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LEDs–An Overview of the State of the Art in Technology and Application

Stephen Johnson

Abstract

Solid state lighting in the form of Light Emitting Diodes (LEDs) is bringing new sources with different operating characteristics to the market. With the control in dimension, optics, intensity and color, these sources have the potential to transform the way we use light. This paper will review the recent improvements in performance that have been achieved by these devices, focusing on those product attributes identified as being critical to end users. The paper will conclude with a consideration of applications capitalizing on the LEDs' unique operating and physical properties.

Introduction

Over the last hundred years electric lighting sources have undergone a series of technological transitions, from the carbon filament lamp to the currently ever present incandescent lamp, and then to the introduction of plasma discharge sources: the fluorescent lamp, high pressure sodium, metal halide and most recently sulfur lamps. Indeed, we are now at the beginning of a new era, with the introduction of Solid State light sources. The most advanced of these technologies is inorganic light emitting diodes, LEDs.

LEDs were first introduced in the early 1960's as indicator lights and they had an efficacy of a .01 lumens per watt. By the early 1980's the red LEDs performance had increased to over 20 lumens per watt and most recently this technology has produced amber LEDs that, in the laboratory, had an efficacy greater than 100 lumens per watt.[1] To complement the red and orange LEDs associated with gallium arsenide (GaAs) / gallium phosphide (GaP) technology, gallium nitride (GaN) devices were developed in the early 1990's and their efficacies have improved over the last decade to over 30 lumens per watt for the white light sources. The GaN LEDs complement the color scheme by providing violet, blue and green sources. GaN white LEDs are made from either an ultraviolet or a blue LED exciting a phosphor to provide a white light. LED manufacturers project that the current white LEDs, available at 20-30 lumens per watt, will ultimately meet and exceed the efficacy of other white light sources, achieving a goal of between 150 and 200 lumens per watt. In principal, there are no know reasons why this cannot be achieved, and the technology is progressing to overcome barriers that currently limit the devices' performance.

Review of Current Product Performance

To gain a better understanding of this emerging technology and how it relates to lighting application, the discussion will progress through a series of performance characteristics and attributes that are of keen interest to the lighting community. The first attribute to be discussed is the light pattern or distribution characteristic of these sources. The small LED with which we are most familiar is identified by its small plastic "bullet shaped" appearance with two wire leads extending from the base of the lamp. In the marketplace this package is identified as a T 1¾, as shown in **Figure 1**. The light-emitting die is located in the center of a conductive reflecting cavity, which acts as an optical element to focus the light from the die in a forward direction. The die are typically 300 microns on edge, smaller than a pepper flake, while the encasing T 1¾ package is 5 mm in diameter. The die and reflector are encased by an epoxy package. The round end of the package acts as a lensing element for light reflected by the reflector cup. The T 1¾ device is designed to provide an even distribution of light. Looking at the LED end-on, the emitting area of the die is 1/250th of the area of the package; hence, placement of the die within this space is critical for good optical performance. The manufacturers provide specifications for the devices giving different spatial distributions reminiscent of standard light sources. However, the observed luminance distribution is generally less uniform and maybe unacceptable for many applications. Alignment of the cup and die within the package is critical, and frequently the geometrical and the optical access of the light emitted from the device are not the same, resulting in poor optical performance for arrays using multiple devices, **Figure 2**.[2] The recent introduction of a new package design, **Figure 3**, that mechanically aligns the LED die within the optical element has been introduced within the last year.[3] This new package design has greatly improved the optical control relative to the geometric axis of the

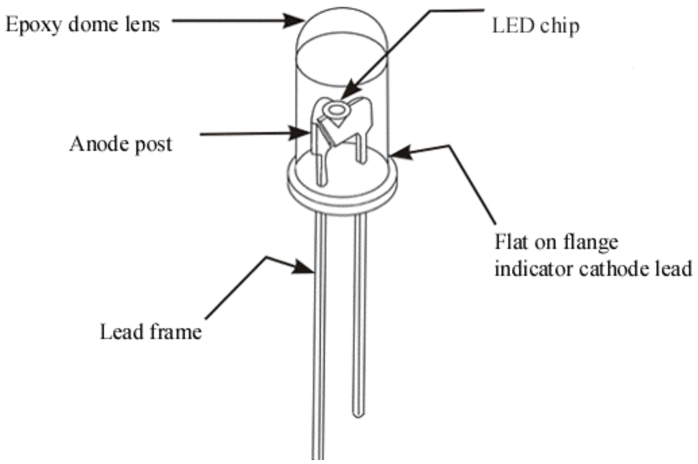


Figure 1. T 1 ¾ LED Construction.

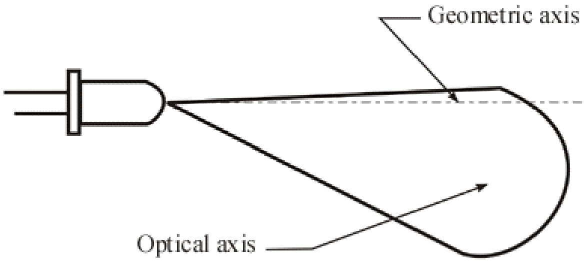
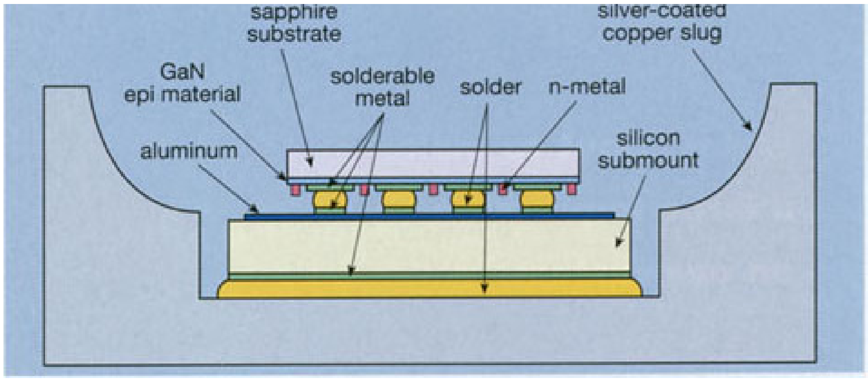


Figure 2. Optical alignment of product:optical versus geometric axis.

device, and has also improved the extraction efficiency and provided a more stable platform for original equipment manufacturers to assemble the devices. The new design also provides much better thermal management of the die, which is critical in maintaining the performance of the device during operation and for life.

The second performance attribute to be discussed is the light output of these devices, including both the flux density and the associated efficiency of producing the light. The last decade has seen a steady improvement in flux density per die, as is dramatically demonstrated by the reduction in the number of red LEDs used in the head of a traffic light. In 1993 over 200 LEDs were used per traffic head. In 1996 that number reduced to over 100, and in 1998 the number was further reduced to less than 20. Recently, manufacturers have demonstrated a single LED light source for this application. The increase in performance has been achieved by improvements in:

- the internal quantum efficiency of the die
- the extraction efficiency of the die
- the change in geometry for attaching the electrodes
- the performance of larger die size, and
- the packaging, providing better thermal management and optics



Optical Control

- **Improved control of optical and geometric axis**
- **Improved extraction efficiency**
- **Improved platform for OEM applications**

Figure 3. Improved optical control.

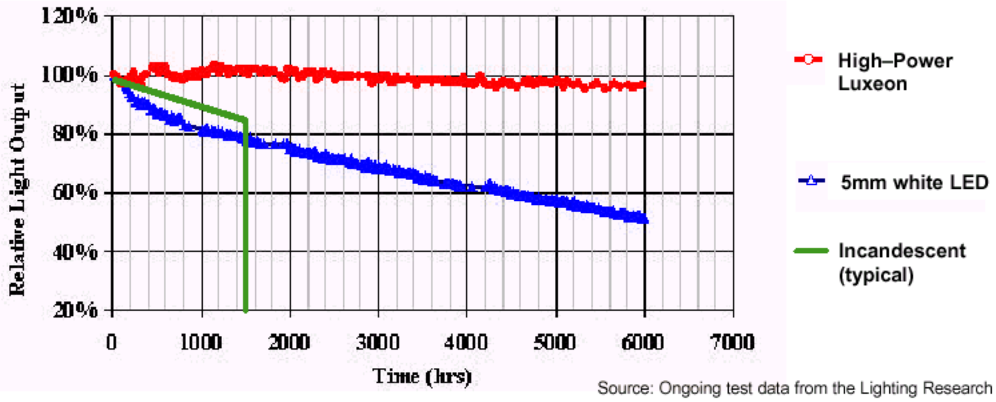
The efficiency of converting electrical energy into light within the die, the internal quantum efficiency, is greater than 90% for GaAs/GaP devices, and although lower for GaN die it continues to improve. Despite the high internal efficiencies of the devices, efficiency for extracting light from the die has been low due to the large difference in the refractive indices between the die and the surrounding medium, which results in many self-absorbing internal reflections. The probability for a photon to escape from the die has been improved by changing the geometry of the die through chip shaping. Increased efficiency has also been achieved by developing die structures on which the bonding pad and wire for the electrodes on top of the die are placed next to the reflector and no longer obstruct the emission from the die. Within the last year there has been a dramatic increase in GaN die size from the standard 300-micron on-edge dimension to 1mm on-edge die. This change results in a minor loss in efficiency but a major gain in light flux per device. The larger die have proportionally greater power and, consequently, generate more heat, which can be deleterious to performance and life of the product if not removed. Therefore, it has become imperative to create packages with better thermal management. The change in package design in order to provide better thermal management of the die now allows devices to operate at higher current loadings without significant degradation in device performance.

The two types of LEDs, GaAs/GaP and GaN, cover different portions of the spectrum and within that range have different performance characteristics. Physical principals limit the spectral range for each technology and within that range the efficiency decreases as the limits are reached. The GaAs/GaP LEDs operate in the visible portion of the spectrum between 540 and 670nm with a peak efficacy at 611nm. GaN devices emit from the ultraviolet up to 550nm, with their current peak efficiency at 420nm.

The third performance attribute to be discussed is color; including both color rendering index and color temperature for the white light made from these devices. There are two approaches in producing white light with LEDs. One, as mentioned earlier, is to use a UV or blue LED plus a phosphor. The other approach is to blend colored LEDs (red, green and blue) to provide the desired color. The most prevalent white light devices used in the market utilizes a yellow phosphor, which is excited by a blue LED, where the blue light provides balance in the blue portion of the spectrum. In the T 1¾ package the phosphor, a Cerium doped $(Y,Gd)_3 Al_5O_{12}$ garnet, is suspended around the die in the epoxy encapsulate. The resulting source has a color temperature around 4000K, and a color rendering index of 75 or lower. The variability in color from source to source, due to the differences in the blue LEDs, is often detectable and the lower color rending quality of the light greatly limits the number of acceptable applications for the light sources. The use of UV LEDs significantly reduces the variability in color form source to source, and greatly improves the color rendition of the lamps. Two phosphor devices have also been proposed which provide much greater flexibility in selecting a color temperature and in improving the color rendition of the devices.[4] Since LEDs are available in red, green and blue, it is possible to mix the LEDs to provide white or any other color desired. This is a popular concept for display applications, as well as other applications that can take advantage of this dynamic effect. To make a single white source from the concept requires control of the intensity of the devices over changes in the operating temperature and life, since performance of the die varies with each parameter and changes in color would be detectable if not controlled. It is possible to achieve color renditions of greater than 80 with 3 carefully selected LEDs but the best performance can be achieved by using 4 or 5 different colored LEDs.[5] While white light from multiple LEDs would be the most efficacious method of producing the light, a single white light source for lighting applications using this technology appears to be a product of the future.

The fourth attribute to be discussed is controllability of these new sources. The LED is made to be controlled, offering more flexibility than another light source. Increasing or deceasing the current through the device easily controls the light intensity; also the energy efficiency of the device is maintained or improved as the device is dimmed. Lower operating currents have a positive affect on the life of the device and if temperature is stabilized there is no change in color at different current loadings. Color can also be controlled over the entire color pallet by varying the intensity of three or more different colored die as discussed in the previous section. A final possibility is that given the low voltage of these devices and the future package configuration it is very feasible that sources will be addressable, allowing the greatest control of performance in future lighting applications.

The fifth attribute to be discussed is product life and lumen maintenance. Product life of LEDs is specified differently from standard light sources. It is defined as the point at which the device reaches 50% of initial light output. Under this definition LEDs without phosphors have lives that exceed those of filament light sources, by a multiple of 2-3 times. Much poorer performance has been realized for white LEDs; however, recent package changes in which the phosphor is suspended in silicon around the die have resulted in white LEDs having better



Source: Ongoing test data from the Lighting Research Center

Figure 4. Relative light output.

lumen performance at 10,000 hours than current fluorescent product, **Figure 4**.[6] This is principally due to the removal of the epoxy from the packaging, which was coloring with age. Hence, product life of LEDs is expected to approach that of LEDs without phosphor.

As these devices become more available due to their increased application in the display and signage industry the cost of product will continue to be reduced. The improvements in performance cited previously, along with reduced manufacturing costs due to process cost reduction and improved yields, are giving greater uniformity and reproducibility among the products, and are thus propelling LEDs towards becoming a significant light source in future lighting applications.

Utilizing LEDs Today

Despite the limits in performance characteristics raised in the technical review above, I encourage potential users of the devices to capitalize on the new form factor that these solid-state devices present. There are three defining characteristics that may appear to be limiting but which, in reality, provide new opportunities. These three characteristics are low operating power, low operating voltage and the very small size of the device.

Low power per device becomes a desired attribute if wattage is a defining limitation of the power system. For example, I was involved in a utility program in Indonesia in 1996 that was designed to transition residences receiving subsidized electricity from incandescent light sources to compact fluorescent lamps. In order to control the subsidy, the utility limited the power supplied to the individual housing units. If the residence exceeded their power limit the circuit to the house would be broken and the residence would be without power. To stay within their rationed power, residences used very low wattage lamps. A typical residence had two 5-watt incandescent lamps, having an efficacy of 10 lm/W. In this application, LEDs may provide a solution for providing more efficient lighting for these residences with a greater number of sources throughout the residence, as well as with added opportunity of aggregating multiple sources at one location when more light is required.

Wattage of the source may also be a significant consideration when the power is limited by the constraints of the delivery system, such as battery life. Extending the electric grid into lesser-developed areas may not always be practical or feasible, and the battery has become the necessary choice of reserved power for many of these locations. The use of LEDs takes advantage of a battery's second characteristic, low operating voltage. The low operating voltage permits LEDs to be powered by a battery without expensive power conversion circuitry or losses to such circuitry. This is exemplified by the work of Dr. Irvine-Halliday [7] within Nepal where the low voltage white LED was the perfect choice for the conversion of power from a small hydro/battery system. Because low ambient light levels were much more acceptable than no light at all, the battery-white LED system provided a rugged, compact, and efficient light source that could be operated for long hours on a relatively small battery system. Examples of this type of application are not limited to less developed countries. For example, a photovoltaic battery-powered LED system was developed by Lars Bylund [8] for use as a guideway lighting system on a highway in Sweden. The system provided sufficient power to operate the LEDs, even through the longest winter nights. The installation provided a cost effective alternative to the installation of costly underground wiring.

Finally, I would like to address taking advantage of the small size of the LED devices. LEDs represent a new form factor in lighting. They are the ultimate point source, given their high surface brightness and very small size. The very small size of the LED permits consideration of different form factors in which optics are integrated with the source to optimize the desired distribution with the greatest system efficiency; sources are available which are efficient and which have very focused beams. At Lawrence Berkeley National Lab, we sought applications that would take advantage of these characteristics. One application, luminaires used to illuminate the doorways of apartments or homes, is currently being studied. In North America the majority of the sources used in this application are incandescent lamps, with compact fluorescent becoming prevalent for buildings that are professionally maintained. The hours of operation are long and may be maintained throughout the night for security purposes. A variety of prototypes have been developed that are energy efficient alternatives to both the incandescent and CFL luminaires currently being used. The new systems utilize an efficient amber LED with a source efficacy > 50 lm/W. Even greater system efficiency is achieved relative to the CFL products, because of the focused distribution pattern of the LED sources, which can be utilized without additional optics. The amber light has the added advantage of not attracting flying insects. This example represents one of many opportunities that exist for these sources where they can effectively compete as energy efficient alternatives to existing light sources, with the added advantages of life, size and durability.

Summary

The signal and display markets have created a demand for LEDs and the market demands of those industries have caused an evolution in their performance. These changes make the LED technology a realistic consideration for lighting applications. Lighting applications require sources with repeatable and uniform characteristics from source to source. The industry has responded to these requirements with improvements in die performance and packaging characteristics, resulting in a remarkable improvement in performance over the last decade, and especially within the last three years. There is every expectation that this improvement will continue, as demonstrated by the product roadmap for performance for white LEDs for one of the leading manufacturers, as shown in **Figures 5 and 6**. [9]

With increases in flux from 25 lumens to 150 lumens per source and with improvements in efficacy from 20 lm/W today to 60 lm/W, all within 3 years, the industry sees the potential of addressing the lighting market and has a plan to provide sources to meet that need.

As these improvements expand the LEDs' potential for general lighting applications, opportunities will arise for using the current technology in many new applications to improve energy efficiency and lighting quality by capitalizing on the unique characteristics of these sources.

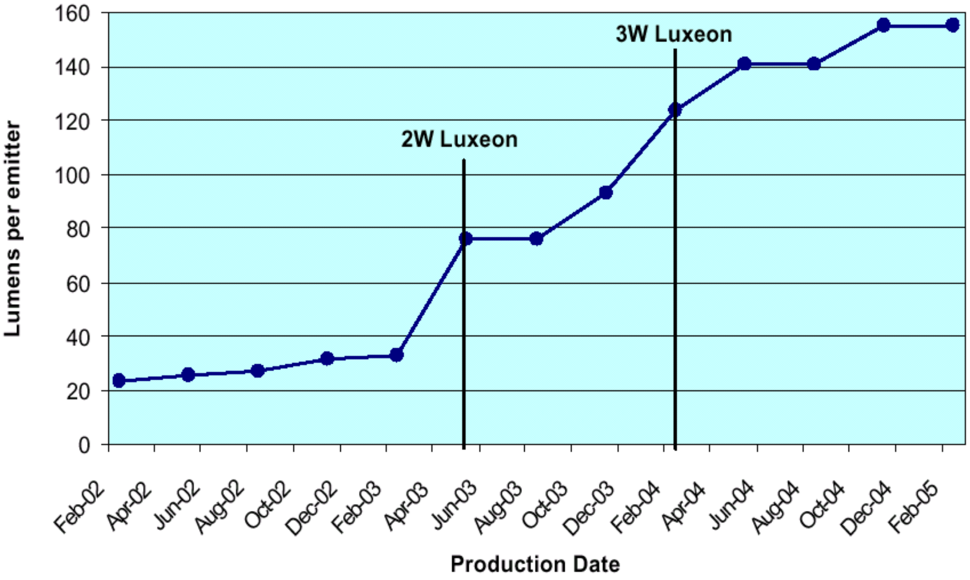


Figure 5. Increase in LED lumen output from present to 2005.

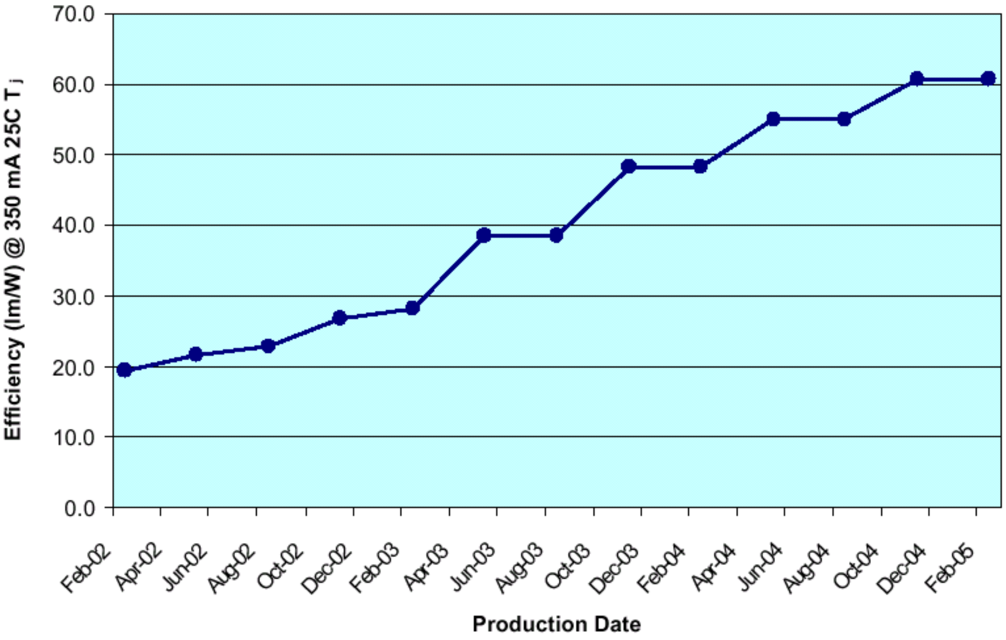


Figure 6. Increase in LED efficiency from present to 2005.

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