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LED Lighting – Separating Fact From Fiction

2014 Update

The Potential of LED Systems

The planet is facing an energy crisis, and while much of the focus is on increasing existing capacity and developing alternative energy sources, energy conservation technologies are a crucial component of any long-term energy solution.

Lighting is the largest consumer of electric energy in U.S. retail establishments and office buildings and accounts for nearly 20% of the world's total electric consumption. However, conventional lighting technologies have already peaked, and they do not offer the efficiency characteristics necessary to meet the growing energy needs of the planet.

LED sources are a new provider of white light with the potential to change the way we live and the rate at which we consume energy. When this clean, energy-efficient technology realizes its full technological and market potential:

- Worldwide electricity consumption due to lighting will be decreased by more than 50%, and total consumption of electricity will be decreased by more than 10%.
- Carbon emissions and new capital infrastructure associated with electric power generation will decrease proportionately.
- Hazardous waste that exists in today's conventional light sources, such as mercury in fluorescent and high--intensity discharge (HID) lamps, will be eliminated.

This white paper explains the basics of LED technology, clarifies the current challenges of LED products, and examines the benefits of emerging LED solutions. This information will allow the reader to compare the various LED lighting products available on the market and choose a system that best fits his or her application needs.

Description of LEDs

How They Work

A light-emitting diode, or LED, is a semiconductor that, when connected to the appropriate electrical input, yields photons of light. It is a two-terminal diode composed of a positive layer and a negative layer that meet at a junction called a depletion region. Under operation, electrons flow across the depletion region, which in turn releases photons.

LEDs are typically grouped into two families: indium gallium nitride (InGaN) and aluminum idium gallium phosphide (AlInGaP). InGaN LEDs have a larger energy band gap between the positive and negative layers and are used in applications targeting wavelengths below 600nm, visible as purple/blue/green light. AlInGaP LEDs have a small energy band gap between the layers and are used in applications targeting wavelengths longer than 600nm, visible as yellow/amber/red light. Due to the different material makeup between these two LEDs, they do not exhibit the same properties. Typically, InGaN LEDs are more thermally stable in regard to emission and dominant wavelength compared to AlInGaP LEDs.

Since white is not a single wavelength (or color), but rather a collection of wavelengths, there are two popular ways to achieve a "white" output from LEDs. The first is called phosphor-converted, or PC. This method relies on the use of a shorter-wavelength (InGaN) LED coated with a scintillator (type of phosphor), which mixes with the shorter wavelength LED output to create a white output to the human eye. The other method is called color mixing. This method relies on the mixing of multiple individual LEDs (sometimes within the same package) to achieve an overall white output in appearance. PC white is currently the most popular method in lighting, but it is expected that color mixing will become the dominant form of achieving white once the LED industry has matured, because it will allow for greater efficacy and control.

LED Power Levels

There are four main types of LED packages:

1. Low-power, which are typically used in indicator applications and driven at ≤0.15W of power.
2. Mid-power, which are typically used in uniformity and illumination applications and driven at 0.15W–1W of power.
3. High-power, which are typically used in illumination applications and driven at >1W of power.
4. Very-high-power, which are typically used in outdoor and directional illumination applications and driven at >10W of power.

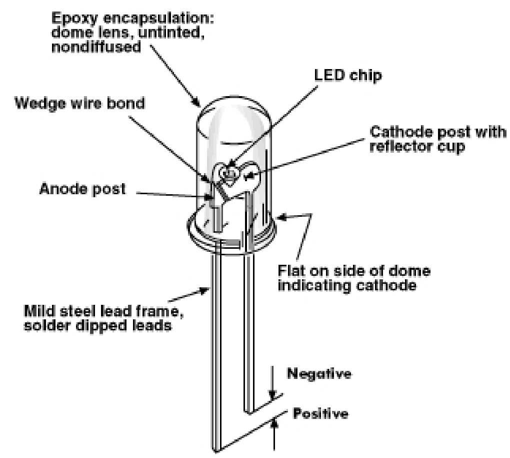

Figure 1: Diagram of a through-hole LED

LED Packaging

There are three main types of LED packaging techniques:

1. Through-hole (sometimes called 3mm, 5mm or 10mm as defined by the diameter) (Figure 1)
2. Surface-mount device (SMD) (Figure 2)
3. Chip-on-board (CoB) (Figure 3)

Through-hole packaging is typically found in low-power applications since it cannot provide good heat dissipation due to packaging constraints. The diagram (right) shows the construction of these packages. The LED die (or chip) is held in a tiny reflector cup that is suspended in an epoxy lens, with the cathode and anode leads extending from the bottom.

Surface-mount device packaging is found for all types of LED power levels since it is a standard mounting technique for electrical manufacturing of printed circuit boards (PCBs) and exhibits good thermal characteristics. The diagram (below) is an example of the construction of these devices. The LED die rests in a reflective cavity and is enclosed with a silicone/epoxy hybrid material. The anode and cathode leads are typically moved to opposite sides at the bottom of the package. Depending on the LED topology used, either the anode/cathode can dissipate heat or an isolated heat sink (IHS) can be used to directly channel heat away from the device to the PCB. In some cases, an additional light-collecting dome or lens can be affixed to the top of the package.

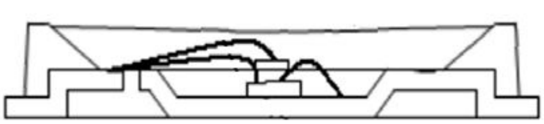

Figure 2: Diagram of an SMD LED

Chip-on-board packages are a relatively new method, typically utilized in very-high-power illumination applications. Unlike the through-hole and SMD packages, the CoB package does not require the use of a PCB. It is designed to attach directly to a heat sink for superior thermal dissipation. In addition, there are typically a high number of LED dies (for instance 10 to 500) packaged very tightly under a single scintillating phosphor. The diagram (right) shows the construction of these packages. The LED dies rest on a substrate (usually ceramic) and are connected in series/parallel configurations via bond wires. The encapsulant is a scintillating phosphor mixture that mixes with the output of the LED dies to create the desired white light. Heat is typically conducted from the LED dies through the substrate and directly to the heat sink to which it attaches.

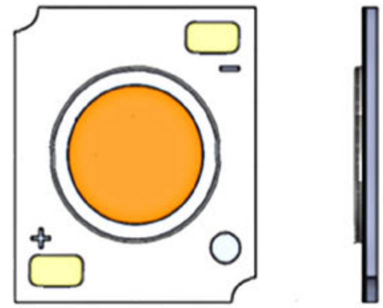

Figure 3: Diagram of a CoB LED.

Operation

LEDs are fundamentally different from conventional light sources, such as incandescent lamps, which produce light by heating a metal filament to extreme temperatures. When metals are used, voltage and current have a linear relationship, as described by Ohm's Law (V=IR, voltage equals current by resistance). LEDs, being semiconductors, have a nonlinear relationship between voltages. To properly control light output, most LED sources use a driver to step down the line voltage (AC) and ensure that the LED system is supplied with constant current (DC).

Current State of LED Lighting

LED Lamp & System Characteristics

Directionality and Control

LEDs provide directional light, whereas incandescent, HID and fluorescent sources are omnidirectional and typically require reflectors to control the light distribution. Optic choices for LEDs are dependent on the application, but in most circumstances, you will see large reflectors only in linear or very-high-output applications. For high-power applications, smaller individual optics are usually used to finely control the distribution to be much smoother than sources that use faceted reflectors. This also grants LED sources far greater control over the cutoff angle by minimizing spill, which can account for as much as 10%-15% of the total lumens lost in incandescent lamps. This enhanced efficiency dramatically increases the range of potential applications.

Dimming

LED sources potentially have a full dimming range of 100%-0% light output and require no re-strike time. Also, because there is no filament, gas or plasma being heated to produce light, dimming is immediate. It should be noted that the power supply is the factor to evaluate in terms of dimming, not the LEDs. There are some LED systems available that are capable of dimming with standard line-voltage incandescent dimmers, but many are not. To ensure the success of dimming capabilities in retrofit applications, the driver electronics of an LED system must be of high quality and carefully matched, there is great variability in the electrical characteristics of each dimmer.

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Benefits of LED Lighting

Energy- and Cost-Efficient

Quality LED systems produce light output equivalent to that of fluorescent and incandescent sources, but use significantly less energy. As a result, LED lighting is uniquely positioned to reduce electric lighting consumption by 50% before the year 2025, a goal set by the U.S. Department of Energy (DOE). This would reduce the total global consumption of electricity by 10%, resulting in a drastic lowering of CO2 emissions. Also, unlike fluorescent and HID sources, LEDs meet Restriction of Hazardous Substances (RoHS) requirements by not incorporating known hazardous materials.

Currently, LEDs consume one-sixth of the energy as compared to incandescent sources, and one-third of the energy as compared to compact-fluorescent (CFL) sources. Additionally, the useful life of current LEDs is approximately 10x–20x longer than incandescent sources and 2x–5x longer than CFL sources. The less frequent lamp replacement additionally results in a significant reduction of re-lamping and maintenance costs. Despite the higher up-front/initial costs of LED sources, the extensive energy savings result in rapid payback on these systems.

Life

LED chips do not typically catastrophically fail, but rather slowly degrade over time. Thus, the proper way to describe LED life is by how long the chips remain useful. The industry standard for LED general lighting applications is the “L70 life rating,” or the number of hours until light output drops to 70% of the initial light output in more than 50% of the products tested.

A quality white-LED system has a useful life typically in the 20,000- to 50,000-hour range, depending on the application. The restriction of its life is usually associated with electrical driver components and not the failure of the LEDs themselves. This greatly exceeds the life of incandescent sources, which typically burn out within 2,500 hours, and CFL sources that have a usable life within 10,000 hours.

Rugged Flexibility

LED lighting systems are comparably highly resistant to shock and vibration. In incandescent systems, suspended filaments and glass enclosures are susceptible to breakage. Fluorescent and HID sources are gas-filled or vacuum-sealed and require careful handling. LEDs are not nearly as sensitive and even operate more effectively than other lighting sources in cold conditions. These features make LED systems ideal for a broad range of applications such as automotive, traffic, refrigeration and commercial/industrial lighting.

Another advantage over conventional sources is that light emitted from LED systems contains such minute traces of ultraviolet and infrared wavelengths that it can be considered absent. These wavelengths can be very damaging to art, museum artifacts, retail merchandise and grocery produce. Additionally, the slim profiles and minimal space requirements of LED systems afford tremendous flexibility and advantage in a broad range of potential applications.

Current Challenges Facing LED Lighting

Thermal Management

The single most important factor in determining LED system performance, in terms of both spectral and electrical properties, is the temperature at the junction of the depletion region. This value is known as the junction temperature.

As electrons flow through the depletion region, they must match up with "holes" to produce photons. Inherently, there are mismatches, friction and other physical interactions that produce heat, causing thermal buildup. High junction temperatures result in less light output, color shift toward the higher end of the spectrum, and accelerated degradation. As a result, thermal management systems in LEDs (heat sinking, active cooling, etc.) are essential to maintaining the maximum expected useful life.

Currently, the most common approach to thermal management for commercially available LED systems is through the use of heat sinks, which generally are finned metal encasements that conduct accumulated heat away from the LED. In low-output applications, such as gimbal-ring track lighting and other open-air accent lighting, heat sinks are a viable solution. For high-output applications, the requisite heat sinks can become large and heavy, thereby restricting the application versatility. Additionally, many high-output applications, such as recessed downlights for general lighting, require the lamp to be in an enclosure, resulting in gradual heat buildup around the LEDs. Therefore, it is important to consider the intended application of the LED when choosing between the different thermal management systems.

Another method of thermal management is active cooling. Active-cooling thermal management systems incorporate small, low-speed fans or impulse coolers. Many common high-end electronic devices (computers, televisions, stereo systems, processors, etc.) utilize active-cooling systems as their primary cooling solutions. As LEDs are also electronic devices, the use of active cooling for LED systems is a logical evolution in design. The low speed and long life of an electronic fan, as well as the overwhelming benefit of continuous cooling for the function and life of the LED system, make active cooling the ideal thermal management system in high-output applications. Actively cooled LED systems also have an advantage over heat sink approaches in that they do not add significant bulk or excessive weight, thus maintaining broad application versatility.

Glare and Brightness Levels

High-power LEDs emit large amounts of light from extremely small sources, resulting in high levels of luminance. This may result in a high perception of brightness, so LED products should have proper shielding. Glare can be easily controlled using quality lenses and optics.

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Industry Standards

As they are fundamentally different from incandescent, fluorescent and HID sources, LED systems require novel standards for performance testing. Currently, the DOE is working closely with the American National Standards Institute (ANSI), the Illuminating Engineering Society of North America (IESNA), the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), ENERGY STAR®, the Federal Trade Commission (FTC), the International Commission on Illumination (CIE), and other organizations, to develop such standards. These recommendations and guidelines for LED performance testing continually raise the quality of commercially available products.

IESNA: LM-79

One of the first steps for LED system testing began in 2008 when the IESNA published LM-79-08, titled "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products." This document provides a basis for which you are able to compare different systems at the beginning of their operation. It should be noted that LM-79 reports utilize absolute photometry – as opposed to relative photometry found in other technologies – because each LED system is unique. In addition, LM-79 does not indicate any life estimation or future performance prediction.

IESNA: LM-80

LM-80-08 specifies procedures for measuring the lumen depreciation of LED light sources, arrays and modules over a period of testing of at least 6,000 hours in a controlled environment. It provides a means for comparing different LED life performances. It does not include measurement of luminaires or provide methods for estimating useful life beyond the testing period.

IESNA: TM-21

TM-21-11 is a method developed by the IESNA to estimate long-term performance of an LED based on LM-80 test data. It was developed by a committee of LED manufacturers, lighting manufacturers and government representatives. Under their expertise, a function was developed that takes into account the typical degrading mechanisms to arrive at a life estimation. Using at least 6,000 hours of data, one is able to use this algorithm to estimate up to 6x the length of the LM-80 test period. Therefore, to achieve the general target of 50,000 hours, the LM-80 test on an LED source will need to be at least 8,334 hours.

ASSIST

Useful life ratings have been developed by ASSIST for two main application types: general lighting and decorative lighting. General lighting applications have a rating of L70, which means the end of life occurs when light output drops below 70% in more than 50% of the tested product population. Decorative lighting applications have a rating of L50, which means the end of life occurs when light output drops below 50% in more than 50% of the tested product population.

ENERGY STAR®

The U.S. Environmental Protection Agency, through its ENERGY STAR® program, has developed very strict efficiency, quality and lifetime criteria that LED lighting must meet to obtain certification. LED lamp standards require LED products to have light output (quantity and distribution) equal to that of existing technologies, a 35,000-hour minimum life and quality dimming capabilities.

DesignLights Consortium (DLC)

The DLC was founded in 1996 by the Northeast Energy Efficiency Partnerships (NEEP) with a focus on pushing innovation through the lighting industry. Unlike the ENERGY STAR® program, DLC efforts have always been focused on commercial applications. In 2010, it began its qualified-product list program, which is used today as a resource by many groups to specify quality lighting products for rebate and incentive programs.

U.S. DOE: Lighting Facts

To address consumer confusion, the U.S. DOE is sponsoring "Lighting Facts," a program based on the labeling requirements established by the FTC that allow comparison between LED products and other lighting technologies. The result is the Lighting Facts label, analogous to the Nutrition Facts label on food, which lists in a common format factors such as lumen output, estimated energy costs, efficacy, life, correlated color temperature (CCT), color rendering index (CRI) and energy used (wattage). This labeling also requires the disclosure of any hazardous materials contained within the product, such as mercury or lead, which are common in conventional lighting technologies. This Lighting Facts label is also a part of the SSL Quality Advocates pledge, a voluntary oath to ensure accurate representation of LED lighting and to help drive acceptance of solid-state lighting (SSL) products.

What to Look For When Buying LED Lighting Systems

The LED lighting market is flooded with products of varying quality, and differentiating between them can be difficult. A number of factors should be considered when identifying LED products for a desired application, including life, lumen output, intensity distribution curves, CCT, and CRI.

Life

Claims of long life can be misleading, given the significant difference between the life of a diode and useful life of an LED system. In a laboratory, under ideal and controlled operating conditions, a single LED has the potential to last 100,000 hours or more. By contrast, LED systems in real-world applications are susceptible to lumen depreciation and driver failure due to electrical overstress and high temperatures, which reduce the useful life span. Quality white-LED lamps typically have a useful life between 20,000 and 50,000 hours.

A major factor influencing actual useful life of an LED system is the lamp's application. The most common application that shortens useful lamp life is recessed lighting. Underwriters Laboratories (UL), which establishes and tests many consumer products for safety and compliance, has also set the industry standard for rating recessed-lighting housing. The two classifications for recessed lighting are: type IC installations and type non-IC installations. Type IC installations are those where the housing is in direct contact with insulation. In this type of housing, the potential for temperature buildup is greatest, and therefore LED useful life is reduced the most. Type non-IC installations are those where the housing is not in direct contact with insulation and those that have a 3-inch clearance from any nearby insulation. This type of housing allows for some ventilation, which helps reduce temperature levels and maximize LED useful life. However, in most instances, even the type non-IC installations will reduce LED useful life more than any open-air type of application. These classifications are crucial when choosing an LED PAR lamp since they are typically used in recessed-lighting applications.

Lumen Output and Intensity Distribution

High-output applications require a large number of lumens in a uniform distribution pattern. Two lighting characteristics – lumen output and intensity distribution – should be used together to determine the quality of an LED replacement lamp. LED lamps offer the same beam spreads as incandescent reflector lamps, but when compared side by side, the distribution can differ greatly. An incandescent lamp will typically have a symmetrical, circular distribution of the light, with the brightest area falling in the center and a relatively even drop in brightness toward the circle's perimeter. Low-quality LED lamps may have oblong or non circular distributions or even be completely washed out. Quality LED lamps, on the other hand, provide better distribution than incandescent sources because LED optics eliminate the striations and limit the spill caused by metal reflectors. When choosing a proper replacement lamp, it is important to know its center-beam candlepower (CBCP, which expresses luminous intensity), intensity distribution curve and lumen output. High-quality LED lamps are equivalent to comparable incandescent sources because they use quality optical components and high-performance thermal management systems.

Correlated Color Temperature

Choosing the correct LED replacement for an incandescent lamp requires choosing a product with a comparable CCT. White LEDs can typically be found with CCTs ranging 2700K-6500K. Incandescent lamps have a warmer CCT, typically 2400K-3000K, while fluorescent and HID lamps typically run 3500K-5000K. Therefore, it is important to choose the correct and preferred CCT for your application.

Color Rendering Index

The CRI metric is used to determine how well a light source reproduces the colors of an object in comparison to ideal lighting conditions. It has been used to compare the color rendering quality of incandescent, fluorescent and HID sources for over 40 years. The CIE does not recommend the use of CRI testing for white LED systems because some LED lamps with lower CRI values still produce quality white light. For LED lighting, revised color-quality testing metrics are still under development; in the meantime, comparison of CRI values should be done cautiously. When possible, the color rendering of an LED source should be evaluated in person and preferably in the context of the intended application.

The Promise of LED Lighting

LEDs are safe, high-performing light sources that outperform other illumination technologies in low-temperature operations and rugged environments. The DOE projects that LED lighting could reduce total electric lighting consumption by 50% before the year 2025, amounting to $100 billion in annual worldwide energy cost savings. As the technology continues to advance, and as the industry refines and adopts newly established standards and regulations, LEDs will allow for an ever-expanding range of lighting applications and performance milestones. The broadening portfolio of applications, as well as the increasing realization of how LED performance compares with other lighting solutions, speaks to the needs of ecologically- and economically-conscious companies and consumers interested in the double bottom line of financial and environmental sustainability. This is why most industry experts, technology developers and government officials agree that LED technology is the future of energy-efficient and cost-efficient lighting.