Light-emitting diode

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Light-emitting diode

Red, green and blue LEDs of the 5mm type

Type	Passive, optoelectronic
Working principle	Electroluminescence
Invented	Nick Holonyak Jr. (1962)

Electronic symbol

Pin configuration	Anode and Cathode

A **light-emitting diode** (**LED**) (pronounced /ˌɛl iː ˈdiː/[1]) is a semiconductor light source. LEDs are used as indicator lamps in many devices, and are increasingly used for lighting. Introduced as a practical electronic component in 1962,[2] early LEDs emitted low-intensity red light, but modern versions are available across the visible, ultraviolet and infrared wavelengths, with very high brightness.

When a light-emitting diode is forward biased (switched on), electrons are able to recombine with holes within the device, releasing energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor. An LED is usually small in area (less than 1 mm^2), and integrated optical components are used to shape its radiation pattern and assist in reflection.[3] LEDs present many advantages over incandescent light sources including lower energy consumption, longer lifetime, improved robustness, smaller size, faster switching, and greater durability and reliability. LEDs powerful enough for room lighting are relatively expensive and require more precise current and heat management than compact fluorescent lamp sources of comparable output.

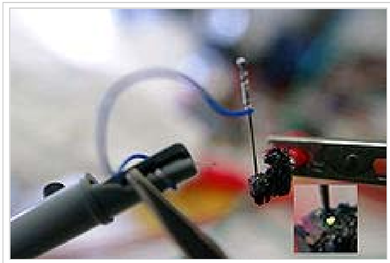
Light-emitting diodes are used in applications as diverse as replacements for aviation lighting, automotive lighting (particularly indicators) and in traffic signals. The compact size of LEDs has allowed new text and video displays and sensors to be developed, while their high switching rates are useful in advanced communications technology. Infrared LEDs are also used in the remote control units of many commercial products including televisions, DVD players, and other domestic appliances.

Contents

History

Discoveries and early devices

Electroluminescence was discovered in 1907 by the British experimenter H. J. Round of Marconi Labs, using a crystal of silicon carbide and a cat's-whisker detector.[4][5] Russian Oleg Vladimirovich Losev independently reported on the creation of an LED in 1927.[6][7] His research was distributed in Russian, German and British scientific journals, but no practical use was made of the discovery for several decades.[8][9] Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955.[10] Braunstein observed infrared emission generated by simple diode structures using gallium antimonide (GaSb), GaAs, indium phosphide (InP), and silicon-germanium (SiGe) alloys at room temperature and at 77 kelvin.



Green electroluminescence from a point contact on a crystal of SiC recreates H. J. Round's original experiment from 1907.

In 1961, American experimenters Robert Biard and Gary Pittman working at Texas Instruments,[11] found that GaAs emitted infrared radiation when electric current was applied and received the patent for the infrared LED.

The first practical visible-spectrum (red) LED was developed in 1962 by Nick Holonyak Jr., while working at General Electric Company.[2] Holonyak is seen as the "father of the light-emitting diode".[12] M. George Craford,[13] a former graduate student of Holonyak, invented the first yellow LED and improved the brightness of red and red-orange LEDs by a factor of ten in 1972.[14] In 1976, T.P. Pearsall created the first high-brightness, high efficiency LEDs for optical fiber telecommunications by inventing new semiconductor materials specifically adapted to optical fiber transmission wavelengths.[15]

Up to 1968 visible and infrared LEDs were extremely costly, on the order of US $200 per unit, and so had little practical application.[16] The Monsanto Company was the first organization to mass-produce visible LEDs, using gallium arsenide phosphide in 1968 to produce red LEDs suitable for indicators.[16] Hewlett Packard (HP) introduced LEDs in 1968, initially using GaAsP supplied by Monsanto. The technology proved to have major applications for alphanumeric displays and was integrated into HP's early handheld calculators. In the 1970s commercially successful LED devices at under five cents each were produced by Fairchild Optoelectronics. These devices employed compound semiconductor chips fabricated with the planar process invented by Dr. Jean Hoerni at Fairchild Semiconductor.[17] The combination of planar processing for chip fabrication and innovative packaging techniques enabled the team at Fairchild led by optoelectronics pioneer Thomas Brandt to achieve the necessary cost reductions. These techniques continue to be used by LED producers.[18]

Practical use

Red, yellow and green (unlit) LEDs used in a traffic signal in Sweden.

The first commercial LEDs were commonly used as replacements for incandescent and neon indicator lamps, and in seven-segment displays,[19] first in expensive equipment such as laboratory and electronics test equipment, then later in such appliances as TVs, radios, telephones, calculators, and even watches (see list of signal applications). These red LEDs were bright enough only for use as indicators, as the light output was not enough to illuminate an area. Readouts in calculators were so small that plastic lenses were built over each digit to make them legible. Later, other colors became widely available and also appeared in appliances and equipment. As the LED materials technology became more advanced, the light output was increased, while maintaining the efficiency and the reliability to an acceptable level. The invention and development of the high power white light LED led to use for illumination[20][21] (see list of illumination applications). Most LEDs were made in the very common 5 mm T1¾ and 3 mm T1 packages, but with increasing power output, it has become increasingly necessary to shed excess heat in order to maintain reliability,[22] so more complex packages have been adapted for efficient heat dissipation. Packages for state-of-the-art high power LEDs bear little resemblance to early LEDs.

Continuing development

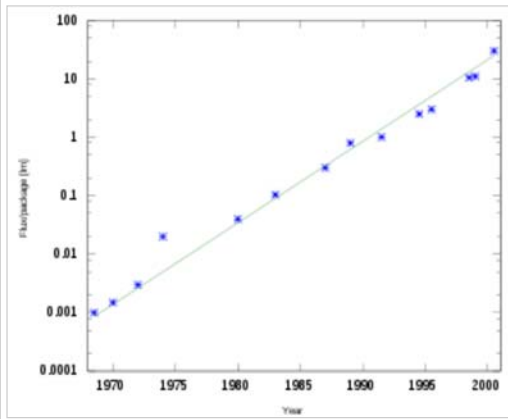


Illustration of Haitz's Law. Light output per LED as a function of production year, note the logarithmic scale on the vertical axis.

The first high-brightness blue LED was demonstrated by Shuji Nakamura of Nichia Corporation and was based on InGaN borrowing on critical developments in GaN nucleation on sapphire substrates and the demonstration of p-type doping of GaN which were developed by Isamu Akasaki and H. Amano in Nagoya. In 1995, Alberto Barbieri at the Cardiff University Laboratory (GB) investigated the efficiency and reliability of high-brightness LEDs and demonstrated a very impressive result by using a transparent contact made of indium tin oxide (ITO) on (AlGaInP/GaAs) LED. The existence of blue LEDs and high efficiency LEDs quickly led to the development of the first white LED, which employed a $Y_3Al_5O_{12}$:Ce, or "YAG", phosphor coating to mix yellow (down-converted) light with blue to produce light that appears white. Nakamura was awarded the 2006 Millennium Technology Prize for his invention.[23]

The development of LED technology has caused their efficiency and light output to increase exponentially, with a doubling occurring about every 36 months since the 1960s, in a way similar to Moore's law. The advances are generally attributed to the parallel development of other semiconductor technologies and advances in optics and material science. This trend is normally called Haitz's Law after Dr. Roland Haitz. [24]

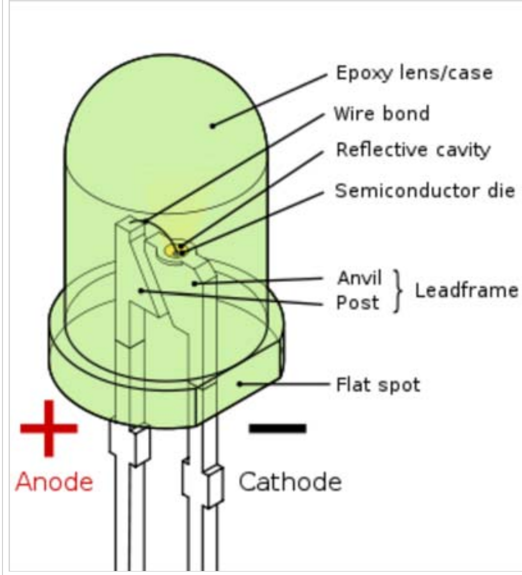
In February 2008, Bilkent university in Turkey reported 300 lumens of visible light per watt luminous efficacy (not per electrical watt) and warm light by using nanocrystals.[25]

In 2009, researchers from Cambridge University reported a process for growing gallium nitride (GaN) LEDs on silicon. Epitaxy costs could be reduced by up to 90% using six-inch silicon wafers instead of two-inch sapphire wafers. The team was led by Colin Humphreys.[26]

Technology

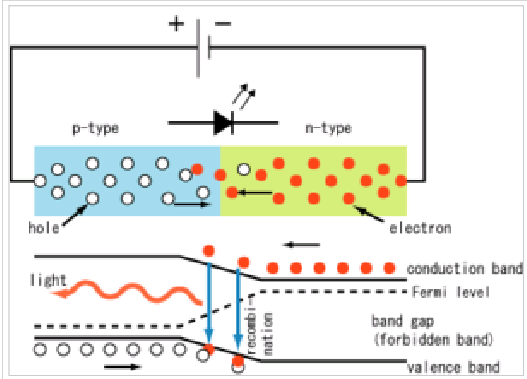
Physics

Like a normal diode, the LED consists of a chip of semiconducting material doped with impurities to create a *p-n junction*. As in other diodes, current flows easily from the p-side, or anode, to the n-side, or cathode, but not in the reverse direction. Charge-carriers—electrons and holes—flow into the junction from electrodes with different voltages. When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon.



Parts of an LED

The wavelength of the light emitted, and therefore its color, depends on the band gap energy of the materials forming the *p-n junction*. In silicon or germanium diodes, the electrons and holes recombine by a *non-radiative transition* which produces no optical emission, because these are indirect band gap materials. The materials used for the LED have a direct band gap with energies corresponding to near-infrared, visible or near-ultraviolet light.



The inner workings of an LED

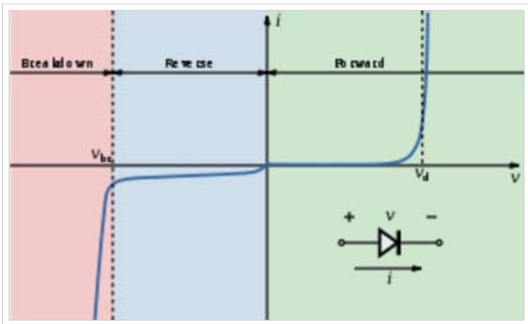
LED development began with infrared and red devices made with gallium arsenide. Advances in materials science have made possible the production of devices with ever-shorter wavelengths, producing light in a variety of colors.

LEDs are usually built on an n-type substrate, with an electrode attached to the p-type layer deposited on its surface. P-type substrates, while less common, occur as well. Many commercial LEDs, especially GaN/InGaN, also use sapphire substrate.

Most materials used for LED production have very high refractive indices. This means that much light will be reflected back into the material at the material/air surface interface. Therefore *Light extraction in LEDs* is an important aspect of LED production, subject to much research and development.

Efficiency and operational parameters

Typical indicator LEDs are designed to operate with no more than 30–60 milliwatts [mW] of electrical power. Around 1999, Philips Lumileds introduced power LEDs capable of continuous use at one watt [W]. These LEDs used much larger semiconductor die sizes to handle the large power inputs. Also, the semiconductor dies were mounted onto metal slugs to allow for heat removal from the LED die.



I-V diagram for a diode an LED will begin to emit light when the on-voltage is exceeded. Typical on voltages are 2-3 Volt

One of the key advantages of LED-based lighting is its high efficiency, as measured by its light output per unit power input. White LEDs quickly matched and overtook the efficiency of standard incandescent lighting systems. In 2002, Lumileds made five-watt LEDs available with a luminous efficacy of 18–22 lumens per watt [lm/W]. For comparison, a conventional 60–100 W incandescent lightbulb produces around 15 lm/W, and standard fluorescent lights produce up to 100 lm/W. A recurring problem is that efficiency will fall dramatically for increased current. This effect is known as droop and effectively limits the light output of a given LED, increasing heating more than light output for increased current.[27][28][29]

In September 2003, a new type of blue LED was demonstrated by the company Cree, Inc. to provide 24 mW at 20 milliamperes [mA]. This produced a commercially packaged white light giving 65 lm/W at 20 mA, becoming the brightest white LED commercially available at the time, and more than four times as efficient as standard incandescents. In 2006 they demonstrated a prototype with a record white LED luminous efficacy of 131 lm/W at 20 mA. Also, Seoul Semiconductor has plans for 135 lm/W by 2007 and 145 lm/W by 2008, which would be approaching an order of magnitude improvement over standard incandescents and better even than standard fluorescents.[30] Nichia Corporation has developed a white LED with luminous efficacy of 150 lm/W at a forward current of 20 mA.[31]

High-power (≥ 1 W) LEDs are necessary for practical general lighting applications. Typical operating currents for these devices begin at 350 mA.

Note that these efficiencies are for the LED chip only, held at low temperature in a lab. In a lighting application, operating at higher temperature and with drive circuit losses, efficiencies are much lower. United States Department of Energy (DOE) testing of commercial LED lamps designed to replace incandescent lamps or CFLs showed that average efficacy was still about 46 lm/W in 2009 (tested performance ranged from 17 lm/W to 79 lm/W).[32]

Cree issued a press release on February 3, 2010 about a laboratory prototype LED achieving 208 lumens per watt at room temperature. The correlated color temperature was reported to be 4579 K.[33]

Lifetime and failure

Main article: List of LED failure modes

Solid state devices such as LEDs are subject to very limited wear and tear if operated at low currents and at low temperatures. Many of the LEDs produced in the 1970s and 1980s are still in service today. Typical lifetimes quoted are 25,000 to 100,000 hours but heat and current settings can extend or shorten this time significantly. [34]

The most common symptom of LED (and diode laser) failure is the gradual lowering of light output and loss of efficiency. Sudden failures, although rare, can occur as well. Early red LEDs were notable for their short lifetime. With the development of high-power LEDs the devices are subjected to higher junction temperatures and higher current densities than traditional devices. This causes stress on the material and may cause early light output degradation. To quantitatively classify lifetime in a standardized manner it has been suggested to use the terms L75 and L50 which is the time it will take a given LED to reach 75% and 50% light output respectively.[35]

Like other lighting devices, LED performance is temperature dependent. Most manufacturers' published ratings of LEDs are for an operating temperature of 25°C. LEDs used outdoors, such as traffic signals or in-pavement signal lights, and that are utilized in climates where the temperature within the luminaire gets very hot, could result in low signal intensities or even failure.[36]

LEDs maintain consistent light output even in cold temperatures, unlike traditional lighting methods. Consequently, LED technology may be a good replacement in areas such as supermarket freezer lighting[37][38][39] and will last longer than other technologies. Because LEDs do not generate as much heat as incandescent bulbs, they are an energy-efficient technology to use in such applications such as freezers. On the other hand, because they do not generate much heat, ice and snow may build up on the LED luminaire in colder climates.[40] This lack of waste heat generation has been observed to cause sometimes significant problems with street traffic signals and airport runway lighting in snow prone locations, although some research has been done to try to develop heat sink technologies in order to transfer heat to alternative areas of the luminaire.[41]

Colors and materials

Conventional LEDs are made from a variety of inorganic semiconductor materials, the following table shows the available colors with wavelength range, voltage drop and material:

Color	Wavelength (nm)	Voltage (V)	Semiconductor Material
Infrared	$\lambda > 760$	$\Delta V < 1.9$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)

Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	1.9[42] $< \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm)[43] Boron nitride (215 nm)[44][45] Aluminium nitride (AlN) (210 nm)[46] Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm)[47]
White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Ultraviolet and blue LEDs


Blue LEDs.

Blue LEDs are based on the wide band gap semiconductors GaN (gallium nitride) and InGaN (indium gallium nitride). They can be added to existing red and green LEDs to produce the impression of white light, though white LEDs today rarely use this principle.

The first blue LEDs were made in 1971 by Jacques Pankove (inventor of the gallium nitride LED) at RCA Laboratories.[48] These devices had too little light output to be of much practical use. However, early blue LEDs found use in some low-light applications, such as the high-beam indicators for cars.[49] In the late 1980s, key breakthroughs in GaN epitaxial growth and p-type doping[50] ushered in the modern era of GaN-based optoelectronic devices. Building upon this foundation, in 1993 high brightness blue LEDs were demonstrated.[51]

By the late 1990s, blue LEDs had become widely available. They have an active region consisting of one or more InGaN quantum wells sandwiched between thicker layers of GaN, called cladding layers. By varying the relative InN-GaN fraction in the InGaN quantum wells, the light emission can be varied from violet to amber. AlGaN aluminium gallium nitride of varying AlN fraction can be used to manufacture the cladding and quantum well layers for ultraviolet LEDs, but these devices have not yet reached the level of efficiency and technological maturity of the InGaN-GaN blue/green devices. If the active quantum well layers are GaN, as opposed to alloyed InGaN or AlGaN, the device will emit near-ultraviolet light with wavelengths around 350–370 nm. Green LEDs manufactured from the InGaN-GaN system are far more efficient and brighter than green LEDs produced with non-nitride material systems.

With nitrides containing aluminium, most often AlGaN and AlGaInN, even shorter wavelengths are achievable. Ultraviolet LEDs in a range of wavelengths are becoming available on the market. Near-UV emitters at wavelengths around 375–395 nm are already cheap and often encountered, for example, as black light lamp replacements for inspection of anti-counterfeiting UV watermarks in some documents and paper currencies. Shorter wavelength diodes, while substantially more expensive, are commercially available for wavelengths down to 247 nm.[52] As the photosensitivity of microorganisms approximately matches the absorption spectrum of DNA, with a peak at about 260 nm, UV LED emitting at 250–270 nm are to be expected in prospective disinfection and sterilization devices. Recent research has shown that commercially available UVA LEDs (365 nm) are already effective disinfection and sterilization devices.[53]

Deep-UV wavelengths were obtained in laboratories using aluminium nitride (210 nm),[46] boron nitride (215 nm)[44][45] and diamond (235 nm).[43]

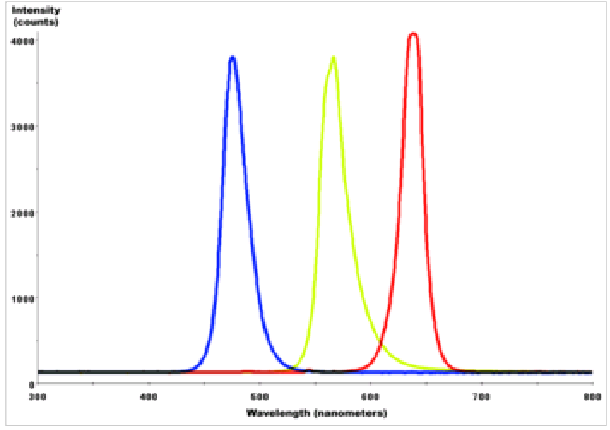
White light

There are two primary ways of producing high intensity white-light using LEDs. One is to use individual LEDs that emit three primary colors[54]—red, green, and blue—and then mix all the colors to produce white light. The other is to use a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, much in the same way a fluorescent light bulb works.

Due to metamerism, it is possible to have quite different spectra that appear white.

RGB systems

White light can be produced by mixing differently colored light, the most common method is to use red, green and blue (RGB). Hence the method is called multi-colored white LEDs (sometimes referred to as RGB LEDs). Because its mechanism is involved with electro-optical devices to control the blending and diffusion of different colors, this approach is little used to produce white lighting. Nevertheless this method is particularly interesting in many applications because of the flexibility of mixing different colors,[55] and, in principle, this mechanism also has higher quantum efficiency in producing white light.



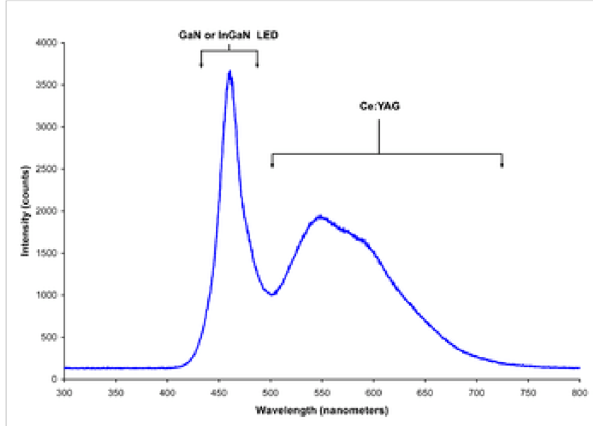
Combined spectral curves for blue, yellow-green, and high brightness red solid-state semiconductor LEDs. FWHM spectral bandwidth is approximately 24–27 nm for all three colors.

There are several types of multi-colored white LEDs: di-, tri-, and tetrachromatic white LEDs. Several key factors that play among these different approaches include color stability, color rendering capability, and luminous efficacy. Often higher efficiency will mean lower color rendering, presenting a trade off between the luminous efficiency and color rendering. For example, the dichromatic white LEDs have the best luminous efficacy (120 lm/W), but the lowest color rendering capability. Conversely, although tetrachromatic white LEDs have excellent color rendering capability, they often have poor luminous efficiency. Trichromatic white LEDs are in between, having both good luminous efficacy (>70 lm/W) and fair color rendering capability.

What multi-color LEDs offer is not merely another solution of producing white light, but is a whole new technique of producing light of different colors. In principle, most perceivable colors can be produced by mixing different amounts of three primary colors, and this makes it possible to produce precise dynamic color control as well. As more effort is devoted to investigating this technique, multi-color LEDs should have profound influence on the fundamental method which we use to produce and control light color. However, before this type of LED can truly play a role on the market, several technical problems need to be solved. These certainly include that this type of LED's emission power decays exponentially with increasing temperature,[56] resulting in a substantial change in color stability. Such problems are not acceptable for industrial usage. Therefore, many new package designs aimed at solving this problem have been proposed and their results are now being reproduced by researchers and scientists.

Phosphor-based LEDs

This method involves coating an LED of one color (mostly blue LED made of InGaN) with phosphor of different colors to produce white light, the resultant LEDs are called **phosphor-based white LEDs**.[57] A fraction of the blue light undergoes the Stokes shift being transformed from shorter wavelengths to longer. Depending on the color of the original LED, phosphors of different colors can be employed. If several phosphor layers of distinct colors are applied, the emitted spectrum is broadened, effectively increasing the color rendering index (CRI) value of a given LED.[58]



Spectrum of a “white” LED clearly showing blue light which is directly emitted by the GaN-based LED (peak at about 465 nm) and the more broadband Stokes-shifted light emitted by the Ce^{3+}:YAG phosphor which emits at roughly 500–700 nm.

Phosphor based LEDs have a lower efficiency than normal LEDs due to the heat loss from the Stokes shift and also other phosphor-related degradation issues. However, the phosphor method is still the most popular technique for manufacturing high intensity white LEDs. The design and production of a light source or light fixture using a monochrome emitter with phosphor conversion is simpler and cheaper than a complex RGB system, and the majority of high intensity white LEDs presently on the market are manufactured using phosphor light conversion.

The greatest barrier to high efficiency is the seemingly unavoidable Stokes energy loss. However, much effort is being spent on optimizing these devices to higher light output and higher operation temperatures. For instance, the efficiency can be increased by adapting better package design or by using a more suitable type of phosphor. Philips Lumileds' patented conformal coating process addresses the issue of varying phosphor thickness, giving the white LEDs a more homogeneous white light.[59] With development ongoing, the efficiency of phosphor based LEDs is generally increased with every new product announcement.

Technically the phosphor based white LEDs encapsulate InGaN blue LEDs inside of a phosphor coated epoxy. A common yellow phosphor material is cerium-doped yttrium aluminium garnet (Ce^{3+}:YAG).

White LEDs can also be made by coating near ultraviolet (NUV) emitting LEDs with a mixture of high efficiency europium-based red and blue emitting phosphors plus green emitting copper and aluminium doped zinc sulfide (ZnS:Cu, Al). This is a method analogous to the way fluorescent lamps work. This method is less efficient than the blue LED with YAG:Ce phosphor, as the Stokes shift is larger and more energy is therefore converted to heat, but yields light with better spectral characteristics, which render color better. Due to the higher radiative output of the ultraviolet LEDs than of the blue ones, both approaches offer comparable brightness. Another concern is that UV light may leak from a malfunctioning light source and cause harm to human eyes or skin.

Other white LEDs

Another method used to produce experimental white light LEDs used no phosphors at all and was based on homoepitaxially grown zinc selenide (ZnSe) on a ZnSe substrate which simultaneously emitted blue light from its active region and yellow light from the substrate.[60]

Organic light-emitting diodes (OLEDs)

Main article: Organic light-emitting diode

If the emitting layer material of the LED is an organic compound, it is known as an organic light emitting diode (OLED). To function as a semiconductor, the organic emitting material must have conjugated pi bonds. [61] The emitting material can be a small organic molecule in a crystalline phase, or a polymer. Polymer materials can be flexible; such LEDs are known as PLEDs or FLEDs.

Compared with regular LEDs, OLEDs are lighter, and polymer LEDs can have the added benefit of being flexible. Some possible future applications of OLEDs could be:

- Inexpensive, flexible displays
- Light sources
- Wall decorations

- Luminous cloth

OLEDs have been used to produce visual displays for portable electronic devices such as cellphones, digital cameras, and MP3 players. Larger displays have been demonstrated,[62] but their life expectancy is still far too short (<1,000 hours) to be practical[*citation needed*].

Today, OLEDs operate at substantially lower efficiency than inorganic (crystalline) LEDs.[63]

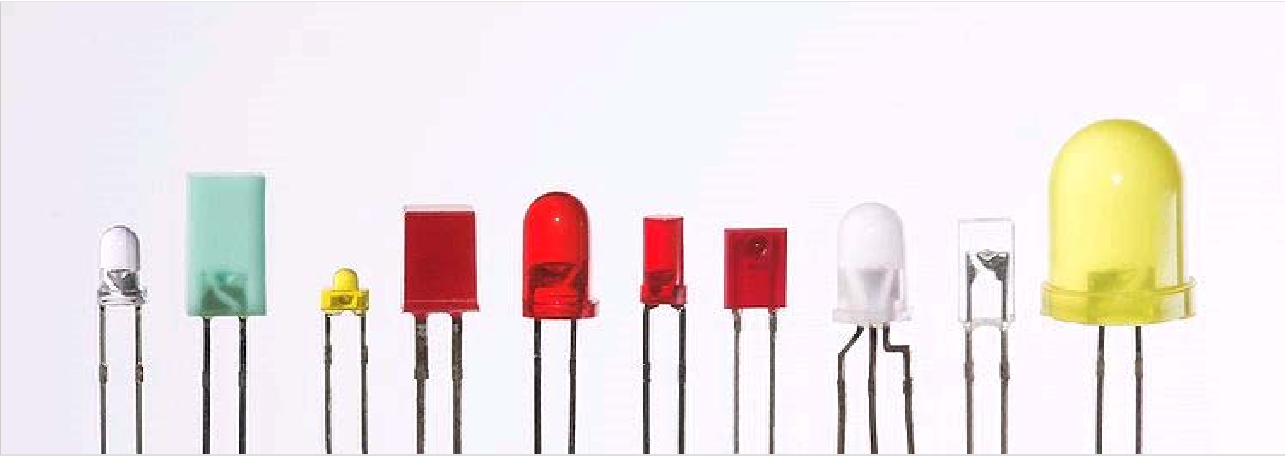
Quantum dot LEDs (experimental)

A new technique developed by Michael Bowers, a graduate student at Vanderbilt University in Nashville, involves coating a blue LED with quantum dots that glow white in response to the blue light from the LED. This technique produces a warm, yellowish-white light similar to that produced by incandescent bulbs.[64]

Quantum dots are semiconductor nanocrystals that possess unique optical properties.[65] Their emission color can be tuned from the visible throughout the infrared spectrum. This allows quantum dot LEDs to create almost any color on the CIE diagram. This provides more color options and better color rendering than white LEDs. Quantum dot LEDs are available in the same package types as traditional phosphor based LEDs.

In September 2009 Nanoco Group announced that it has signed a joint development agreement with a major Japanese electronics company under which it will design and develop quantum dots for use in light emitting diodes (LEDs) in liquid crystal display (LCD) televisions.[66]

Types



LEDs are produced in a variety of shapes and sizes. The 5 mm cylindrical package (red, fifth from the left) is the most common, estimated at 80% of world production.[*citation needed*] The color of the plastic lens is often the same as the actual color of light emitted, but not always. For instance, purple plastic is often used for infrared LEDs, and most blue devices have clear housings. There are also LEDs in SMT packages, such as those found on blinkies and on cell phone keypads (not shown).

The main types of LEDs are miniature, high power devices and custom designs such as alphanumeric or multi-color.

Miniature LEDs

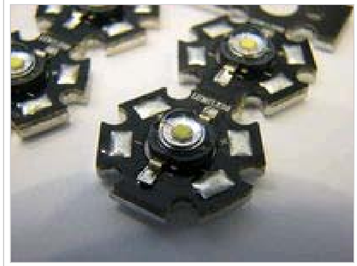
Main article: Miniature light-emitting diode

Different sized LEDs. 8 mm, 5 mm and 3 mm, with a wooden match-stick for scale.

These are mostly single-die LEDs used as indicators, and they come in various-sizes from 2 mm to 8 mm, through-hole and surface mount packages. They are usually simple in design, not requiring any separate cooling body.[67] Typical current ratings ranges from around 1 mA to above 20 mA. The small scale sets a natural upper boundary on power consumption due to heat caused by the high current density and need for heat sinking.

High power LEDs

See also: Solid-state lighting and LED lamp



High-power light emiting diodes (Luxeon, Lumileds)

High power LEDs (HPLED) can be driven at currents from hundreds of mA to more than an ampere, compared with the tens of mA for other LEDs. Some can produce over a thousand [68][69] lumens. Since overheating is destructive, the HPLEDs must be mounted on a heat sink to allow for heat dissipation. If the heat from a HPLED is not removed, the device will burn out in seconds. A single HPLED can often replace an incandescent bulb in a torch, or be set in an array to form a powerful LED lamp.

Some well-known HPLEDs in this category are the Lumileds Rebel Led, Osram Opto Semiconductors Golden Dragon and Cree X-lamp. As of September 2009 some HPLEDs manufactured by Cree Inc. now exceed 105 lm/W [70] (e.g. the XLamp XP-G LED chip emitting Cool White light) and are being sold in lamps intended to replace incandescent, halogen, and even fluorescent style lights as LEDs become more cost competitive.

LEDs have been developed by Seoul Semiconductor that can operate on AC power without the need for a DC converter. For each half cycle part of the LED emits light and part is dark, and this is reversed during the next half cycle. The efficacy of this type of HPLED is typically 40 lm/W.[71] A large number of LED elements in series may be able to operate directly from line voltage. In 2009 Seoul Semiconductor released a high DC voltage capable of being driven from AC power with a simple controlling circuit. The low power dissipation of these LEDs affords them more flexibility than the original AC LED design.[*citation needed*]

Mid-range LEDs

Medium power LEDs are often through-hole mounted and used when an output of a few lumen is needed. They sometimes have the diode mounted to four leads (two cathode leads, two anode leads) for better heat conduction and carry an integrated lens. An example of this is the Superflux package, from Philips Lumileds. These LEDs are most commonly used in light panels, emergency lighting and automotive tail-lights. Due to the larger amount of metal in the LED, they are able to handle higher currents (around 100 mA). The higher current allows for the higher light output required for tail-lights and emergency lighting.

Application-specific variations

- *Flashing LEDs* are used as attention seeking indicators without requiring external electronics. Flashing LEDs resemble standard LEDs but they contain an integrated multivibrator circuit which causes the LED to flash with a typical period of one second. In diffused lens LEDs this is visible as a small black dot. Most flashing LEDs emit light of a single color, but more sophisticated devices can flash between multiple colors and even fade through a color sequence using RGB color mixing.

Calculator LED display, 1970s.

- *Bi-color LEDs* are actually two different LEDs in one case. They consist of two dies connected to the same two leads antiparallel to each other. Current flow in one direction produces one color, and current in the opposite direction produces the other color. Alternating the two colors with sufficient frequency causes the appearance of a blended third color. For example, a red/green LED operated in this fashion will color blend to produce a yellow appearance.
- *Tri-color LEDs* are two LEDs in one case, but the two LEDs are connected to separate leads so that the two LEDs can be controlled independently and lit simultaneously. A three-lead arrangement is typical with one common lead (anode or cathode).[*citation needed*]

- *RGB LEDs* contain red, green and blue emitters, generally using a four-wire connection with one common lead (anode or cathode). These LEDs can have either common positive or common negative leads. Others however, have only two leads (positive and negative) and have a built in tiny electronic control unit.

- *Alphanumeric LED displays* are available in seven-segment and starburst format. Seven-segment displays handle all numbers and a limited set of letters. Starburst displays can display all letters. Seven-segment LED displays were in widespread use in the 1970s and 1980s, but increasing use of liquid crystal displays, with their lower power consumption and greater display flexibility, has reduced the popularity of numeric and alphanumeric LED displays.

Considerations for use

Power sources

Main article: LED power sources

The current/voltage characteristic of an LED is similar to other diodes, in that the current is dependent exponentially on the voltage (see Shockley diode equation). This means that a small change in voltage can lead to a large change in current. If the maximum voltage rating is exceeded by a small amount the current rating may be exceeded by a large amount, potentially damaging or destroying the LED. The typical solution is therefore to use constant current power supplies, or driving the LED at a voltage much below the maximum rating. Since most household power sources (batteries, mains) are not constant current sources, most LED fixtures must include a power converter. However, the I/V curve of nitride-based LEDs is quite steep above the knee and gives an I_f of a few milliamperes at a V_f of 3 V, making it possible to power a nitride-based LED from a 3 V battery such as a coin cell without the need for a current limiting resistor.

Electrical polarity

Main article: Electrical polarity of LEDs

As with all diodes, current flows easily from p-type to n-type material.[72] However, no current flows and no light is produced if a small voltage is applied in the reverse direction. If the reverse voltage becomes large enough to exceed the breakdown voltage, a large current flows and the LED may be damaged. If the reverse current is sufficiently limited to avoid damage, the reverse-conducting LED is a useful noise diode.

Safety

The vast majority of devices containing LEDs are "safe under all conditions of normal use", and so are classified as "Class 1 LED product"/"LED Klasse 1". At present, only a few LEDs—extremely bright LEDs that also have a tightly focused viewing angle of 8° or less—could, in theory, cause temporary blindness, and so are classified as "Class 2".[73] In general, laser safety regulations—and the "Class 1", "Class 2", etc. system—also apply to LEDs.[74]

Advantages

- **Efficiency:** LEDs produce more light per watt than incandescent bulbs.[75] Their efficiency is not affected by shape and size, unlike Fluorescent light bulbs or tubes.
- **Color:** LEDs can emit light of an intended color without the use of the color filters that traditional lighting methods require. This is more efficient and can lower initial costs.
- **Size:** LEDs can be very small (smaller than 2 mm^2[76]) and are easily populated onto printed circuit boards.
- **On/Off time:** LEDs light up very quickly. A typical red indicator LED will achieve full brightness in under a microsecond.[77] LEDs used in communications devices can have even faster response times.
- **Cycling:** LEDs are ideal for use in applications that are subject to frequent on-off cycling, unlike fluorescent lamps that burn out more quickly when cycled frequently, or HID lamps that require a long time before restarting.
- **Dimming:** LEDs can very easily be dimmed either by pulse-width modulation or lowering the forward current.
- **Cool light:** In contrast to most light sources, LEDs radiate very little heat in the form of IR that can cause damage to sensitive objects or fabrics. Wasted energy is dispersed as heat through the base of the LED.
- **Slow failure:** LEDs mostly fail by dimming over time, rather than the abrupt burn-out of incandescent bulbs.[78]
- **Lifetime:** LEDs can have a relatively long useful life. One report estimates 35,000 to 50,000 hours of useful life, though time to complete failure may be longer.[79] Fluorescent tubes typically are rated at about 10,000 to 15,000 hours, depending

partly on the conditions of use, and incandescent light bulbs at 1,000–2,000 hours.
- **Shock resistance:** LEDs, being solid state components, are difficult to damage with external shock, unlike fluorescent and incandescent bulbs which are fragile.
- **Focus:** The solid package of the LED can be designed to focus its light. Incandescent and fluorescent sources often require an external reflector to collect light and direct it in a usable manner.
- **Low toxicity:** LEDs do not contain mercury, unlike fluorescent lamps.

Disadvantages

- Some **Fluorescent lamps** can be more efficient.
- **High initial price:** LEDs are currently more expensive, price per lumen, on an initial capital cost basis, than most conventional lighting technologies. The additional expense partially stems from the relatively low lumen output and the drive circuitry and power supplies needed.
- **Temperature dependence:** LED performance largely depends on the ambient temperature of the operating environment. Over-driving the LED in high ambient temperatures may result in overheating of the LED package, eventually leading to device failure. Adequate heat-sinking is required to maintain long life. This is especially important when considering automotive, medical, and military applications where the device must operate over a large range of temperatures, and is required to have a low failure rate.
- **Voltage sensitivity:** LEDs must be supplied with the voltage above the threshold and a current below the rating. This can involve series resistors or current-regulated power supplies.[80]
- **Light quality:** Most cool-white LEDs have spectra that differ significantly from a black body radiator like the sun or an incandescent light. The spike at 460 nm and dip at 500 nm can cause the color of objects to be perceived differently under cool-white LED illumination than sunlight or incandescent sources, due to metamerism,[81] red surfaces being rendered particularly badly by typical phosphor based cool-white LEDs. However, the color rendering properties of common fluorescent lamps are often inferior to what is now available in state-of-art white LEDs.
- **Area light source:** LEDs do not approximate a “point source” of light, but rather a lambertian distribution. So LEDs are difficult to use in applications requiring a spherical light field. LEDs are not capable of providing divergence below a few degrees. This is contrasted with lasers, which can produce beams with divergences of 0.2 degrees or less.[82]
- **Blue hazard:** There is a concern that blue LEDs and cool-white LEDs are now capable of exceeding safe limits of the so-called blue-light hazard as defined in eye safety specifications such as ANSI/IESNA RP-27.1-05: Recommended Practice for Photobiological Safety for Lamp and Lamp Systems.[83][84]
- **Blue pollution:** Because cool-white LEDs (i.e., LEDs with high color temperature) emit proportionally more blue light than conventional outdoor light sources such as high-pressure sodium lamps, the strong wavelength dependence of Rayleigh scattering means that cool-white LEDs can cause more light pollution than other light sources. The International Dark-Sky Association discourages the use of white light sources with correlated color temperature above 3,000 K.[*citation needed*]

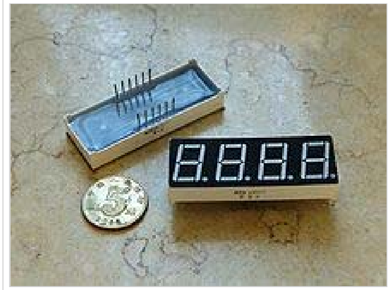
Applications


LED lighting in a aircraft cabin of the Airbus A320 Enhanced.


A large LED display behind a disc jockey.

LED destination displays on buses, one with a colored route number.

An information sign outside a parking garage in Sweden. The blinking effect is due to the rapid multiplexing of each LED row.



LED digital display that can display 4 digits along with points.

Traffic light using LED

Western Australia Police car using LED

Printhead of an Oki LED printer

LED daytime running lights of Audi A4

Application of LEDs fall into four major categories:

- Visual signal application where the light goes more or less directly from the LED to the human eye, to convey a message or meaning.
- Illumination where LED light is reflected from object to give visual response of these objects.
- Generate light for measuring and interacting with processes that do not involve the human visual system.[85]
- Narrow band light sensors where the LED is operated in a reverse-bias mode and is responsive to incident light instead of emitting light.


LED panel light source used in an experiment on plant growth. The findings of such experiments may be used to grow food in space on long duration missions.

Indicators and signs

The low energy consumption, low maintenance and small size of modern LEDs has led to applications as status indicators and displays on a variety of equipment and installations. Large area LED displays are used as stadium displays and as dynamic decorative displays. Thin, lightweight message displays are used at airports and railway stations, and as destination displays for trains, buses, trams, and ferries.

The single color light is well suited for traffic lights and signals, exit signs, emergency vehicle lighting, ships' lanterns and LED-based Christmas lights. In cold climates, LED traffic lights may remain snow covered.[86] Red or yellow LEDs are used in indicator and alphanumeric displays in environments where night vision must be retained: aircraft cockpits, submarine and ship bridges, astronomy observatories, and in the field, e.g. night time animal watching and military field use.

Because of their long life and fast switching times, LEDs have been used for automotive high-mounted brake lights and truck and bus brake lights and turn signals for some time, but many vehicles now use LEDs for their rear light clusters. The use of LEDs also has styling advantages because LEDs are capable of forming much thinner lights than incandescent lamps with parabolic reflectors. The significant improvement in the time taken to light up (perhaps 0.5 s faster than an incandescent bulb) improves safety by giving drivers more time to react. It has been reported that at normal highway speeds this equals one car length increased reaction time for the car behind. White LED headlamps are beginning to make an appearance. In a dual intensity circuit(i.e. rear markers and brakes) if the LEDs are not pulsed at a fast enough frequency, they can create a phantom array, where ghost images of the LED will appear if the eyes quickly scan across the array.

Due to the relative cheapness of low output LEDs, they are also used in many temporary applications such as glowsticks, throwies, and the photonic textile Lumalive. Artists have also used LEDs for LED art.

Weather/all-hazards radio receivers with Specific Area Message Encoding (SAME) have three LEDs: red for warnings, orange for watches, and yellow for advisories & statements whenever issued.

Lighting

Main article: LED lamp

With the development of high efficiency and high power LEDs it has become possible to incorporate LEDs in lighting and illumination. Replacement light bulbs have been made as well as dedicated fixtures and LED lamps. LEDs are used as street lights and in other architectural lighting where color changing is used. The mechanical robustness and long lifetime is used in automotive lighting on cars, motorcycles and on bicycle lights.

LED street lights are employed on poles and in parking garages. In 2007, the Italian village Torraca was the first place to convert its entire illumination system to LEDs.[87]

LEDs are used in aviation lighting. Airbus has used LED lighting in their Airbus A320 Enhanced since 2007, and Boeing plans its use in the 787. LEDs are also being used now in airport and heliport lighting. LED airport fixtures currently include medium intensity runway lights, runway centerline lights and obstruction lighting.

LEDs are also suitable for backlighting for LCD televisions and lightweight laptop displays and light source for DLP projectors (See LED TV). RGB LEDs increase the color gamut by as much as 45%. Screens for TV and computer displays can be made increasingly thin using LEDs for backlighting.[88]

LEDs are being used increasingly commonly for aquarium lighting. Particular for reef aquariums, LED lights provide an efficient light source with less heat output to help maintain optimal aquarium temperatures. LED-based aquarium fixtures also have the advantage of being manually adjustable to produce a specific color-spectrum for ideal coloration of corals, fish, and invertebrates while optimizing photosynethically active radiation (PAR) which increases growth and sustainability of photosynthetic life such as corals, anemones, clams, and macroalgae. These fixtures can be electronically programmed in order to simulate various lighting conditions throughout the day, reflecting phases of the sun and moon for a dynamic reef experience. LED fixtures typically cost up to five times as much as similarly rated fluorescent or high-intensity discharge lighting designed for reef aquariums and are not as high output to date.

The lack of IR/heat radiation makes LEDs ideal for stage lights using banks of RGB LEDs that can easily change color and decrease heating from traditional stage lighting, as well as medical lighting where IR-radiation can be harmful.

Since LEDs are small, durable and require little power they are used in hand held devices such as flashlights. LED strobe lights or camera flashes operate at a safe, low voltage, as opposed to the 250+ volts commonly found in xenon flashlamp-based lighting. This is particularly applicable to cameras on mobile phones, where space is at a premium and bulky voltage-increasing circuitry is undesirable. LEDs are used for infrared illumination in night vision applications including security cameras. A ring of LEDs around a video camera, aimed forward into a retroreflective background, allows chroma keying in video productions.

LEDs are used for decorative lighting as well. Uses include but are not limited to indoor/outdoor decor, limousines, cargo trailers, conversion vans, cruise ships, RVs, boats, automobiles, and utility trucks. Decorative LED lighting can also come in the form of lighted company signage and step and aisle lighting in theaters and auditoriums.

Smart lighting

Light can be used to transmit broadband data, which is already implemented in IrDA standards using infrared LEDs. Because LEDs can cycle on and off millions of times per second, they can, in effect, become wireless routers for data transport.[89] Lasers can also be modulated in this manner.

Sustainable lighting

Efficient lighting is needed for sustainable architecture. A 13 watt LED lamp produces 450 to 650 lumens.[90] which is equivalent to a standard 40 watt incandescent bulb. [91] A standard 40 W incandescent bulb has an expected lifespan of 1,000 hours while an LED can continue to operate with reduced efficiency for more than 50,000 hours, 50 times longer than the incandescent bulb.

Environmentally friendly options

A single kilowatt-hour of electricity will generate 1.34 pounds (610 g) of CO_2 emissions.[92] Assuming the average light bulb is on for 10 hours a day, a single 40-watt incandescent bulb will generate 196 pounds (89 kg) of CO_2 every year. The 13-watt LED equivalent will only be responsible for 63 pounds (29 kg) of CO_2 over the same time span. A building's carbon footprint from lighting can be reduced by 68% by exchanging all incandescent bulbs for new LEDs in warm climates. In cold climates, the energy saving may be lower, since more heating would be needed to compensate for the lower temperature.

LEDs are also non-toxic unlike the more popular energy efficient bulb option: the compact fluorescent a.k.a. CFL which contains traces of harmful mercury. While the amount of mercury in a CFL is small, introducing less into the environment is preferable.

Economically sustainable

LED light bulbs could be a cost-effective option for lighting a home or office space because of their very long lifetimes. Consumer use of LEDs as a replacement for conventional lighting system is currently hampered by the high cost and low efficiency of available products. 2009 DOE testing results showed an average efficacy of 35 lm/W, below that of typical CFLs, and as low as 9 lm/W, worse than standard incandescents.[90] The high initial cost of the commercial LED bulb is due to the expensive sapphire substrate which is key to the production process. The sapphire apparatus must be coupled with a mirror-like collector to reflect light that would otherwise be wasted.

In 2008, a materials science research team at Purdue University succeeded in producing LED bulbs with a substitute for the sapphire components.[93] The team used metal-coated silicon wafers with a built-in reflective layer of zirconium nitride to lessen the overall production cost of the LED. They predict that within a few years, LEDs produced with their revolutionary, new technique will be competitively priced with CFLs. The less expensive LED would not only be the best energy saver, but also a very economical bulb.

Non-visual applications

Light has many other uses besides for seeing. LEDs are used for some of these applications. The uses fall in three groups: Communication, sensors and light matter interaction.

The light from LEDs can be modulated very quickly so they are used extensively in optical fiber and Free Space Optics communications. This include remote controls, such as for TVs and VCRs, where infrared LEDs are often used. Opto-isolators use an LED combined with a photodiode or phototransistor to provide a signal path with electrical isolation between two circuits. This is especially useful in medical equipment where the signals from a low voltage sensor circuit (usually battery powered) in contact with a living organism must be electrically isolated from any possible electrical failure in a recording or monitoring device operating at potentially dangerous voltages. An optoisolator also allows information to be transferred between circuits not sharing a common ground potential.

Many sensor systems rely on light as the signal source. LEDs are often ideal as a light source due to the requirements of the sensors. LEDs are used as movement sensors, for example in optical computer mice. The Nintendo Wii's sensor bar uses infrared LEDs. In pulse oximeters for measuring oxygen saturation. Some flatbed scanners use arrays of RGB LEDs rather than the typical cold-cathode fluorescent lamp as the light source. Having independent control of three illuminated colors allows the scanner to calibrate itself for more accurate color balance, and there is no need for warm-up. Furthermore, its sensors only need be monochromatic, since at any one point in time the page being scanned is only lit by a single color of light. Touch sensing: Since LEDs can also be used as photodiodes, they can be used for both photo emission and detection. This could be used in for example a touch-sensing screen that register reflected light from a finger or stylus.[94]

Many materials and biological systems are sensitive to, or dependent on light. Grow lights use LEDs to increase photosynthesis in plants[95] and bacteria and viruses can be removed from water and other substances using UV LEDs for sterilization.[53] Other uses are as UV curing devices for some ink and coating applications as well as LED printers.

The use of LEDs is particularly interesting to plant cultivators, mainly because it is more energy efficient, less heat is produced (can damage plants close to hot lamps) and can provide the optimum light frequency for plant growth and bloom periods compared to currently used grow lights: HPS (high pressure sodium), MH (metal halide) or CFL/low-energy. It has however not replaced these grow lights due to it having a higher retail price, as mass production and LED kits develop the product will become cheaper.

LEDs have also been used as a medium quality voltage reference in electronic circuits. The forward voltage drop (e.g., about 1.7 V for a normal red LED) can be used instead of a Zener diode in low-voltage regulators. Red LEDs have the flattest I/V curve above the knee; nitride-based LEDs have a fairly steep I/V curve and are not useful in this application. Although LED forward voltage is much more current-dependent than a good Zener, Zener diodes are not widely available below voltages of about 3 V.

Light sources for machine vision systems

Machine vision systems often require bright and homogeneous illumination, so features of interest are easier to process. LEDs are often used to this purpose, and this field of application is likely to remain one of the major application areas until price drops low enough to make signaling and illumination applications more widespread. Barcode scanners are the most common example of machine vision, and many inexpensive ones used red LEDs instead of lasers. LEDs constitute a nearly ideal light source for machine vision systems for several reasons:

The size of the illuminated field is usually comparatively small and machine vision systems are often quite expensive, so the cost of the light source is usually a minor concern. However, it might not be easy to replace a broken light source placed within complex machinery, and here the long service life of LEDs is a benefit.

LED elements tend to be small and can be placed with high density over flat or even shaped substrates (PCBs etc.) so that bright and homogeneous sources can be designed which direct light from tightly controlled directions on inspected parts. This can often be obtained with small, inexpensive lenses and diffusers, helping to achieve high light densities with control over lighting levels and homogeneity. LED sources can be shaped in several configurations (spot lights for reflective illumination; ring lights for coaxial illumination; back lights for contour illumination; linear assemblies; flat, large format panels; dome sources for diffused, omnidirectional illumination).

LEDs can be easily strobed (in the microsecond range and below) and synchronized with imaging. High power LEDs are available allowing well lit images even with very short light pulses. This is often used in order to obtain crisp and sharp “still” images of quickly moving parts.

LEDs come in several different colors and wavelengths, easily allowing to use the best color for each application, where different color may provide better visibility of features of interest. Having a precisely known spectrum allows tightly matched filters to be used to separate informative bandwidth or to reduce disturbing effect of ambient light. LEDs usually operate at comparatively low working temperatures, simplifying heat management and dissipation, therefore allowing plastic lenses, filters and diffusers to be used. Waterproof units can also easily be designed, allowing for use in harsh or wet environments (food, beverage, oil industries).

See also

- Display examples
- Laser diode
- LED circuit
- LED lamp
- LED as light sensor
- Luminous efficacy
- Nixie tube
- Photovoltaics
- Seven-segment display
- Solar lamp
- Solid state lighting (SSL)

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External links

- Light-emitting diode (http://www.dmoz.org/Business/Electronics_and_Electrical/Optoelectronics_and_Fiber/Vendors//) at the Open Directory Project

- Dendrimers in the spotlight (http://www.rsc.org/Publishing/ChemTech/Volume/2008/11/dendrimers_insight.asp) - an Instant Insight (http://www.rsc.org/Publishing/ChemTech/Instant_insights.asp) examining the use of dendrimers in organic light-emitting diodes from the Royal Society of Chemistry
- Photonics Sources Group, Tyndall National Institute (http://www.tyndall.ie/gan) GaN and other photonics research at the Tyndall National Institute, Ireland.
- LEDWire (http://www.ledwire.ca) Canadian LED industry news wire service.
- MAKE Presents: The LED - A movie about the origins of the LED and how to make your own from carborundum! (http://blog.makezine.com/archive/2008/11/make_presents_the_led_a_m.html)
- Rensselaer Electrical Engineering Department (http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/) LED information arranged in textbook form, aimed at introductory to advanced audience
- Uncertainty evaluation for measurement of LED colour (http://stacks.iop.org/0026-1394/46/704)
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- Lighting Research Center's Solid-State Lighting program (http://www.lrc.rpi.edu/programs/solidstate/index.asp)

Categories: Optical diodes | Lighting | Signage | Semiconductor devices | 1907 introductions | Light-emitting diodes | American inventions | Russian inventions | Soviet inventions

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