor-filled coating needs to be of a non-yellowing/non-aging silicone if significant degradation over time and temperature is to be avoided. Also, consistent deposition of the coating is proving to be a challenge. Coating thickness, which is never 100% perfect, results in some wavelength shifting anomalies. Much is heard about HBLD makers needing to bin their products into various performance categories. The phosphor-emission variation is one of the principal factors.

## **Lessons From The Silicon Semiconductor Industry**

It becomes apparent that HBLEED technology is dependent on many support technologies other than quantum physics alone (ie how to more effectively make electrons jump around and create photons). These considerations parallel what happened in the silicon semiconductor industry 40 years ago when the breakthrough "planar" process was introduced. In hindsight it seems so obvious an approach. It had nothing to do with the fundamentals of the chip physics but allowed subsequent major processing, packaging and reliability improvements, leading to sharp cost reductions. Without the geometries and junction passivation made possible by the planar process, it is hard to envision where the IC or computer industries would be today.

A similar development took place in power semiconductors but took longer to go mainstream. Originally power semiconductors employed varnish-like substances to passivate their easily-contaminated junctions. Eventually, proprietary micro-thin glass coating processes were developed by a handful of companies (with great secrecy). Not until the 80s did the glass passivation of power semiconductors become mainstream and the ability to make devices rated far above 400 V became routine. Without such planar or glass processes, the power semiconductor industry would not be as we know it. Today, all computers are full of ICs using the planar passivation technique, along with power supplies with high-voltage power devices using glass passivation.

A number of other manufacturing-driven advances (as opposed to theoretical chip designs) have also had profound impact on the semiconductor industry: the TO-220 plastic package; plasma instead of chemical etching; ion implantation instead of diffusion; bonded wafer technology instead of expensive, epitaxially grown materials; robotic handling of wafers to eliminate breakage.

One important thing should be mentioned and that is the proverbial "elephant in the room:" wafer size. In the 60s discrete semiconductors, as earlier mentioned, were routinely produced as a die from 2-inch wafers. As die size started to creep up folks started to talk about 3-inch wafers but feared the processing complexity and breakage issues. When 3-inch became somewhat common folks began to talk about 4-inch wafers, with the same fears about complexity and breakage. This kind of fearful progress has, with a few prominent exceptions, continued right up to the present among companies who only make non-IC semiconductors.

The IC/microprocessor industry, early on, started with a blank sheet and developed entirely new rationales for producing wafers. The larger die size production volumes encouraged companies to embrace new manufacturing methodologies. Times and temperatures were automated, variable chemical processes were replaced by automated mechanisms, and breakage was eliminated by robotic handling.

The result today is common use of wafers thought impossible 20 years ago. It is interesting that the only discrete semiconductor makers employing very large wafers today are those companies also housing IC processing expertise. Aside from all the

laudable effort going into improving the quantum efficiency of LEDs and phosphors, the largest factor limiting the HBLED from having impact in the illumination markets is wafer size.

For example, if the LED industry was to magically convert to 8-inch wafers it would be able to produce 120 x 120 mil chips at a cost not far from today's largest (40 mil). Furthermore they would be able to have nearly a ten-times lower thermal resistance, in turn allowing ten times the brightness in a single chip. You begin to see the implications? While there are several breakthroughs expected that could enable 4 - 6-inch wafers in the next three to five years, the small diameters, and attendant high per-chip processing costs are the current market realities we have to live with today.

### **Where Are HBLEDs Headed?**

In about 1975 an RCA Semiconductor press release stated that the nascent microprocessor would one day be found in every computer, car, and major appliance. It was clear that the release was intended more for Wall Street than anything else. This author was a semiconductor product manager at the time and remembers that press release as though it were yesterday. To say that there was a bit of skepticism about that projection among rank-and-file semiconductor people would be an understatement.

That prediction turned out to be 100% correct (although it wasn't through RCA clairvoyance) The fulfilling of the prophecy years later was helped along the way by a few companies like Intel, Texas Instruments, IBM, Microsoft, Apple, Motorola and others who collectively invested tens of billions of dollars in manufacturing infrastructures and end-product innovations to put the microprocessor in all the places it is today.

Despite their current limitations HBLEDs do have a bright future, as we can reasonably expect the handful of breakthroughs that will enable higher power, lower cost, and greater efficiency. If we look ahead 30 years we can envision:

- HBLED chips being produced on bonded 8-inch wafers, giving us \$0.10 120 x 120 mil die
- Entirely new forms of lighting fixtures
- Homes, offices and factories designed to accommodate the new technologies, such as how buildings now accommodate wireless networking
- Dozens of specialized firms producing state-of-the-art electronics and cooling products, designed specifically for LEDs
- Fundamentally new consumer lighting usage habits

What we don't know is how this graph of change will be shaped, and just how and when all the elements to make these quantum changes will arrive. But, for the near future, we can probably get some sense of what's to come from the words of Mark Twain (or was it the incandescent lamp?) who once said:

"Reports of my demise are greatly exaggerated"

## About The Author

Ed Rodriguez holds a BSEE and has spent over 35 years as an electronics engineer, product manager, and technical executive, with over half that time as a high-tech CEO. His focus has been in power semiconductors and ICs, LED-based optoelectronics, and high-density switch-mode power conversion.

As founder/CEO of PowerMicro in the early 90s Ed conceived/directed four separate advanced technology joint ventures, involving major firms in US and the PRC. Following PowerMicro's acquisition by Unipower in 1999, he directed Unipower's efforts in advanced technology power supplies for computer and telecom applications. In 2004 he formed OptoThermal Technologies, a special-purpose consulting firm, developing new concepts for mid-range companies wishing to leveraging their existing US infrastructures in response to globalization challenges. He is currently working with several firms to develop and commercialize advanced technology lighting and power management components for both the consumer and industrial OEM markets.

Mr. Rodriguez has also directed numerous major joint ventures in the US and Asia, has been awarded nearly two dozen patents, written numerous technical articles and papers on both optoelectronics and power conversion. His work has been published in EDN, PCIM/Power Electronics, Electronic Design, and Electronics magazines.

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