White Paper

The Transition to High Brightness LEDs

Greg Caswell

Introduction

Current lighting technology is long overdue for an overhaul. The light bulb as we know it is extremely inefficient, fades over time, requires a high degree of maintenance, is fragile, and has a very short lifetime. More recent innovations like the compact incandescent bulb, efficient but expensive, or halogen lamps with poor efficiency and short lifetime are not the answer. The High Brightness Light Emitting Diode (HB-LED) offers a solution.

Historical Perspective

No other records of semiconductor light emission are known until the mid-1920s when self-educated Russian scientist Oleg Losov noticed light emission from Silicon Carbide (SiC), as well as zinc oxide radio detectors.   Losov published multiple scientific papers in Russia, England and Germany between 1924 and 1930 describing the spectrum of light emission in relation to the current-voltage characteristics of SiC cat's whisker diodes. Losov's discoveries include establishing the v=eV/h formula that links diode voltage drop to emission frequency and, in 1927, he patented a 'light relay' which is probably the first reference to LED-based optical communications.

Also worth mentioning are Rubin Braunstein and Egon Loebner, working at RCA who in 1958 patented a green LED made from a lead antimonide dot alloyed to p-type Germanium (Ge).

Another early character to have touched LEDs is Kurt Lehovec, who is best known for inventing junction isolation for integrated circuits when he worked for Sprague, patenting it in 1959.

In 1960 Dr Nick Holonyak of General Electric was developing an unusual material, Gallium Arsenide Phosphide (GaAsP), as a route to wide bandgap tunnel diodes.   With advice from GaAs laser pioneer and fellow GE employee Dr Robert Hall, Holonyak made his visible laser later in 1962.   Less well known is that in 1952 he applied for a patent on SiC visible light LEDs.

Holnyak then joined the University of Illinois where he became the supervisor of aspiring GaAsP LED - researcher George Craford.   Craford moved to Monsanto in 1967 and with a team of researchers invented orange, yellow and green LEDs using GaAsP on GaAs substrates.   The key was nitrogen doping, the idea for which Craford credits a presentation by a Bell Labs researcher – Bell Labs was working with GaP LEDs, trying both ZnO and N as dopants.

Monsanto was probably the first firm to make affordable LEDs.   Craford moved on to HP in 1969, heading a group that pioneered Aluminum Gallium Arsenide (AlGaAs) for bright red LEDs and Aluminum Indium Gallium Phosphide (AlInGaP) for bright orange and green. Craford is now CTO at white LED maker Lumileds which, with Avago, is one of the two descendants of HP's LED business.[1]

By the end of September 1991, Nichia researcher Naruhito Iwasa discovered a production compatible way to make p-GaN. Like HP before it, Nichia was a hotbed of innovation which finally led it to open the door to white LEDs, and ultimately lighting class LEDs.

Nichia researcher Yoshinori Shimizu – initially as part of a program to make blue die emit green - identified YAG phosphors as materials tough enough to survive in an LED. Yasunobu Noguchi then developed a gadolinium YAG phosphor that could convert blue light to yellow, and Kensho Sakano combined Noguchi's phosphor with a blue LED die to make a white LED.

With the advances in materials, design and manufacture of LED devices, we are seeing a wide spectrum of LEDs that are cheaper, more colorful, more efficient, more intense, and more reliable.
LED applications include signs and indicators, sensors, communication devices, displays, and increasingly solid state lighting and backlighting for TVs and monitors. The supply chain of LED can include producers of LED chips, packaging houses, LED driver chips and system integrators (e.g., LED light bulb). Large players in LED chip manufacture include Nichia, Philips, Osram and Cree.

Clearly, LED technology has been in existence for many years. This technology has now evolved into High Brightness LEDs which due to their higher current carrying capability also have a higher level of heat to be removed.

HB-LED Markets

Before delving into the thermal issues of these devices, let's take a look at the markets for these devices as shown in Figure 1 is data from Strategies Unlimited that shows the continued growth in the use of HB-LEDs particularly in signs and displays, lighting, and automotive applications. Mobile appliances, which originally led the industry, are on the decline.
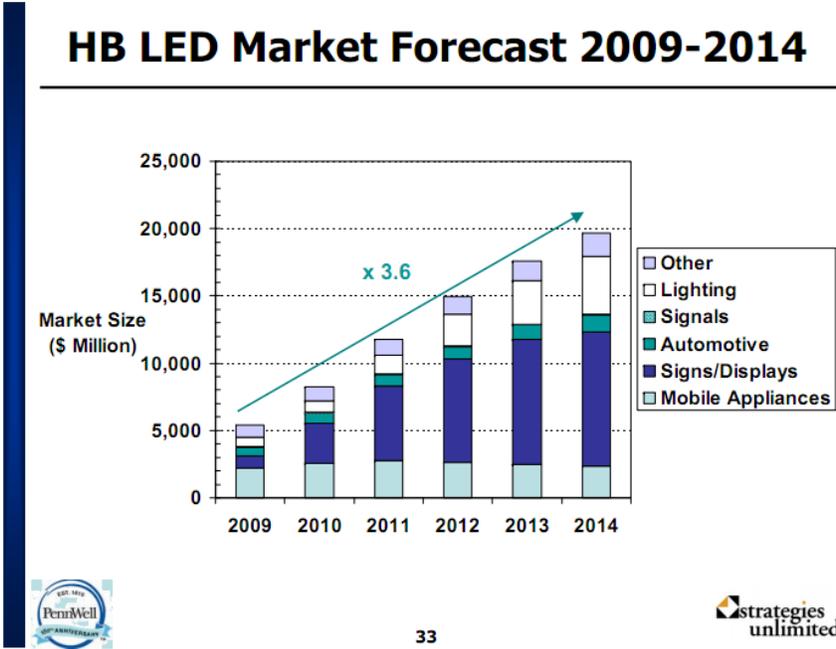
HB LED Market Forecast 2009-2014

Figure 1– HB-LED Markets and Growth

The Problem

The world has recognized that the current incandescent lamps used must be phased out. Table 1 shows the timelines for many countries for either the prohibition of these lamps completely or the plan for their reduction. These decisions are a driving force behind the transition to HB-LEDs.

Country/Region	Announcement	Plan of Action
ECU	2007/3	Phase out incandescent lamps starting in 2009. Plan to reduce 20% GHG emission by 2020
UK	2007/9	Phase out incandescent lamps starting in 2010 and prohibit use before 2012
Japan	2008/4	Prohibit use and production of incandescent lamps in 2012
Australia	2007/2	Phase out incandescent lamps starting in 2010. Plan to prohibit the use by 2012 completely
New Zealand	2007/3	Plan to prohibit use of incandescent lamps in 2010
Canada	2007/42007	Start to reduce the use of incandescent lamps in 2010 and completely by 2012. Plan to reduce GHG emission by 2020.
United States	2007/12	DOE law to ban the use of incandescent lamps starting in 2012
Korea	2007	30% of all lamps with LEDs by 2015
Taiwan	2007/11	Phase out incandescent lamps starting in 2010 and prohibit use before 2012
China	2007	Phase out the use of incandescent lamps over next 10 years (Target 2017) to meet national lighting industry savings target of 50% by 2020

Table 1 – Timelines for Countries Eliminating Incandescent Lighting

Getting the Light Out – What is an LED?

To state the obvious, LEDs are diodes. They are P-N junctions that emit energy at a wavelength that corresponds to visible light when forward biased.   Combinations of different semiconductor materials and dopants vary the energy drop across the junction, and the color emitted corresponds to that energy drop. Significant work has gone into making every color of the spectrum, and some LEDs incorporate an extra step to mix colors to produce white light. These components use phosphors to absorb blue or ultraviolet light emitted from the die and re-emit it as yellow. Blue and yellow are at sufficiently opposite ends of the visible spectrum to fool our eyes into seeing white light. Crystalline semiconductor atomic arrangement determines the bandgap (specifies optical properties) of the LED while impurity doping provides p- and n-type regions. When forward biased, injected electrons and holes recombine.   Energy is then released as radiative (light) or non-radiative (heat) as illustrated in Figure 2.
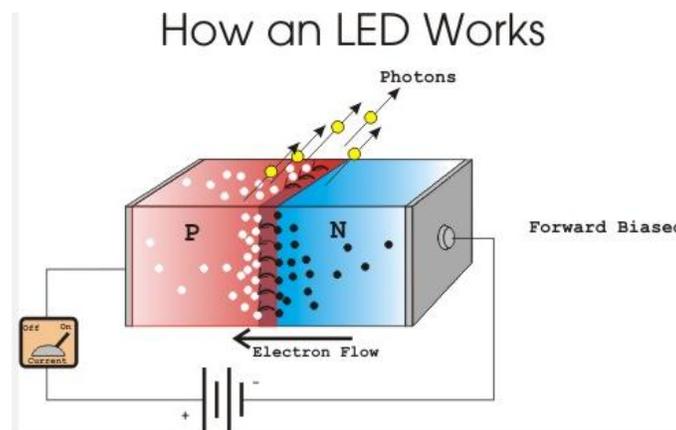

Figure 2– How an LED Works[3]

Figure 3 is an oblique X-ray micrograph of a through-hole white LED. One lead forms a cone shaped cup on which the die is mounted, the other forms the lead of opposite polarity. This lead is connected to one side of the die with a wire bond, usually gold. The other side can be connected to the lead with another wire bond, as on this LED, or directly through the bottom of the die through the die attach. What is not visible on the X-ray image is the silicone bead that protects the die. A small drop of the translucent viscoelastic material provides a measure of compliance to the delicate die and wire bonds. The entire component is molded into an epoxy casing that provides directionality to the light and further protection to the die and leads. [4]
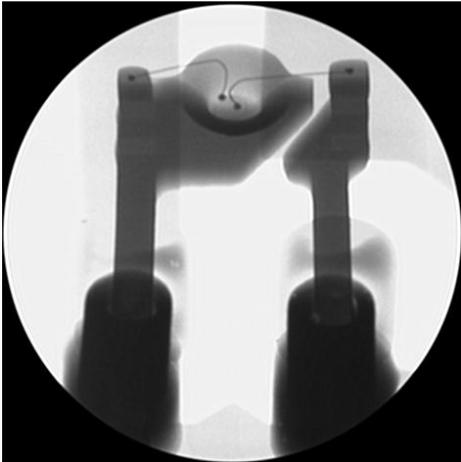
Figure 3– Oblique View X-Ray of an LED

At the device level, an LED is a forward-biased diode that enables radiative carrier recombination resulting in light output. LEDs can be classified according to the light colors or power intensities. Or they can be distinguished based on the base materials systems such as GaAs, InGaP, GaN, ZnSe, Si and even organic compounds. They can also be differentiated based on the device and package designs, e.g., quantum dot LEDs, top emitting and side-emitting LEDs. The typical construction of a packaged HB-LED is shown in Figure 4.
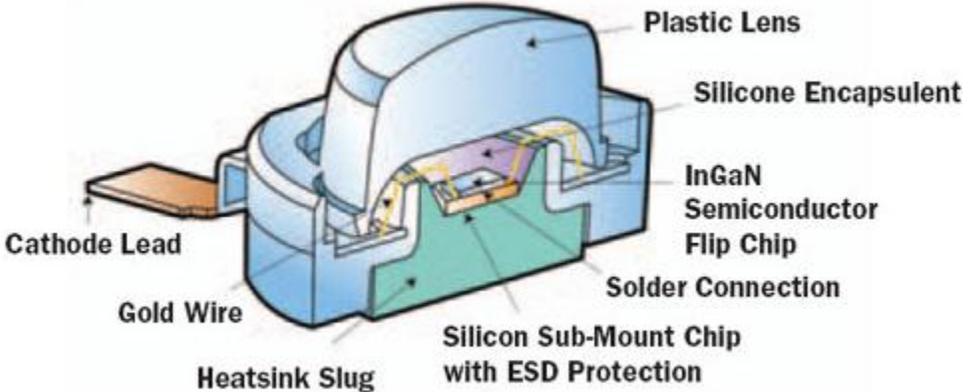

Figure 4– Typical Cross Sectional Depiction of a HB-LED Package Construction

LED Failure Modes

If LEDs are permitted to get hot-several issues can occur; their brightness will go down significantly; their color may change – leading to problems where the balance of red/green/blue (RGB) generated white light will be impacted. Similarly, electrical characteristics, such as Vf will drift with temperature and cause design changes; and high junction temperatures accelerate degradation-reducing lifetime. All of these issues require an understanding of next level packaging. But first, let's look at some of the failure mechanisms that can affect the LED die.

Degradation

Most LEDs have a natural lifespan that ends in a wear-out mechanism. Defects within the active region can spur nucleation and dislocation growth and are particularly affected by temperature and current. Phosphors in white LEDs will degrade with time and temperature-resulting in a change of the light color (usually becoming bluer) and the epoxy package can yellow with time. Degradation failures are unavoidable – yet correct utilization will assure that they do not degrade within the life of the product.

LEDs typically display a wearout failure mode due to long term drift of critical output characteristics, e.g., light intensity or color shifts. LED component suppliers often use 50% light intensity degradation as the LED failure criteria, though the actual end usage scenario can drive application-specific requirements such as those related to the color correctness, intensity, uniformity of the LED light output.

When it comes to predicting the wearout life of an LED, the typical durability of LEDs makes it impractical to obtain meaningful experimental data relevant to real applications, as it is hard to extrapolate future behaviors across populations based on limited testing scope.   For solid state lighting, Philips prescribed a simplified approach that helps the lighting designer to define operation conditions related to the so-called "B50/L70" lifetime, i.e., when 50% of the products have at least 70% lumen maintenance for the projected operating hours. It is unknown what design margins are provided based on this approach and one can expect variations across vendor bases, technology platforms, production processes, and more importantly, specific system design and deployment. Frequently, a quality LED that is properly integrated into a system can experience much longer life than the rest of the system and may be the last concern when evaluating the overall system reliability. The lifetime of an LED is a function of the thermal impacts of the current flow as shown in Figure 5.
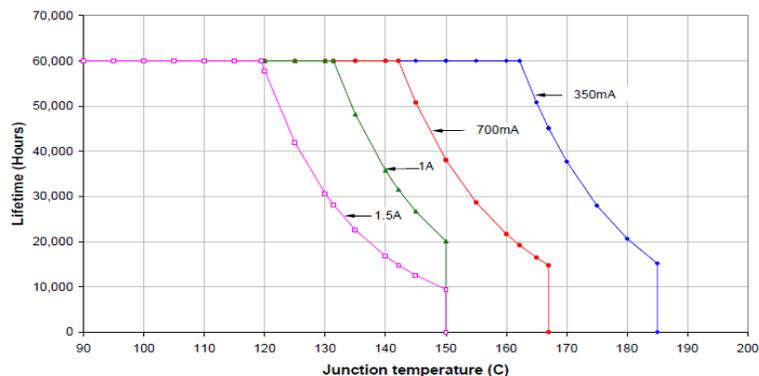

Figure 5– Lifetime versus Junction Temperature Relationship for HB-LEDs

Electrical

One of the major causes of an electrical open in an LED is thermomechanical stress of the wire bonds. Often the gap between the wire bond and the die can be viewed under X-Ray microscopy. The CTE of the epoxy encapsulant and the silicone bead protecting the die can differ extensively. At elevated temperatures, the differing forces of the expanding materials can pull the wire bond from the surface of the die, especially if the component is heated cyclically or for a prolonged period of time, as shown in Figure 6[5]. Eventually, plastic deformation or creep will result in a permanent electrical open. Electrical shorts in LEDs can also occur and tend to occur on die, as opposed to the package-although there are many sources for electrical shorts, two of the more common are threading dislocations and degraded passivation.
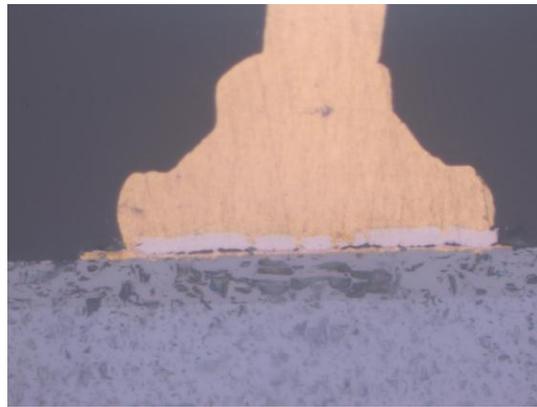

Figure 6 – Open Ball Bond on LED Die Surface.

Thermal Runaway

Poorly made LEDs may develop areas of higher and lower resistance (and temperature) within the substrate due to electromigration or incomplete soldering. This can lead to current crowding, which on HB-LEDs can cause thermal runaway: increases in temperature result in increases in resistance, which in turn increase the temperature further. As a user, always select an LED for higher rated current applications. Thermal impedance is traditionally measured in degrees per watt (°C/W) and uses the symbol "θ" (theta) to denote the value. For instance, the value of θsa equal to 20°C/W refers to the heat-sink (s) to ambient air thermal impedance and will cause a temperature rise of 20° for every watt of power dissipated.

Threading Dislocations

Threading dislocations form at the interface of the substrate and epitaxial layer. They propagate toward the surface of the epitaxial layer and are often called micro or nanopipes because of the open core nature of the defect. Threading dislocations form in the highest densities on sapphire based GaN LEDs. Atomic Force Microscopy (AFM) can be used to examine this failure mode. Elevated dislocation density can result in an increase in leakage current during operation. The mechanism is migration of contact metal through the hollow center of the dislocation, creating an ohmic path between the P and N regions of the die. Pitting near the edge of the P-region has formed due to metal migration through the dislocations.[6] Figure 7 left is a pictorial of a dislocation site while the right image is a SEM photo of a true dislocation site.
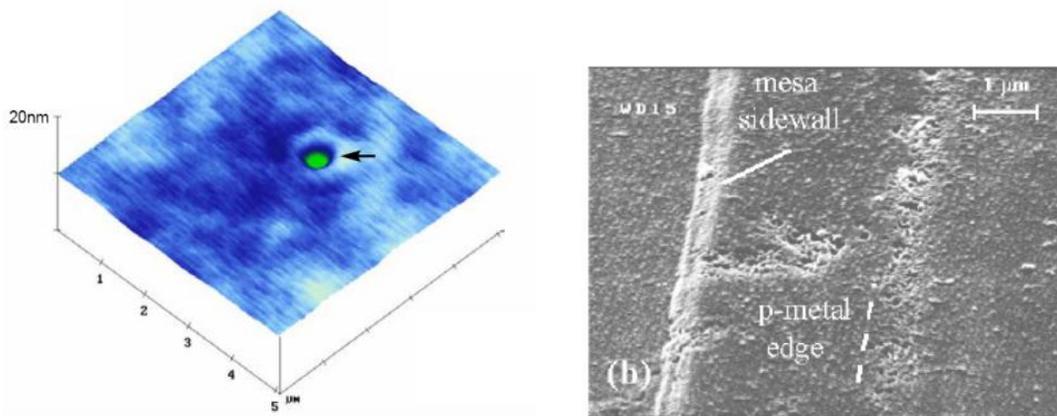
Figure 7 – Dislocation site (left) and P metal edge of dislocation (right)

ESD/EOS

Another cause of electrically open failures, particularly on LEDs with sapphire substrates, is Electrostatic Discharge (ESD) or Electrical Overstress (EOS) to the die. The forward biased ESD pulse will pass through the LED without damage, but a reversed biased pulse can prove catastrophic. It is important to check for this failure mechanism when an open between the die and wire bond is not visible. The solution to this issue is relatively simple: Place a correctly rated Zener diode, reverse biased, in parallel with the LED, which will allow voltage spikes to pass through the circuit in both directions without damaging the LED. Addition of a capacitor to smooth an input signal is a method for alleviating EOS. Figure 8 is two images of the effects of an EOS instance on an LED, with the right image showing the damaged area at higher magnification.
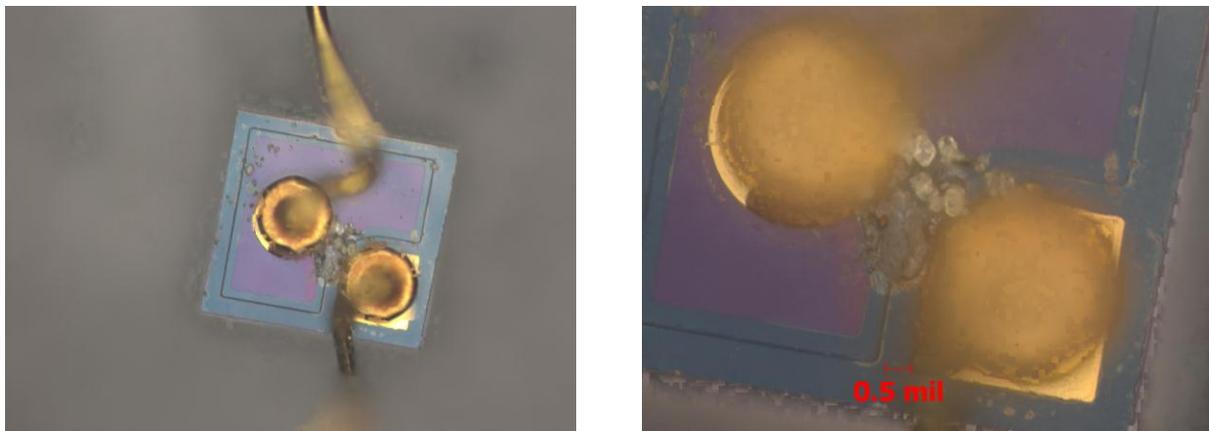

Figure 8 – Two images of the Effect of EOS on an LED (right image higher magnification)

LED Package Issues

Packaging provides a means for protecting the semiconductor die from direct environmental exposures and facilitates the interconnection of LED to the system. The LED package also play an essential role for the LED optical, thermal, mechanical and electrical performance and reliability requirements.

Optical

Package optical properties can be affected by epoxy and phosphor degradations when exposed to temperature, moisture, UV radiation. Optical performance is also affected when an air gap forms, e.g., due to delamination, or when materials optical property/geometry changes. Such changes can modify the optical path, reflectivity and index of refraction matching across the device layers before photons can be emitted efficiently.

Thermal:

Thermally, low power LEDs dissipate heat primarily through their leads whereas high brightness LEDs depend more on the packages. For example, many high power LEDs are SMT type that can be directly mounted onto a heat sink and linked through a thermal slug on the base of the package. In some cases, package degradation can contribute more to the light output degradation than the LED die itself, as silicone and epoxy may deteriorate faster over time. Packages for state-of-the-art high power LEDs are much more sophisticated than early LEDs, e.g., they may be mounted on metal-core PCBs to provide efficient heat transfer. However, one should not simply be satisfied with an acceptable "macro" junction temperature. LEDs with design or manufacture package flaws may result in non-uniform heat conduction across the die active region, resulting in current crowding and local heating, posing risks of thermal runaway.

Phosphors can also degrade and the degradation rates for them may vary, causing changes in the eventual output light color. For example, purple and pink LEDs with an organic phosphor formulation may degrade after just a few hours of operation resulting in output color shifts. In addition to high temperatures and high humidity operation degradations, an LED package is susceptible to failures during temperature cycling and when the package is exposed to low temperatures. Thermal cycling can cause thermal fatigue failures related to wirebonding, die attach and die-package delamination. This can be traced to the incompatibility of package structures/materials and the environmental/operational stress experienced. The presence of manufactured defects such as poor intermetallic formation at the ballbond or inadequate die attach can be particularly susceptible in these scenarios. In addition to issues exposed at high temperature or temperature cycling, LED packages exposed to very low temperature may exert mechanical stress on the LED die, to the extent of causing die cracks.

Mechanical:

Mechanical integrity of the LED is another critical aspect that demands attention throughout the package design, assembly and system integration. The compound semiconductor used in LEDs possesses different mechanical strength when compared to silicon. The wirebonding process parameters need to be carefully designed and controlled in order to form a quality bond without generating bonding or die weaknesses. In LED assembly to PCBAs, package stress can be introduced due to lead bending or soldering actions, which can introduce package and die defects leading to early failures.

Electrical:

As a semiconductor device, LEDs will be susceptible to electrostatic discharge (ESD) and electrical overstress (EOS). ESD may cause immediate failure at the diode junction, or a shift in its parameters, or latent defect causing delayed functional failures. As EOS examples, power-line coupled transients and surges can degrade LEDs. And the reverse-breakdown mode for some LED types can occur at very low voltages where any excess reverse bias may cause immediate degradation.

Energy Star Requirements

ENERGY STAR Qualified LED lighting reduces energy costs, uses at least 75% less energy than incandescent lighting, saving on operating expenses; reduces maintenance costs; lasts 35 to 50 times longer than incandescent lighting and about 2 to 5 times longer than fluorescent lighting; requires no bulb-replacements, no ladders, or an ongoing disposal program. [7]

Qualified devices reduce cooling costs as LEDs produce very little heat. Energy Star devices are guaranteed, e.g. come with a minimum three-year warranty, which is far beyond the industry standard. They also offer convenient features such as being available with dimming on some indoor models and automatic daylight shut-off and motion sensors on some outdoor models.

To qualify for Energy Star, LED lighting products must pass a variety of tests to prove that the products will display the following characteristics: (1) Brightness is equal to or greater than existing lighting technologies (incandescent or fluorescent) and light is well distributed over the area lighted by the fixture. (2) Light output remains constant over time, only decreasing towards the end of the rated lifetime (at least 35,000 hours or 12 years based on use of 8 hours per day). (3) Excellent color quality. The shade of white light appears clear and consistent over time. (4) Efficiency is as good as or better than fluorescent lighting. (5) Light comes on instantly when turned on. (6) No flicker when dimmed. (7) No off-state power draw. The fixture does not use power when it is turned off, with the exception of external controls, whose power should not exceed 0.5 watts in the off state.[8]

Summarization

The users of HB-LEDs need a system approach to consider the reliability and durability of their products, so that secondary optics and first level packaging optics, thermal management, and cost drivers are ascertained. DfX, design for excellence (manufacturability, assembly, testing, cost etc., to assure concurrent engineering of new products is also vital. The path to successful utilization of HB-LEDs is through the use of software modeling tools that can derive reliability of LEDs in a circuit board configuration and determine the system's ability to meet the long term reliability requirements required. DfR Solutions has such a software package, called Sherlock. Call us to discuss your application.

References

1) Bush, Steve, Electronics Weekly.com -22 September 2010
2) Xiao, Dr. David, APT Electronics Presentation, April 2010
3) Krames, Mike, Lumileds Lighting, Arlington, VA, 3 November 2003
4) Kong, Randy, Factors That Drive LED Reliability – DfR White Paper, August 2010
5) Hare, Ed, Dr., Failure Analysis of LEDs, SEM Lab Inc., October 2004
6) Arnold, Joelle , When the Lights go Out: LED Failure Modes and Mechanisms, DfR Solutions White Paper
7) Brodrick, James Dr., Beyond Energy Star®: DOE's SSL Commercialization Support Strategy, march 18, 2009
8) ENERGY STAR® Program Requirements for Solid State Lighting Luminaires Eligibility Criteria – Version 1.2