IESNA TM-16-05

IESNA Technical Memorandum *on* Light Emitting Diode (LED) Sources *and* Systems

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Prepared by:
The IESNA Light Sources Committee

IESNA TM-16-05

Technical Memorandum on Light Emitting Diode (LED) Sources and Systems

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Prepared by:
The IESNA Light Sources Committee

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Technical Memorandum on Light Emitting Diode (LED) Sources and Systems

FOREWORD

The purpose of this Technical Memorandum is to describe Light Emitting Diode (LED) sources and systems and to answer the most common questions that the lighting industry receives from the curious public. The authors, all members of the IESNA Light Sources Committee, represent a wide cross section of lighting disciplines – from LED-source, lamp, and luminaire manufacturers to lighting-controls producers.

While LEDs operate by converting electrical energy into light energy, this is the only similarity with other light sources in general use today. LEDs look different, are manufactured differently, and are handled differently than other light sources. For example, consumers cannot go to their local hardware store and purchase a replacement “LED lamp.”

LEDs are currently being used in advertising signs, keychain and full-power flashlights, exit signs, traffic signals, and vehicle signaling systems – literally hundreds of unique applications. Research by dozens of companies is underway to deploy LEDs even further. The ultimate goal is to move these special light sources into common usage for general lighting wherever applicable. Therefore, TM-16 will be updated from time to time to report on industry progress toward that end.

1.0 BRIEF HISTORY OF LEDS

1.1 Invention and Development

In 1962, Nick Holonyak of General Electric invented the first practical light-emitting diode operating in the red portion of the visible spectrum. Throughout the later 1960s and 1970s, further invention and development produced additional colors and enabled LEDs to become a readily available commercial product. **Figure 1** illustrates the advances made in LED technology from the 1960s to the year 2000.

1.2 Product Deployment

LEDs were initially deployed as indicators in electronic measurement devices, and later used in seven-segment alpha-numerics that became briefly popular in digital watches and other display applications during the early 1970s. Later, as output power and color variation improved, LEDs were adapted into various other direct displays including traffic lights and automotive applications.

Most often associated with the LED is the classic T-1¾ lamp “bullet shape” because early LEDs retained the outline of the indicator they replaced. Later, surface mount technology (SMT) packaging was adopted because it did not require a through-hole when used on printed circuit boards, and it provided better thermal transfer. As power levels increased, new high-flux packages were developed to handle the increased thermal loads.

2.0 TECHNOLOGY OF LEDs

2.1 How LEDs Work

Basically, LEDs are solid-state semiconductor devices that convert electrical energy into visible light. When certain elements (see **Figure 2**) are combined in specific configurations and electrical current is passed through them, photons (light) and heat are produced. The heart of LEDs, often called a “die” or “chip,” is composed of two semiconductor layers – an n-type layer that provides electrons and a p-type layer that provides holes for the electrons to fall into. The actual junction of the layers (called the p-n junction) is where electrons and holes are injected into an active region. When the electrons and holes recombine, photons (light) are created. The photons are emitted in a narrow spectrum around the energy band gap of the semiconductor material, corresponding to visible and near-UV wavelengths.

Customers can purchase LED products in many different forms since the devices are sold as separate dies or in packages. Engineers, specifiers, and buyers should be directly involved in the specification of the LEDs, drivers, thermal management technology, and other system components to assure that the end product (luminaire) has the performance and life required. Often thermal management, mechanical mounting, driver circuitry, controls, lenses, and optics are offered as an optimized lighting system package (see **Figure 3**).

2.2 Types of LEDs

Discrete LEDs may be sold as the die itself. However, most LEDs are purchased in a package which is a much more usable configuration for the luminaire manufacturer. **Figure 4** shows examples of five different LED packages on the market today and illustrates their approximate size.

2.3 Basic Characteristics

2.3.1 Materials. Assembled as an LED, phosphides and nitrides of aluminum, indium, and gallium produce light of different colors and efficacies. The two major material groups are the InGaP (indium-gallium phosphide) compounds, used to create red and amber, and the GaN (gallium nitride) compounds, used to create blue, cyan, and green. These LED materials can also generate infra-red and ultra-violet radiation outside the visible range.

2.3.2 Size. LED die sizes range from tenths of millimeters for small-signal devices to greater than a square millimeter for the power packages available today. By using multiple dies or groups of packaged LEDs, the light needed by the application can be obtained.

2.3.3 Energy Output. The output of an LED is dissipated as light and heat. The light is emitted from the LED die in all directions. Based on the shape of the die, the material from which it is constructed, and the package in which it is assembled, light from the surface of a packaged LED can be captured for use in a lighting system. Heat is not radiated (as it is with conventional lighting technology) but is retained in the LED package. Heat must be effectively conducted away from the die by the packaging materials or the device leads. Without proper thermal management, internally-generated heat can cause packaged LEDs to fail. No infra-red or ultra-violet energy is emitted in the beam of a visible LED.

2.3.4 Color. The color of an LED is determined by the dominant wavelength of the device. Typical single-wavelength LED output falls on the standard CIE chromaticity diagram as shown in **Figure 5**.

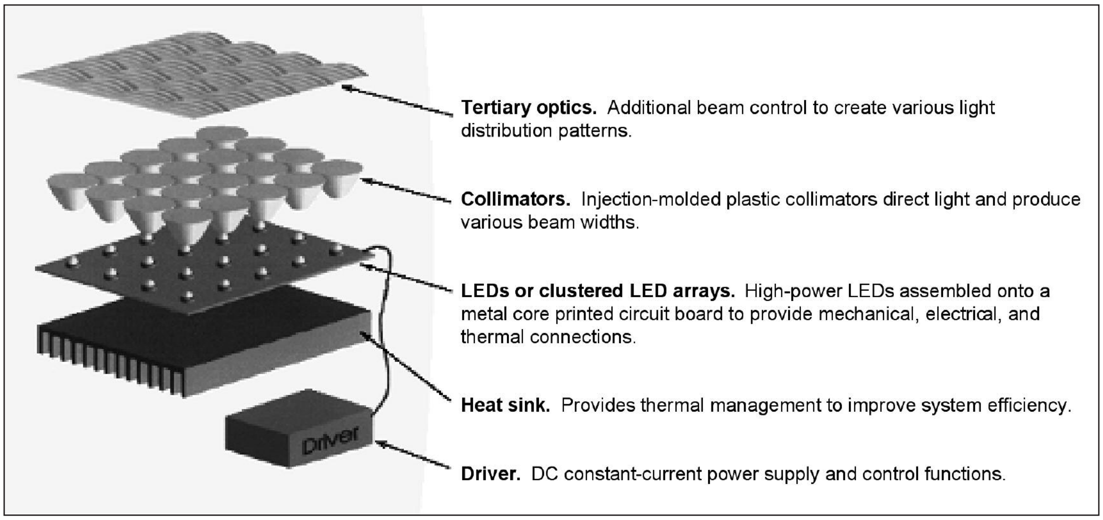


Figure 3. This typical packaged LED system contains multiple elements stacked together for optimum performance.

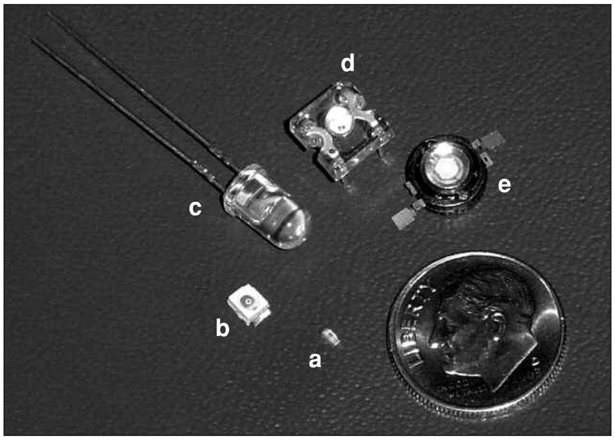


Figure 4: Common LED packages shown alongside a U.S. dime (17.9 mm diameter): (a) surface mount (<1 mm^2 area); (b) surface mount (~3 mm^2 area); (c) T-1¾ lamp style (5 mm diameter), (d) super flux design (7.6 mm^2 area); and (e) high-flux power design (~8 mm diameter).

2.3.5 "White" LEDs. White light can be obtained from LEDs by any of the following three methods:

Color mixing: the primary light from three individual LEDs (red, green, and blue) is mixed together, creating white light (see **Figure 6** for an illustration of the color mixing principle).

Binary complementary wavelength conversion: a blue LED is complemented with a yellow phosphor and white light is created. Cool white LEDs (with a typical color temperature of 5500 K) are produced in this manner. By adding a secondary red phosphor, warm white LEDs (with a typical color temperature of 3200 K) are produced.

Ultra-violet wavelength conversion: a single ultra-violet LED is used to excite a tri-color phosphor, thus creating white light.

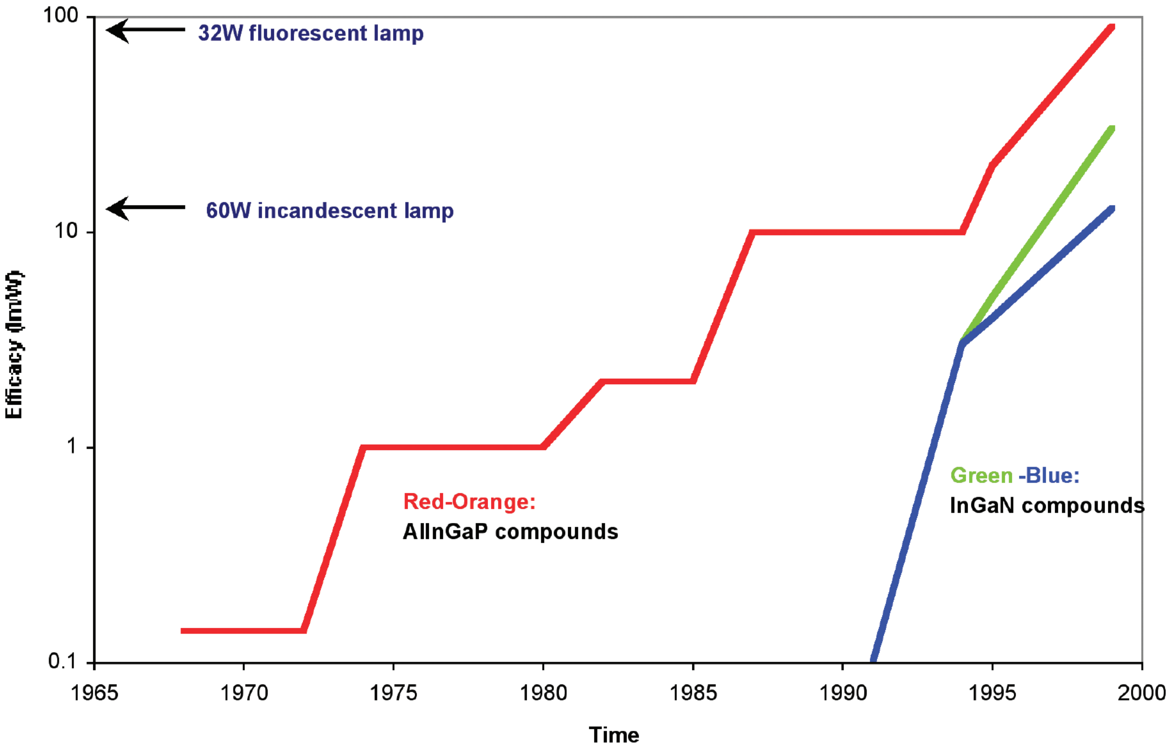
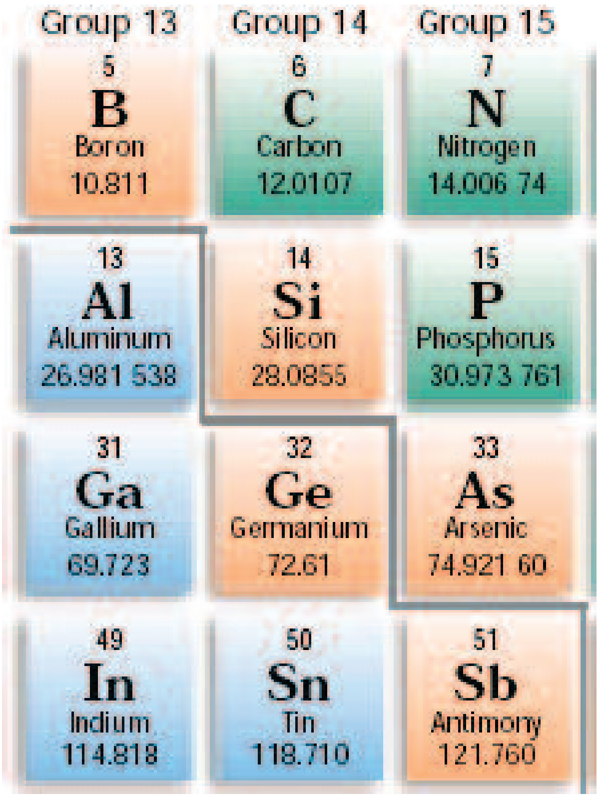


Figure 1. The evolution of efficacy of solid-state lighting technologies as reported for laboratory models. The efficacy of a 60-W incandescent lamp at 14 lm/W and a 32-W fluorescent lamp at 94 lm/W are shown for comparison purposes only. [adapted from *Light emitting diodes (LEDs) for general illumination – an OIDA technology roadmap update 2002*].



Group 13	Group 14	Group 15
5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.006 74
13 Al Aluminum 26.981 538	14 Si Silicon 28.0855	15 P Phosphorus 30.973 761
31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.921 60
49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760

Figure 2. These 12 elements are important to the construction of LEDs. Elements shaded orange are base materials; elements shaded blue are p-type dopants; elements shaded green are n-type dopants.

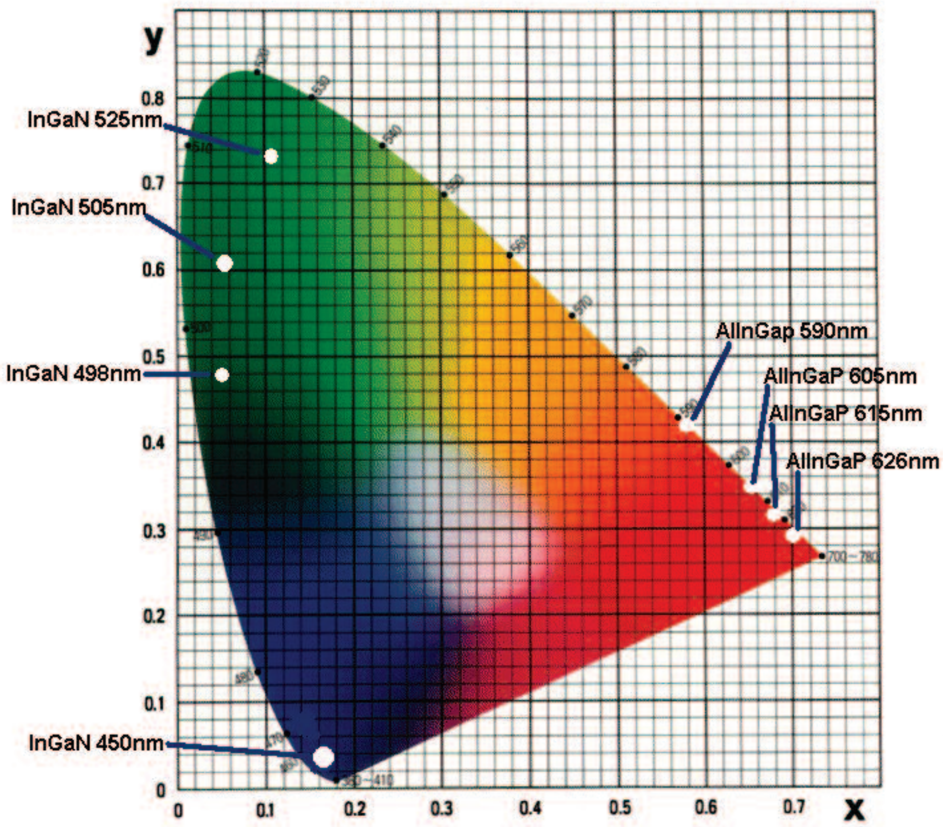


Figure 5. Chromaticity coordinates of typical single-wavelength LEDs shown on a standard CIE chromaticity diagram [adapted from *Schubert and Miller,* 1999].

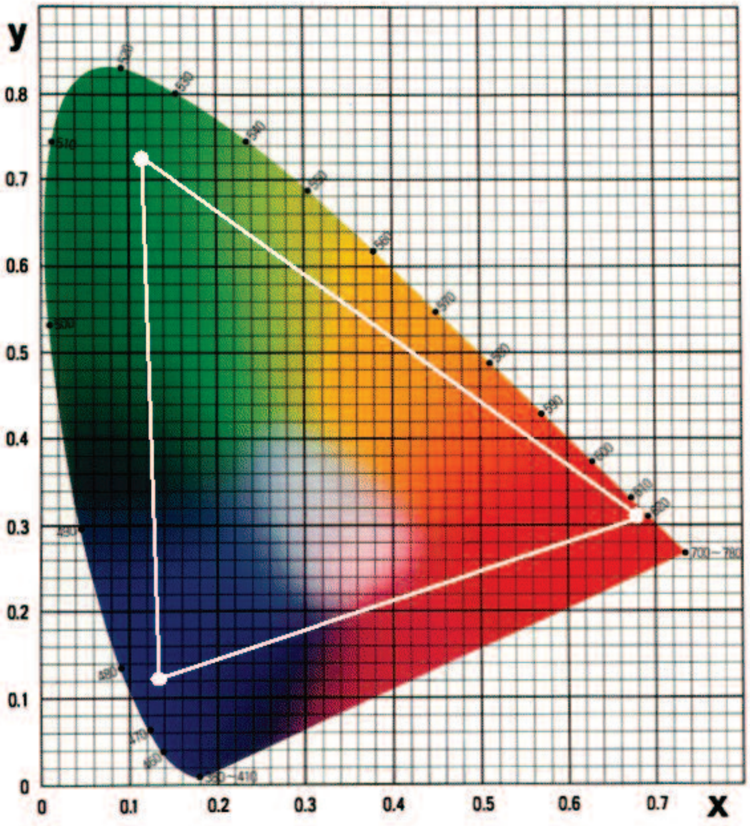


Figure 6. This diagram illustrates the principle of color mixing. The triangular area shows the possible chromaticity coordinates that can result from mixing together the light from red, green, and blue LEDs [adapted from *Schubert*, p. 190].

Table 1: Three Methods of Creating White Light with LEDs (Evaluation Summary)

	(1) RGB White	(2) Blue LED + Yellow (+Red) Phosphor	(3) UV LED +RGB Phosphor
ADVANTAGES	• Color can be changed dynamically • As a luminance source, millions of colors can be produced • Highest efficacy	• High efficacy • Technology exists today • Cool white (5500 K, 70 CRI) • Warm white (3200 K, 90 CRI)	• Potential for limited "tint" variation • Simple ballast (driver) • Good color uniformity
DISADVANTAGES	• Requires more complex driver electronics • Color shifts due to temperature and aging • As an illumination source, color rendition can be poor	• Potential for "tint" variations • Tint variation must be controlled optically and by (bin) selection	• Lower efficacy • New phosphor development required • Potential UV packaging problems • Shorter life • Clouding of the epoxy

The advantages and disadvantages of each method are summarized in **Table 1**.

2.3.6 Luminous Flux. Luminous flux refers to the total light available from an LED and it is measured in lumens (lm). This amount varies according to the LED's color, and depends on the current density the LED die can manage. Package properties also limit the electrical current that can be safely driven through LED assemblies. The more current an LED device can handle, the more luminous flux it will produce. At this time, small-signal white LEDs can produce approximately 2-4 lm in a 5-mm package when driven at 20-30 mA. Power-packaged white LEDs can produce 25-120 lm when driven at 350-1000 mA.

2.3.7 Efficacy. LED system efficacy is defined as the luminous flux (lumens) produced by the system divided by the system power input (Watts) and is expressed lm/W. This efficacy has increased since LEDs were first introduced (see **Figure 1**), and is projected to increase further according to an industry technology roadmap (see **Table 2**).

2.3.8 Life. While LEDs are considered very reliable, there is as yet no agreement on the definition of LED-source or LED-system lifetime. Since LEDs do not have failure-prone filaments, their lifetimes are significantly longer than incandescent or halogen devices. However, the light output from an LED will deteriorate over time due to other mechanisms. An LED's color and the different assembly materials used in LED production cause the light output to decrease at various rates. This effect, termed lumen depreciation, may involve thousands of hours of operation before it is noticeable. Thus, one possible "lifetime" definition is the time required for an LED's output to fall to a certain percentage of its initial output.

The best LEDs achieve 70 percent lumen maintenance at 50,000 hours of operation under standard use conditions. The critical requirement for a successful LED system is that the luminaire remove excess heat from the package, keeping the LED die junction below its maximum rated temperature during system operation. In addition, in phosphor-converted LEDs (phosphors added to the encapsulant material convert the LED color from blue to white), the dome material in some packages can eventually cloud because the blue light affects the epoxy. Clouding causes a rapid degradation in light output so it is critically important to understand what type of white LED is being used in an application to assure the necessary life. It is recommended that the luminaire or LED manufacturer provide lumen maintenance curves that clearly specify the mean percentage of initial luminous flux available from the LEDs being used over the lighting system's expected operating hours. LED system light degradation is extremely dependent on heat management design, support component selection, and manufacturing process control. Therefore, a total system light output degradation curve should also be requested from the manufacturer.

Table 2: SSL-LED Lamp Performance as of 2002 and at Projected Target Dates*
(developed by an industry-wide conference sponsored by the U.S. Department of Energy)

Technology → **[*date*]** →	*SSL-LED 2002*	*SSL-LED 2007*	*SSL-LED 2012*	*SSL-LED 2020*	*Incandescent 2002*	*Fluorescent 2002*
Luminous Efficacy (lm/W)	25	75	150	200	16	>85
Lifetime (khr)	20	>20	>100	>100	1	>20
Flux (lm/lamp)	25	200	1000	1500	1200	3000
Input Power (W/lamp)	1	2.7	6.7	7.5	75	32
Lumens Cost ($/klm)	300	20	<5	<20.4	1.5	
Lamp Cost ($/lamp)	5	4	<5	<3	0.5	5
Color Rendering Index (CRI)	75–90	80–90	80–90	80–90	100	>80
Chip Temperature (°C)	100	300–600	500–750	600–1000		
Input Power Density (W/cm²)	100	300–600	500–750	600–1000		

**Note*:

(1) Metrics for color quality appropriate for SSL-LEDs have not yet been developed; hence the CRI values should be thought of as interim targets.

(2) The lumens and lamp costs shown are “street” costs, roughly two times higher than OEM costs.

(3) Values in the columns denoted by *SSL-LED 2007, SSL-LED 2012,* and *SSL-LED 2020* are targeted (future) values from the LED roadmap developed by an industry-wide conference sponsored by the DOE. Values in all the other columns are valid as of 2002 [adapted from *Light emitting diodes (LEDs) for general illumination – an OIDA technology roadmap update 2002 – November 2002*].

(4) The columns denoted by *Incandescent* and *Fluorescent* contain nominal, commonly-achievable values presented here for reference

2.4 LED System Components and Their Operation

2.4.1 Electrical Model. LEDs are diodes specially designed to convert electrical energy into visible light. Such a diode comprises a layer of n-type material bonded to a layer of p-type material, with electrical connections on each side. This arrangement conducts electricity in only one direction. When no voltage is applied to the diode, electrons from the n-type material fill holes from the p-type material along the junction between the layers, forming a depletion zone. In the depletion zone, the semiconductor material is returned to its original insulating state – all of the holes are filled, so there are no free electrons or empty spaces for electrons, and charge does not flow.

But now consider what happens when a voltage is applied across the p-n junction, with the n-type material connected to the negative side of the circuit and the p-type material to the positive side. If the voltage difference across the junction is high enough, electrons in the depletion zone are boosted out of their holes and begin moving freely again. The depletion zone disappears, current flows, and the interaction between electrons and holes has an interesting side effect – it generates light. This happens because free electrons (moving across the p-n junction) fall into empty holes from the p-type material and release energy. **Figure 7** shows the electrical model for LED operation.

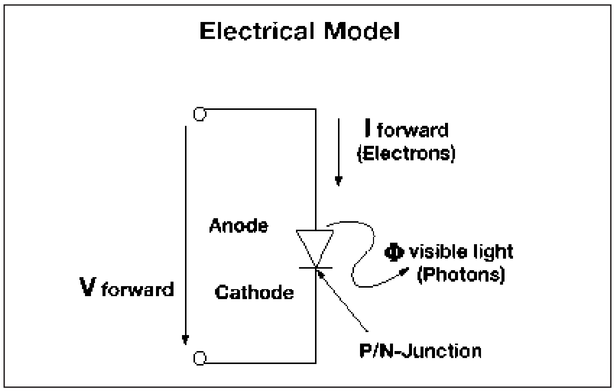


Figure 7. When the external voltage ($V_{forward}$) applied across the p-n junction of an LED is high enough, current ($I_{forward}$) flows and visible light is produced (photons).

2.4.2 Power Source. LEDs are low-voltage current-driven devices. Power sources include electronic circuit choices such as drivers and switch-mode power supplies. A single direct-current (dc) power source may drive one LED or a cluster of LEDs. Essentially there are three ways to design a dc power source for driving an LED cluster: a series circuit, a matrix circuit with one resistor for the entire circuit, and a matrix circuit with one resistor for each LED. Each design option has advantages and disadvantages that depend on the end application and its lighting requirements.

2.4.3 Thermal Interface. Die-to-luminaire thermal resistance, thermal stress, and temperature gradients within the LED are all critical to successful LED system operation. The die-to-luminaire thermal resistance must be less than about 30°C/W (achievable with current high-power LED packaging). Thermal stress reduction requires excellent thermal management so that temperature gradients within the package, particularly at the package/chip interface, are minimized. Thermal management is especially important for multiple-color LED illumination strategies, as the temperature sensitivities of GaN-based and AlInGaP-based LEDs are significantly different. In-package electronics may be required that dynamically adjust the ratio of blue, red, and green to maintain a constant white point.

2.4.4 Optical Coupling. Typically, an LED package uses an optically-clear material (encapsulant) to form a lens atop the LED die. In some cases, such as the T-1¾ package, this material forms the body of the whole device. This provides an optical path, a mechanical means to hold everything together, and protection for the wire bond to the die. As an optical element, the encapsulant should have a high index of refraction and good stability in the presence of humidity, high temperature, and high intensity light. Often additional collimation or tertiary optics is required to properly direct the light from LEDs or LED arrays.

2.5 Limitations

2.5.1 Vibration. LEDs are solid-state devices that do not use gases or filaments. Thus extremely high reliability against mechanical shocks and vibrations is achieved.

2.5.2 Moisture. Individual LEDs are reasonably moisture-tolerant. However, the electronic circuitry that surrounds them in a system is not. LED systems must be properly designed and tested to assure they will operate in a high-moisture environment.

2.5.3 Temperature. For high brightness solid-state lighting, high operating current densities (and thus high junction temperatures) are necessary. To date, reliability of AlInGaP LEDs show dependence on both current density and junction temperature. More light output degradation occurs whenever either of these parameters is increased. Therefore, it is critical that the specified LED junction temperature not be exceeded for effective LED system operation. A well-designed system will follow the LED manufacturer's junction temperature guidelines. Whenever LED systems are deployed in extreme temperature environments, contact the system manufacturer for guidance.

2.5.4 Lumen Depreciation. Lumen depreciation is the lighting attribute most often used to determine the useful life of LED sources. LEDs do not fail abruptly; instead, they dim with time. Although a "100,000 hour" life is commonly cited, it is not an accurate description of an LED's useful or meaningful life. Many LEDs will still emit some light at 100,000 hours, although the amount might not be enough for many applications. It is now common to quote "70 percent of original light output" as the light required for most illumination needs. Therefore, industry committees are now recommending that "70 percent lumen maintenance at 50,000 hours of use" be adopted as a standard for LED sources in illumination applications.

LEDs of different colors do not have identical lumen depreciation rates. Various packaging materials and manufacturing methodologies can also influence depreciation rates in the same base color. When a system uses multiple-color LEDs, the driver/control software should take into account these varied depreciation rates so that system performance change is minimized over time.

For illumination applications, white LEDs have been studied by independent research laboratories, and the resulting lumen maintenance data have been published (see **Figure 8**).

It is important that the customer specify exactly what LEDs the manufacturer will install in the finished product. Lumen depreciation curves should be provided upon request. Of critical importance is that the expected LED performance is only possible if the LED manufacturer's published operating specifications are met. The lumen depreciation specification of the luminaire must allow for system operation. Thermal management, control, current levels, and other electrical considerations must be taken into account. If the application requires the longevity of a properly integrated LED system, it is recommended that the luminaire manufacturer provide the specifier with system-level lumen depreciation data.

2.5.5 Reducing Batch Variations. With the current manufacturing technology, small (but noticeable) vari-

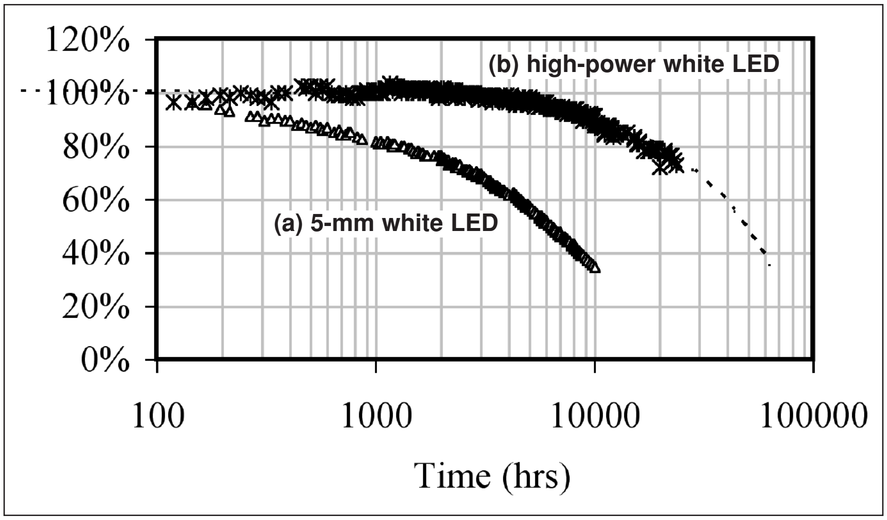


Figure 8: Lumen maintenance data at room temperature for two types of white LEDs: curve "a" describes a 5-mm white LED driven at 20 mA; curve "b" is for a high-power white LED (adapted from N. Narendran and L. Deng, "Performance characteristics of light emitting diodes," ***Proceedings of the IESNA Annual Conference*****, pp. 157-164, Illuminating Engineering Society of North America, Salt Lake City, Utah, August 4-7, 2002)**

ations in initial color appearance and light output occur between LEDs. To reduce the variation within batches, manufacturers test and sort the LEDs into bins. This way, customers can purchase LED batches with a consistent appearance.

2.5.6 Chip-level Light Extraction. Though already an efficient light source, LEDs still have a long way to go before their full potential is realized. While up to 95 percent of the electrons passing through LEDs produce photons, the LED chip itself is effectively a "photon trap" – most of the light generated is internally reflected by the chip surfaces and absorbed, creating heat. Only about 15 percent of the light gets out of the LED package.

Manufacturers are developing techniques to improve the light extraction from LED chips. There is also research underway at the quantum level regarding the material structure itself that will further augment efficiency.

The efficacy of individual LEDs varies by material type, packaging, radiation pattern, phosphors, and processing. The best LEDs in production today deliver 10 to >55 lm/W. (Experimental LED dies in the research labs have already yielded greater than 100 lm/W.) The efficacy range can best be observed by color. The luminous efficacy of a representative manufacturer's production run of 1-watt LEDs (as of 2004) is shown in **Table 3**:

Table 3: Luminous Efficacy of Production Run 1-watt LEDs (as of 2004)

Color	Wavelength (nm)	Efficacy (lm/W)
White (5500 K)		25
Warm white (3200 K)		22
Green	530	30
Blue	470	10
Red	625	44
Red-Orange	617	55
Amber	590	36

From a lighting system perspective, there are two important factors to note regarding LED system efficiency, *energy efficiency* and *utilization efficiency*:

1. A solid-state LED luminaire must be considered a lighting system and the total *energy efficiency* of the system must be accounted for, not just the efficiency of the LEDs. For instance, LED luminaires that use twenty 1-watt LEDs will consume more than 20 watts because the driver and other design elements in the luminaire also use energy. Depending on the efficiency of these other elements, the total power consumption for the luminaire could be 21-25 watts. When specifying the entire energy requirements for a site, the total power consumption of each luminaire should be taken into account.

2. With LED luminaires the *utilization efficiency* of the produced light must also be taken into account. LEDs typically provide directed light, whereas conventional non-reflector lamps emit omni-directional light. This directional quality can actually be turned to considerable advantage in a properly engineered LED luminaire. For instance, consider a High Pressure Sodium (HPS) lamp delivering 100 lm/W vs. an amber LED yeilding 50 lm/W. In a directional application (e.g., light for a pathway), light from the HPS lamp must be collected and re-directed. Generally, the smoother the beam pattern and the sharper the cut-off, the lower the system efficacy. Thus, to place even light on a pathway, the HPS luminaire might deliv-

er only 40 percent of the lamp's luminous flux onto the surface. Such a luminaire, with a 100-lm/W HPS lamp inside, has a system efficacy of just 40 lm/W. Now consider light from LEDs that is typically directed from the outset. For path lighting, the necessary optics need only collimate the light. Assuming the same need for beam control (and assuming a 20 percent loss from luminaire optics), a 50 lm/W amber LED will also deliver 40 lm/W to the path surface. While this simple example underestimates the efficiencies of both HPS pathway lights and LED optics, the significantly higher utilization efficiencies possible with LEDs in directional applications (relative to conventional sources) should be considered.

2.5.7 Light Degradation and Color Uniformity. One of the key limitations affecting LEDs is temperature. The maximum die junction temperature will vary from one LED manufacturer to another, so it is best to refer directly to each manufacturer's specification sheet. A common maximum junction temperature rating is 135°C (275°F), although many manufacturers continue to improve upon this number. A good rule of thumb is that the higher the design junction temperature, the faster the light output will degrade. To establish a specific light degradation rate, caution demands an appropriate luminaire design. For a minimum die junction temperature, things such as ambient temperature and the thermal resistance of the overall package must be accounted for. Most leading LED manufacturers offer technical support in this area. It is recommended that designers contact them directly with any detailed questions about heat dissipation.

An area of limitation for "white" LEDs is full distribution color uniformity because white LEDs have a range of chromaticity coordinates. Compared to fluorescent lamps, the range is wider and produces noticeable color differences to the human eye. But batch binning is often not necessary since multiple LEDs are usually required and the light from all these LEDs is blended together. Distribution effects can be further minimized by using a lightly tinted color filter/gel or by having an acrylic lens for the design made from tinted resins. These practices are already common to fluorescent luminaire applications.

2.6 Specifications

The general specifications for LEDs as of 2002, as well as the anticipated roadmapped values were developed by an industry-wide conference sponsored by the U.S. Department of Energy (see **Table 2**).

2.7 Safety

Since LEDs are low-voltage devices, LED systems are safer than other lamp systems that require high voltages. In addition, visible-wavelength LEDs do not generate appreciable amounts of ultra-violet or infra-red. If the application involves high-flux LEDs deliverring a very collimated light pattern, eye safety standards may be applicable and should be investigated. For more information refer to the ANSI/IESNA RP-27 publication series on photo biological safety.

2.8 Environmental and Disposal Issues

As LED systems become more efficient, the environmental benefits from decreased energy consumption will increase. Since LEDs are solid-state devices, they do not contain mercury, glass, filaments, or gases. Because LEDs are small and have long lifetimes, their use might reduce the material flow entering the waste-stream. Consult local regulations concerning disposal.

3.0 LED APPLICATIONS

3.1 Existing Applications

Traffic Signage – The traffic signage market has a largely incandescent base and includes traffic signals, pedestrian signs ("ped heads"), highway sign panels, railroad signals, marine navigation, and beacon lights at airports. The main drivers for conversion to LEDs are higher efficiency, reduced maintenance, and increased visibility.

Architectural – LEDs lend themselves to architectural lighting. Various shapes and sizes are available in a wide variety of colors that easily adapt to multiple *exterior* and *interior* tasks.

- *Exterior:* Exterior effects can be achieved easily with LED lighting. The wide variety of colors can be controlled to produce a changing semblance based on particular variables such as the time of day or season. Due to their long life, LEDs can be used in hard-to-reach areas where maintenance is difficult. Such areas include bridges, stairs, walkways, and building structure outlines. There are already installations where 4-8 stories of architectural building elements are illuminated with LED arrays. As LED light output levels keep rising, architectural lighting use will continue to expand.

- *Interior:* Their rich colors, long life, low operating costs, and tremendous design flexibility make LEDs a serious choice for interior decorative lighting and feature lighting. LEDs already provide mood and effect lighting in many clubs and restaurants. Mall food courts, kiosks, seasonal displays, movie theaters, gaming, and point-of-sale displays are just some of the other interior areas that can similarly benefit.

Signage – While backlighting with fluorescent lamps is still economical and practical for signs with large surface areas, LEDs are advantageous for the smaller sizes. Current use includes exit signs, channel letters*, and street signs. Long life and superior visibility make LEDs an excellent choice during emergency conditions.

Safety – Long life, directional output, and design flexibility make LEDs a good choice for exit signs, ingress/egress lighting, walkway lighting, and step lighting. For ingress/egress lighting, one popular use involves embedding LED strips into the floor of spaces that are often dark or that only have low-level lighting (such as a movie theater). LED strips are also designed into passenger aircraft to provide light during emergency conditions. Walkway and step lighting can also benefit from such LED strips.

Automotive – In automotive interiors, LEDs serve as switch indicators and map lights. On automotive exteriors, LEDs are found in center (high mount) stop lamps, rear combi-lamps (stop, turn, tail), side marker lights, and mirror puddle lamps†.

Displays – LEDs can be used for backlighting liquid crystal displays, or they can be the display itself (called an “active display”). In some cases, LEDs are displacing traditional sources such as electro-luminescent (EL) and cold cathode fluorescent (CCFL). One disadvantage in using LEDs for backlighting is non-uniformity over the display area. Active displays include moving messages, marquis, building façade graphics, and scoreboards. These active displays take advantage of the control available over each discrete LED’s state and brightness. A very dynamic presentation can thus be created.

Task Lighting – LEDs can provide *task lighting* for desks, workstations, and display-cases; *downlighting* for elevators and emergency applications; *appliance lighting* for refrigerators and vending machines; and *portable lighting* for flashlights, miners’ lights, and dive lights.

Medical Lighting – Dental headlamps and microscope illuminators exemplify LEDs applied to medical illumination. Additionally, certain LED wavelengths will activate some chemical reactions. Such LEDs are now being used for curing dental epoxies in the mouth and for photocuring compounds used to treat skin cancer, acne, and other dermatological imperfections.

3.2 Potential Future Applications

General Lighting – Because they are nearly point sources, LEDs can deliver directed light efficiently to small areas. Their compactness enables the design flexibility of unobtrusive and architecturally blended luminaires. Ruggedness enables LEDs to mount in high-stress positions. Moreover, it may be possible to program their color and direction for optimal interaction with the human eye. However, designers are still at a very early stage in understanding how new LED applications might emerge based on the following advantages:

- steady output color at all levels of illumination
- ability to continuously vary output color
- simplified and flexible design for mounting and for luminaires
- ease of integration with advanced lighting controls for buildings
- low voltage operation permitting safe power distribution
- ease of miniaturization – the small size of the light source means new LED-based lighting equipment can be smaller, thinner, and lighter
- simple structure – no special devices needed to control the lighting while the components count in the support equipment is reduced
- flexible and efficient light distribution – solid-state lighting devices can be manufactured as flat packages of any shape that can be placed on floors, walls, ceilings, or even furniture, and coupled to light pipes (or other distribution systems)

Feature Lighting – Because solid-state lighting has the unique ability to maintain its luminous efficacy even at very low outputs, dimmability will likely prove an important feature. Moreover, it may be possible to change the color and quality of the light simply by altering the currents that drive LED chips mounted in the lamp.

Automotive – Already announced for 2005 model year cars are forward-projection daytime running lamps. Full LED headlamps are expected to be in production by 2007 or 2008.

Large Screen, LCD Display Backlighting – LED backlighting for liquid crystal display (LCD) screens is currently under development by most major display

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* “Channel letters” are opaque alphanumeric letters used in sign lighting that have the shape of a channel on their back side to accept a linear light source, such as a fluorescent lamp or string of LEDs.

† “Mirror puddle lamps” are LED lights on the underside of exterior car mirrors that illuminate the area around the car door. This (hopefully) permits automobile passengers to notice puddles before stepping into them.

Annex A – For Further Reading

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Annex B – Glossary

AlInGaN (Aluminum Indium Gallium Nitride) semiconductor materials used to make LEDs. Mixtures of these particular elements primarily produce blue, green, and white LEDs. Also referred to as InGaN, GaN, and nitride.

AlInGaP (Aluminum Indium Gallium Phosphide) semiconductor materials used to make LEDs. Mixtures of these particular elements primarily produce red and amber LEDs.

ambient lighting lighting throughout a general area.

ambient temperature temperature of the surrounding environment.

array see **LED array**.

bin, rank, batching, sorting, or **grouping** a subset of the full distribution of product produced in LED manufacturing. During the manufacturing process there are many variables in determining LED characteristics and, as a result, performance can vary from LED to LED. Variations occur in both light output and electrical characteristics, and LEDs are often sorted depending on particular values for these variations. LED manufacturers typically test and identify color, flux or intensity, and forward voltage for each individual LED, then package them in these subsets for ease of manufacturing.

candela, cd unit of luminous intensity. One candela equals one lumen per steradian.

candlepower, cp luminous intensity expressed in candelas.

chip a very small square of semi-conducting material. Also known as a "die," it is the "active" light-emitting component of LEDs.

color see **dominant wavelength**. LEDs are formulated to emit specific colors. In order to specify LEDs, it is beneficial to identify the color or dominant wavelength range required for your application. Some applications may have color constraints in order to meet specific government specifications or regulatory guidelines.

color bin LEDs are sorted according to their wavelength or CIE chromaticity coordinates into different groupings or "bins."

controller see **LED driver**.

CSA Canadian Standards Association.

current control technology this is the technology present in drivers that allows the operation of LEDs at their specified current without the use of resistors or other current-limiting components.

current regulator see **LED driver**.

die see **chip**.

diode usually a semiconductor device that conducts electric current in one direction only.

dominant wavelength a quantitative measure of the color of LEDs as perceived by the human eye. Wavelengths are represented on the perimeter of the CIE chromaticity diagram and are usually measured in nanometers (a billionth of a meter).

driver see **LED driver**.

efficacy a measure of the luminous efficiency of a light source, efficacy is the quotient of the total luminous flux emitted by the total lamp power input, expressed in lm/W.

energy band gap the energy separation between the top of the valence band and the bottom of the conduction band for electrons in a semiconductor.

FCC Federal Communications Commission.

forward current current through a diode in the direction of its greatest conduction. See also **reverse current**.

forward voltage (VF) the voltage across a diode for a given forward current. See also **reverse voltage**.

GaN see **AlInGaN**.

HID high intensity discharge.

IC integrated circuit.

illuminance density of the luminous flux incident at a point on a surface. It is the quotient of the luminous flux divided by the area of the surface when the latter is uniformly illuminated.

InGaN Indium Gallium Nitride. See **AlInGaN**.

intensity bin LEDs are sorted according to their intensity values into different groupings or "bins."

junction see **p-n junction**.

LCD liquid crystal display.

LD laser diode.

leadframe a metallic frame used for mounting and connecting LED chips. The leadframe functions as the electrical path for the device.

LED (light emitting diode) a compound semiconductor, p-n junction device (diode) that converts electrical energy directly into a discrete color of light. LEDs are created from formulations of III-V compounds – combinations of elements from columns III and V in the periodic table. Their energy band gaps span the range appropriate for visible and near-UV light emission.

LED array clusters of LEDs assembled onto a mechanical surface.

LED binning see **bin**.

LED driver (current regulator) LED drivers effectively provide the same function as ballasts in traditional lighting products. Drivers regulate power to the LED, thereby controlling the brightness or intensity of the LED. The driver system converts the supply voltage to a dc voltage and provides a dc output current to the LED. It holds the current at a constant level/output over variable supply voltage ranges.

LED lighting system in LED lighting systems, the basic elements needed to create effective light are the power source, the LED driver, heat management components, and the LED or LED array. The LED driver is the power regulator for the system. Often, collimation and/or secondary optics are needed to maximize light utilization. In more complex systems, communications protocols (software) might be necessary to control the use of the light.

lumen, lm the SI unit of luminous flux, equal to the luminous flux emitted per unit solid angle by a standard point source having a luminous intensity of 1 candela.

luminance density of luminous flux leaving a surface in a particular direction. It is the quotient of the luminous intensity of the source in the direction of measurement by the projected area of the source in that direction.

luminous efficacy see **efficacy**.

luminous intensity a measure of the directional quantity of light generally expressed in candelas. It is defined as luminous flux per unit solid angle (steradian) in a given direction.

milliampere, mA a unit of electrical current equal to one one-thousandth of an ampere.

MRO maintenance, repair, and operation.

MTBF mean time between failures.

n-type semiconductor a semiconductor which has an excess of conduction electrons. It is produced by adding trace amounts other elements to the original semiconductor crystal (such as adding phosphorus to silicon).

nitride see **AlInGaN**.

OLED organic light emitting diode. A light-emitting device built with organic (plastic) semiconductors (compared to LEDs built with inorganic semiconductors).

p-type semiconductor a semiconductor which has an excess of conducting holes. It is produced by adding trace amounts of other elements to the original pure semiconductor crystal (such as adding gallium to silicon).

package a pre-assembled LED unit. LEDs are available in a variety of packages, from surface mount devices to leaded through-hole devices. Common through-hole package sizes include 3 mm (T-1), and 5 mm (T-1¾) diameters. Surface mount packages are available in small-signal (20 mA) and power packages (up to 1 A).

parallel electrical condition where a group of LEDs operates under the same voltage provided by a single driver. If one LED expires, the rest continue to operate.

peak wavelength for a light source, the wavelength at which maximum radiant power is produced. See also **dominant wavelength**.

p-n junction the actual junction of the two types of semiconductor materials used in the construction of the LED die.

reverse current current flowing through a diode in the direction opposite to the direction of maximum conduction.

reverse voltage (VR) voltage across the diode for a given reverse current.

series electrical condition where a series of LEDs operates from current provided by a single driver. Should one LED expire (creating an open circuit), the others in the series will not operate.

steradian, sr the common unit used to measure solid angle, equal to a unit area cut in the surface of the unit sphere. Since the surface area of the unit sphere is

4π, the maximum solid angle is 4π steradians.

SSL solid-state lighting.

SMT surface mount technology.

through-hole the operation of mounting electronic components through holes in a printed circuit board is termed through-hole assembly. Through-hole assembly involves two main processes: (1) inserting the component parts and (2) soldering the component leads to the printed circuit board.

UL Underwriters Laboratories, Inc.

viewing angle the viewing angle of a discrete LED is defined as two times the angle at which the on-axis light emission is diminished to half intensity.

Notes