

Light-emitting diode



Blue, green and red LEDs.

A **light-emitting diode** (LED) is a semiconductor device that emits incoherent narrow-spectrum light when electrically biased in the forward direction. This effect is a form of electroluminescence. The color of the emitted light depends on the composition and condition of the semiconducting material used, and can be near-ultraviolet, visible or infrared.[1] Rubin Braunstein of the Radio Corporation of America first reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955.[2] Experimenters at Texas Instruments, Bob Biard and Gary Pittman, found in 1961 that gallium arsenide gave off infrared (invisible) light when electric current was applied. Biard and Pittman were able to establish the priority of their work and received the patent for the infrared light-emitting diode. Nick Holonyak Jr. of the General Electric Company developed the first practical visible-spectrum LED in 1962.[3]

LED technology

Physical function

A LED is a unique type of semiconductor diode. Like a normal diode, it consists of a chip of semiconducting material impregnated, or doped, with impurities to create a structure called 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 electron 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.

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 bandgap materials. The materials used for an LED have a direct band gap with energies corresponding to near-infrared, visible or near-ultraviolet light. Free standing LEDs are usually constantly illuminated when a current passes through them, but flashing LEDs are also available. Flashing LEDs resemble standard LEDs but they contain a small chip inside which causes the LED to flash with a typical period of one second. This type of

LED comes most commonly as red, yellow, or green. Most flashing LEDs emit light of a single wavelength, but multicoloured flashing LEDs are available too.

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 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. Substrates that are transparent to the emitted wavelength, and backed by a reflective layer, increase the LED efficiency. The refractive index of the package material should match the index of the semiconductor, otherwise the produced light gets partially reflected back into the semiconductor, where it gets absorbed and turns into additional heat.

Conventional LEDs are made from a variety of inorganic semiconductor materials, producing the following colors:

- aluminum gallium arsenide (AlGaAs) - red and infrared
- aluminum gallium phosphide (AlGaP) - green
- aluminum gallium indium phosphide (AlGaInP) - high-brightness orange-red, orange, yellow, and green
- gallium arsenide phosphide (GaAsP) - red, orange-red, orange, and yellow
- gallium phosphide (GaP) - red, yellow and green
- gallium nitride (GaN) - green, pure green (or emerald green), and blue also white (if it has an AlGaN Quantum Barrier)
- indium gallium nitride (InGaN) - near ultraviolet, bluish-green and blue
- silicon carbide (SiC) as substrate - blue
- silicon (Si) as substrate - blue (under development)
- sapphire (Al₂O₃) as substrate - blue
- zinc selenide (ZnSe) - blue
- diamond (C) - ultraviolet
- aluminum nitride (AlN), aluminum gallium nitride (AlGaN) - near to far ultraviolet

Blue and white LEDs



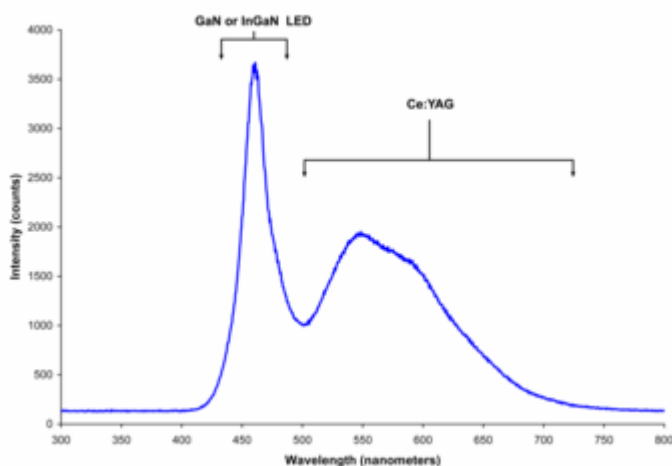
An ultraviolet GaN LED.

Commercially viable blue LEDs based on the wide band gap semiconductor gallium nitride and indium gallium nitride were invented by Shuji Nakamura while working in Japan at

Nichia Corporation in 1993 and became widely available in the late 1990s. They can be added to existing red and green LEDs to produce white light, though white LEDs today rarely use this principle.

Most "white" LEDs in production today use a 450 nm – 470 nm blue GaN (gallium nitride) or InGaN (indium gallium nitride) LED covered by a yellowish phosphor coating usually made of cerium-doped yttrium aluminum garnet ($\text{Ce}^{3+}:\text{YAG}$) crystals which have been powdered and bound in a type of viscous adhesive. The LED chip emits blue light, part of which is efficiently converted to a broad spectrum centered at about 580 nm (yellow) by the $\text{Ce}^{3+}:\text{YAG}$. The single crystal form of $\text{Ce}^{3+}:\text{YAG}$ is actually considered a scintillator rather than a phosphor. Since yellow light stimulates the red and green receptors of the eye, the resulting mix of blue and yellow light gives the appearance of white, the resulting shade often called "lunar white". This approach was developed by Nichia and was used by them from 1996 for manufacturing of white LEDs.

The pale yellow emission of the $\text{Ce}^{3+}:\text{YAG}$ can be tuned by substituting the cerium with other rare earth elements such as terbium and gadolinium and can even be further adjusted by substituting some or all of the aluminum in the YAG with gallium. Due to the spectral characteristics of the diode, the red and green colors of objects in its blue yellow light are not as vivid as in broad-spectrum light. Manufacturing variations and varying thicknesses in the phosphor make the LEDs produce light with different color temperatures, from warm yellowish to cold bluish; the LEDs have to be sorted during manufacture by their actual characteristics. Philips Lumileds patented conformal coating process addresses the issue of varying phosphor thickness, giving the white LEDs a more consistent spectrum of white light.



Spectrum of a "white" LED clearly showing blue light which is directly emitted by the GaN or InGaN LED (peak at about 465 nanometers) and the more broadband Stokes shifted light emitted by the $\text{Ce}^{3+}:\text{YAG}$ phosphor which extends from around 500 to 700 nanometers.

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 aluminum doped zinc sulfide ($\text{ZnS}:\text{Cu,Al}$). This is a method analogous to the way fluorescent lamps work. However the ultraviolet light causes photodegradation to the epoxy resin and many other materials used in LED packaging, causing manufacturing challenges and shorter lifetimes. This method is less efficient than the blue LED with $\text{YAG}:\text{Ce}$ 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.

The newest method used to produce white light LEDs uses no phosphors at all and is based on homoepitaxially grown zinc selenide (ZnSe) on a ZnSe substrate which simultaneously emits blue light from its active region and yellow light from the substrate.

A new technique just 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.

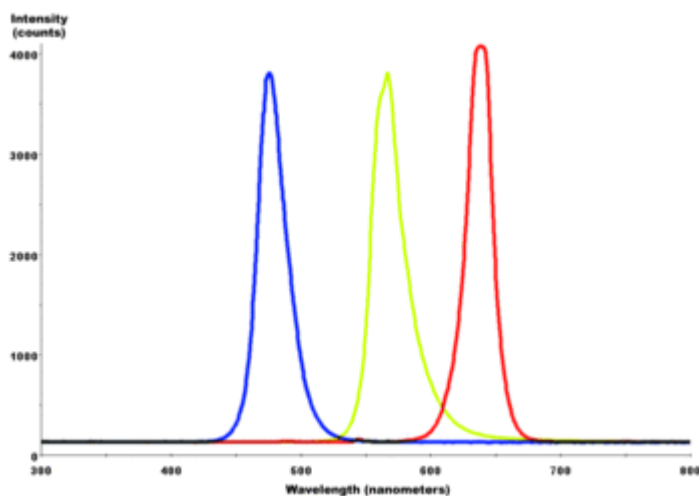
Other colors

Recent color developments include pink and purple. They consist of one or two phosphor layers over a blue LED chip. The first phosphor layer of a pink LED is a yellow glowing one, and the second phosphor layer is either red or orange glowing. Purple LEDs are blue LEDs with an orange glowing phosphor over the chip. Some pink LEDs have run into issues. For example, some are blue LEDs painted with fluorescent paint or fingernail polish that can wear off, and some are white LEDs with a pink phosphor or dye that unfortunately fades after a short time.

Ultraviolet, blue, pure green, white, pink and purple LEDs are relatively expensive compared to the more common reds, oranges, greens, yellows and infrared and are thus less commonly used in commercial applications, however, as of 2006, the "Chernobyl blue" light from blue LEDs has a certain commercial cachet [4] and is used as a styling element in many products such as mobile phones and thus the price has dropped significantly.

The semiconducting chip is encased in a solid plastic lens, which is much tougher than the glass envelope of a traditional light bulb or tube. The plastic may be colored, but this is only for cosmetic reasons or to improve the contrast ratio; the color of the packaging does not substantially affect the color of the light emitted.

Organic light-emitting diodes (OLEDs)



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

If the emitting layer material of an 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. 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

At present (2006) OLEDs are used in small portable color video displays such as cellphone and digital camera screens, and user interfaces on MP3 players. Large-screen color displays have been demonstrated, but their life expectancy is still far too short (<1,000 Hrs) to be practical.

Operational parameters and efficiency

Most typical LEDs are designed to operate with no more than 30-60 milliwatts of electrical power. Around 1999, Philips Lumileds introduced power LEDs capable of continuous use at one watt. These LEDs used much larger semiconductor die sizes to handle the large power input. Also, the semiconductor dies were mounted to metal slugs to allow for heat removal from the LED die. In 2002, Lumileds made 5-watt LEDs available with efficiencies of 18-22 lumens per watt.

In September 2003 a new type of blue LED was demonstrated by the company Cree, Inc. to have 35% efficiency at 20 mA. This produced a commercially packaged white light having 65 lumens per watt at 20 mA, becoming the brightest white LED commercially available at the time. In 2006 they have demonstrated a prototype with a record white LED efficiency of 131 lumens per watt at 20 mA [5].

Today, OLEDs operate at substantially lower efficiency than inorganic (crystalline) LEDs. The best efficiency of an OLED so far is about 10%. These promise to be much cheaper to fabricate than inorganic LEDs, and large arrays of them can be deposited on a screen using simple printing methods to create a color graphic display.

Failure modes

The most common way for LEDs (and diode lasers) to fail is the gradual lowering of light output and loss of efficiency. However, sudden failures can occur as well.

The mechanism of degradation of the active region, where the radiative recombination occurs, involves nucleation and growth of dislocations; this requires a presence of an existing defect in the crystal and is accelerated by heat, high current density, and emitted light. Gallium

arsenide and aluminum gallium arsenide are more susceptible to this mechanism than gallium arsenide phosphide, indium gallium arsenide phosphide, and indium phosphide. Due to different properties of the active regions, gallium nitride and indium gallium nitride are virtually insensitive to this kind of defects; however, high current density can cause electromigration of atoms out of the active regions, leading to emergence of dislocations and point defects, acting as nonradiative recombination centers and producing heat instead of light. Ionizing radiation can lead to creation of such defects as well, which leads to issues with radiation hardening of circuits containing LEDs (eg. in optoisolators). Early red LEDs were notable for their short lifetime.

White LEDs often use one or more phosphors. The phosphors tend to degrade with heat and age, losing efficiency and causing changes in the produced light color.

High electrical currents at elevated temperatures can cause diffusion of metal atoms from the electrodes into the active region. Some materials, notably indium tin oxide and silver, are subject to electromigration. In some cases, especially with GaN/InGaN diodes, a barrier metal layer is used to hinder the electromigration effects. Mechanical stresses, high currents, and corrosive environment can lead to formation of whiskers, causing short circuits.

High-power LEDs are susceptible to current crowding, nonhomogenous distribution of the current density over the junction. This may lead to creation of localized hot spots, which poses risk of thermal runaway. Nonhomogenities in the substrate, causing localized loss of thermal conductivity, aggravate the situation; most common ones are voids caused by incomplete soldering, or by electromigration effects and Kirkendall voiding. Thermal runaway is a common cause of LED failures.

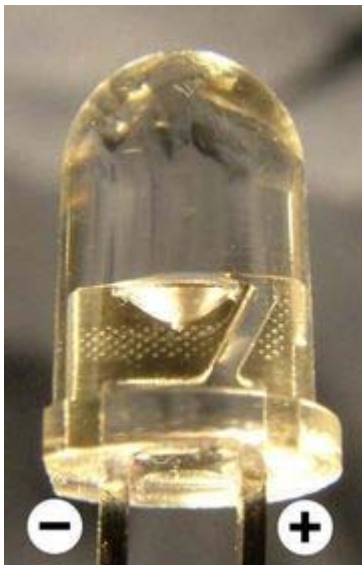
Laser diodes may be subject to catastrophic optical damage, when the light output exceeds a critical level and causes melting of the facet.

Some materials of the plastic package tend to yellow when subjected to heat, causing partial absorption (and therefore loss of efficiency) of the affected wavelengths.

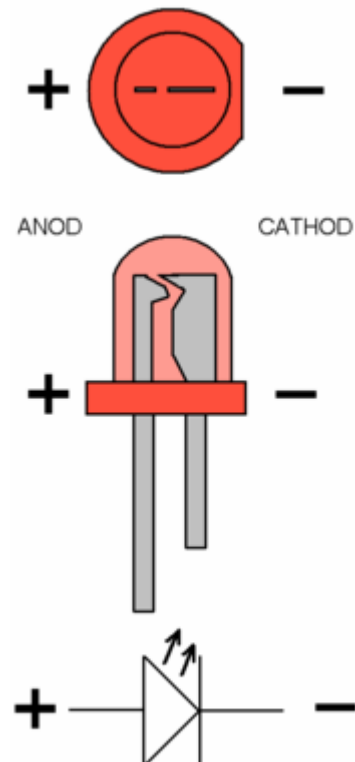
Sudden failures are most often caused by thermal stresses. When the epoxy resin used in packaging reaches its glass transition temperature, it starts rapidly expanding, causing mechanical stresses on the semiconductor and the bonded contact, weakening it or even tearing it off. Conversely, very low temperatures can cause cracking of the packaging.

Electrostatic discharge (ESD) may cause immediate failure of the semiconductor junction, a permanent shift of its parameters, or latent damage causing increased rate of degradation. LEDs and lasers grown on sapphire substrate are more susceptible to ESD damage.

Considerations in use



Close-up of a typical LED, showing the internal structure.



Unlike incandescent light bulbs, which light up regardless of the electrical polarity, LEDs will only light with positive electrical polarity. When the voltage across the p-n junction is in the correct direction, a significant current flows and the device is said to be forward-biased. If the voltage is of the wrong polarity, the device is said to be reverse biased, very little current flows, and no light is emitted. LEDs can be operated on an Alternating current voltage, but

they will only light with positive voltage, causing the LED to turn on and off at the frequency of the AC supply.

The correct polarity of an LED can usually be determined as follows:

| | | |
|--------------|----------|----------|
| sign: | + | - |
| polarity: | positive | negative |
| terminal: | anode | cathode |
| wiring: | red | black |
| leads: | long | short |
| marking: | none | stripe |
| pin: | 1 | 2 |
| PCB: | square | round |
| interior: | small | large |
| exterior: | round | flat |

Bicolor LED units contain two diodes, one in each direction (that is, two diodes in inverse parallel) and each a different color (typically red and green), allowing two-color operation or a range of apparent colors to be created by altering the percentage of time the voltage is in each polarity. Other LED units contain two or more diodes (of different colors) arranged in either a common anode or common cathode configuration. These can be driven to different colors without reversing the polarity.

LED units may have an integrated multivibrator circuit that makes the LED flash.

Advantages of using LEDs



LED schematic symbol

- LEDs are significantly more energy-efficient than incandescent bulbs, this is particularly useful in battery powered devices.
- LEDs can emit light of an intended color without the use of color filters that traditional lighting methods require. This is more efficient and can lower initial costs.
- The solid package of an 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 useable manner.
- LEDs are built inside solid cases that protect them, unlike incandescent and discharge sources, making them extremely durable.
- LEDs have an extremely long life span: typically ten years, twice as long as the best fluorescent bulbs and twenty times longer than the best incandescent bulbs. (Incandescent bulbs can also be made to last an extremely long time by

running at lower than normal voltage, but only at a huge cost in efficiency; LEDs have a long life when operated at their rated power.)

- Further, LEDs fail by dimming over time, rather than the abrupt burn-out of incandescent bulbs.
- LEDs give off much less heat than incandescent light bulbs with similar light output.
- LEDs light up very quickly. A typical red indicator LED will achieve full brightness in microseconds, or possibly less if it's used for communication devices.

LED applications

- 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.
- LED panels are good for outdoor applications because of the brightness even during a sunny day.
- Flashlights and lanterns that utilize white LEDs are becoming increasingly popular due to their durability and longer battery life.

List of LED applications

Some of these applications are further elaborated upon in the following text.

- Architectural Lighting
- Status indicators on all sorts of equipment
- Traffic Lights and Signals
- Railroad Crossing signals
- Continuity indicators
- Flashlights. Some models that do not even use batteries, are of this type.
- Light bars on emergency vehicles.
- Thin, lightweight message displays at airports and railway stations and as destination displays for trains, buses, trams and ferries.
- 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.
- Red, yellow, green, and blue LEDs can be used for Model Railroading applications
- Remote controls for TVs, VCRs, etc, using infrared LEDs.
- In optical fiber communications.
- In dot matrix arrangements for displaying messages.
- In traffic signals, LED clusters are replacing colored incandescent bulbs.
- Glowlights, as a more expensive but longer lasting and reusable alternative to Glowsticks.
- Movement sensors, for example, in optical computer mouse
- Because of their long life, LEDs have been used for automotive high-mounted brake lights and truck and bus brake lights and turn signals for some time, but many high-end vehicles are now starting to use LEDs for their entire rear light

clusters. Besides the gain in reliability, this has styling advantages because LEDs are capable of forming much thinner lights than incandescent lamps with parabolic reflectors.

- Backlighting for LCD televisions and displays. The availability of LEDs in specific colors (RGB) enables a full-spectrum light source which expands the color gamut by as much as 45%.
- New stage lighting equipment is being developed with LED sources in primary red-green-blue arrangements.
- Lumalive, a photonic textile
- LED-based Christmas lights have been available since 2002, but they have yet to gain popularity and acceptance due to their higher initial purchase cost when compared to similar incandescent-based Christmas lights.

Illumination applications



Spotlights made of many individual LEDs

LEDs used as a replacement for incandescent light bulbs and fluorescent lamps are known as solid-state lighting (SSL) - packaged as a cluster of white LEDs grouped together to form a light source (pictured). LEDs are moderately efficient: the average commercial SSL currently outputs 32 lumens per watt (lm/W), and new technologies promise to deliver up to 80 lm/W. The long lifetime of LEDs make SSL very attractive. They are also more mechanically robust than incandescent light bulbs and fluorescent tubes. Currently, solid state lighting is becoming more available for household use, but is relatively expensive, although costs are decreasing. LED flashlights however already have become widely available. Recently a number of manufacturers have started marketing ultra-compact LCD video projectors that use high-powered white LEDs for the light source. Another alternative design is to use red, green, and blue LEDs in a sequential DLP design.

Incandescent bulbs are much less expensive but also less efficient, generating from about 16 lm/W for a domestic tungsten bulb to 22 lm/W for a halogen bulb. Fluorescent tubes are more efficient, providing 50 to 100 lm/W for domestic tubes (average 60 lm/W), but are bulky and fragile and require starter or ballast circuits that sometimes buzz audibly. Compact fluorescent lamps, which include a quiet integrated ballast, are relatively robust and efficient, fit in standard light bulb sockets, and are currently the best choice for efficient household lighting.

Proponents of LEDs expect that technological advances will reduce costs such that SSL can be introduced into most homes by 2020. However, they are still not commercially viable for

general lighting applications, and so LEDs are found today in illumination applications where their special characteristics provide a distinct advantage. This can be seen in the widespread use of LEDs in traffic signals and indicator lamps for trucks and automobiles.

Due to their monochromatic nature, LED lights have great power advantages over white lights when a specific color is required. Unlike traditional white lights, the LED does not need a coating or diffuser that can absorb much of the emitted light. LED lights are inherently colored, and are available in a wide range of colors. One of the most recently introduced colors is the emerald green (bluish green, about 500 nm) that meets the legal requirements for traffic signals and navigation lights.

There are applications that specifically require light without any blue component. Examples are photographic darkroom safe lights, illumination in laboratories where certain photo-sensitive chemicals are used, and situations where dark adaptation (night vision) must be preserved, such as cockpit and bridge illumination, observatories, etc. Yellow LED lights are a good choice to meet these special requirements because the human eye is more sensitive to yellow light (about 500 lm/watt emitted) than that emitted by the other LEDs.

The first residence lit solely by LED's was the "Vos Pad" in London. The entire flat is lit by a combination of white and RGB (colour changing) LED's.