

# Light Emitting Diodes and Technology

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WORLD TECHNOLOGIES

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## Chapter- 1

# Light-Emitting Diode

### Light-emitting diode



Red, green and blue LEDs of the 5mm type

**Type**

Passive, optoelectronic

**Working principle**

Electroluminescence

**Invented**

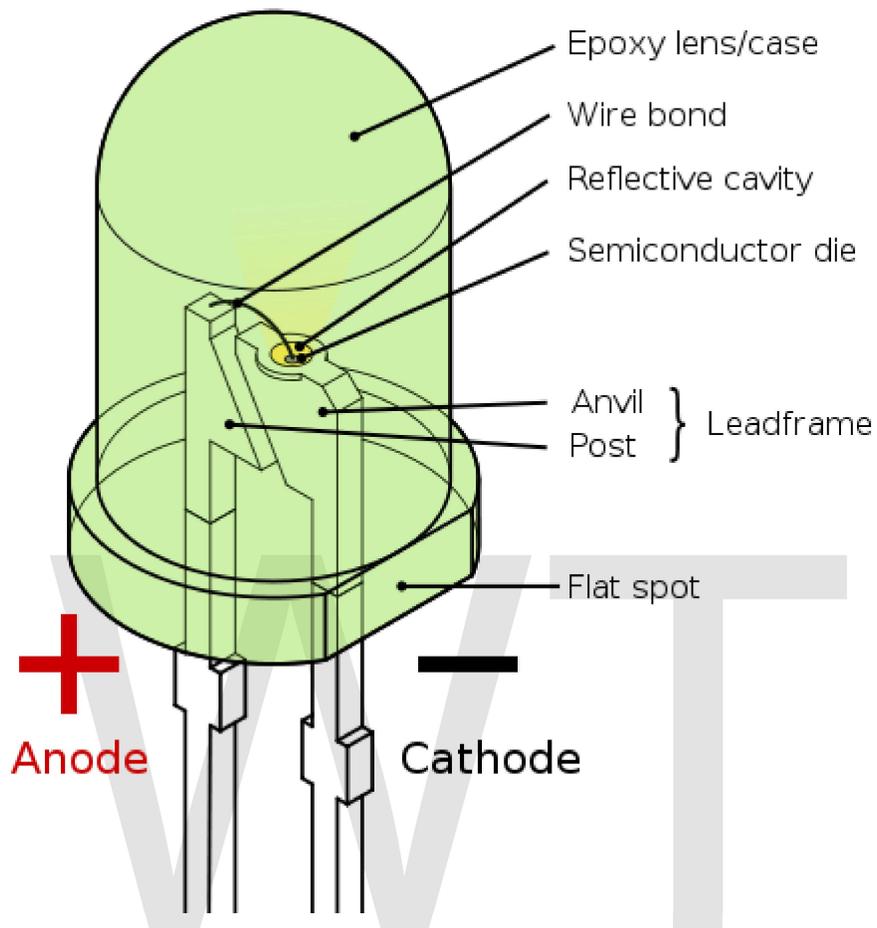
Nick Holonyak Jr. (1962)

**Electronic symbol**



**Pin configuration**

Anode and Cathode



Parts of an LED



LED spotlight using 38 individual diodes for mains voltage power

A **light-emitting diode (LED)** 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, early LEDs emitted low-intensity red light, but modern versions are available across the visible, ultraviolet and infrared wavelengths, with very high brightness.

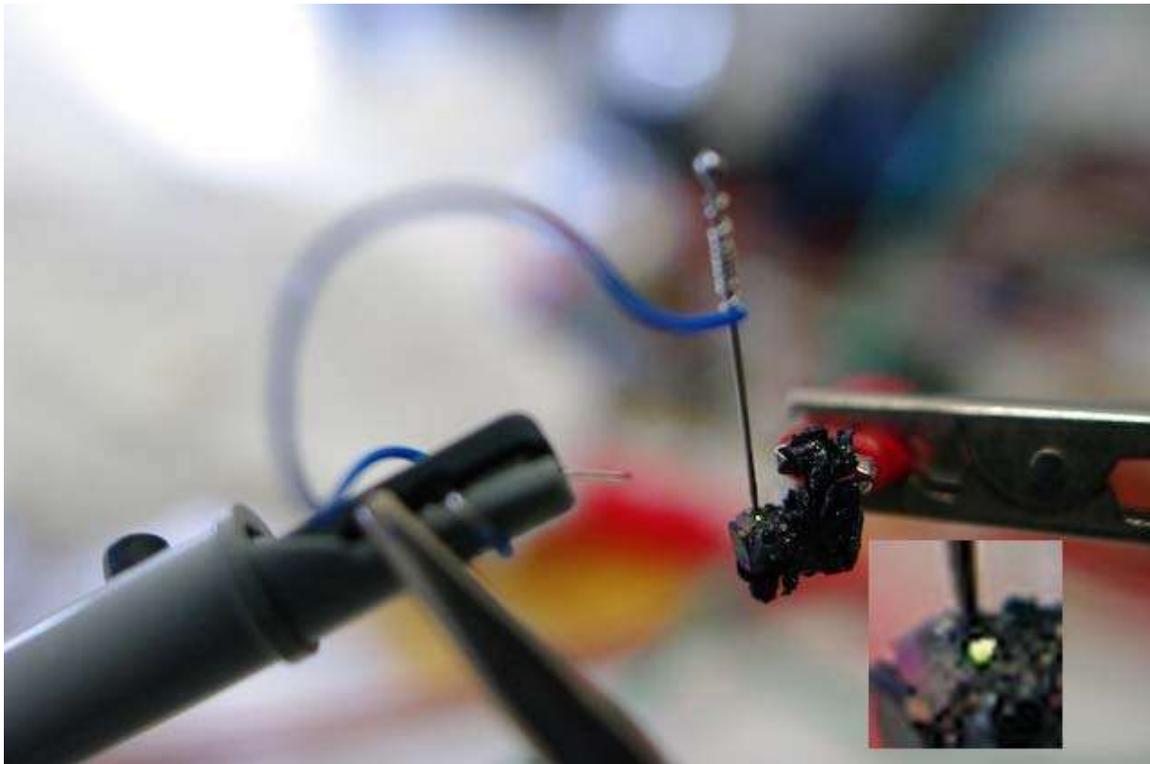
When a light-emitting diode is forward biased (switched on), electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor. An LED is often small in area (less than  $1 \text{ mm}^2$ ), and integrated optical components may be used to shape its radiation pattern. 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 brake lamps, turn signals and indicators) as well as in traffic signals. The compact size, the possibility of narrow bandwidth,

switching speed, and extreme reliability of LEDs has allowed new text and video displays and sensors to be developed, while their high switching rates are also 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.

## History

### Discoveries and early devices



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

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. Russian Oleg Vladimirovich Losev independently reported on the creation of an LED in 1927. His research was distributed in Russian, German and British scientific journals, but no practical use was made of the discovery for several decades. Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955. 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.

In 1961, American experimenters Robert Biard and Gary Pittman working at Texas Instruments, 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. Holonyak is seen as the "father of the light-emitting diode". M. George Craford, 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. 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.

Until 1968, visible and infrared LEDs were extremely costly, on the order of US \$200 per unit, and so had little practical use. 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. Hewlett Packard (HP) introduced LEDs in 1968, initially using GaAsP supplied by Monsanto. The technology proved to have major uses 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. The combination of planar processing for chip fabrication and innovative packaging methods enabled the team at Fairchild led by optoelectronics pioneer Thomas Brandt to achieve the needed cost reductions. These methods continue to be used by LED producers.

## **Practical use**

The first commercial LEDs were commonly used as replacements for incandescent and neon indicator lamps, and in seven-segment displays, first in expensive equipment such as laboratory and electronics test equipment, then later in such appliances as TVs, radios, telephones, calculators, and even watches. 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 grew widely available and also appeared in appliances and equipment. As LED materials technology grew more advanced, light output rose, while maintaining efficiency and reliability at acceptable levels. The invention and development of the high power white light LED led to use for illumination. Most LEDs were made in the very common 5 mm T1<sup>3/4</sup> and 3 mm T1 packages, but with rising power output, it has grown increasingly necessary to shed excess heat to maintain reliability, 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.

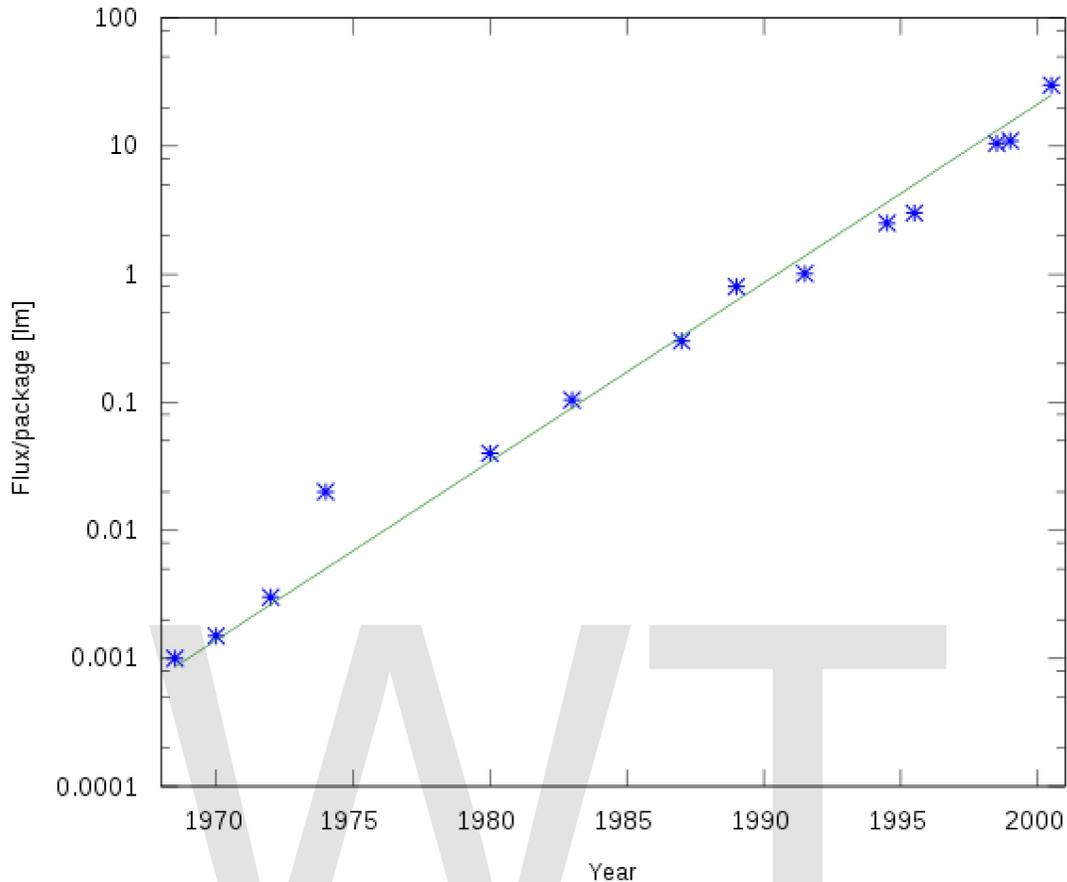


Illustration of Haitz's Law. Light output per LED as a function of production year, note the logarithmic scale on the vertical axis.

### Continuing development

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.

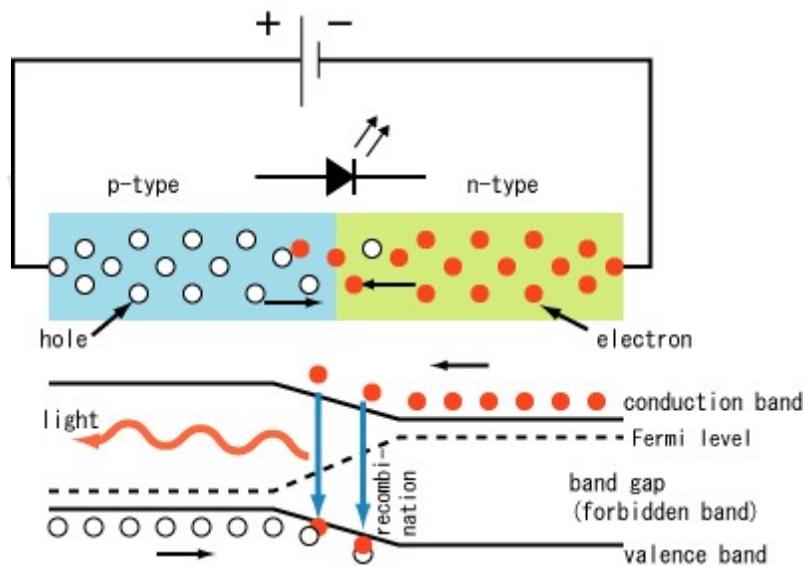
The development of LED technology has caused their efficiency and light output to rise exponentially, with a doubling occurring about every 36 months since the 1960s, in a way similar to Moore's law. The advances are generally attributed to the parallel development

of other semiconductor technologies and advances in optics and material science. This trend is normally called Haitz's Law after Dr. Roland Haitz.

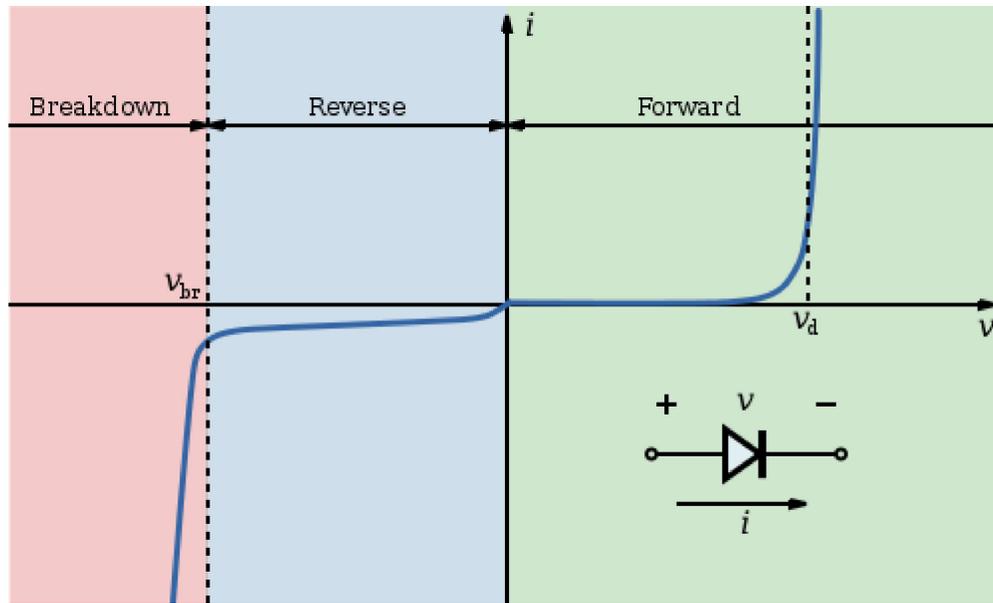
In February 2008, 300 lumens of visible light per watt luminous efficacy (not per electrical watt) and warm-light emission was achieved by using nanocrystals.

In 2009, a process for growing gallium nitride (GaN) LEDs on silicon has been reported. Epitaxy costs could be reduced by up to 90% using six-inch silicon wafers instead of two-inch sapphire wafers.

## Technology



The inner workings of an LED



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 volts

## 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.

The wavelength of the light emitted, and thus 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.

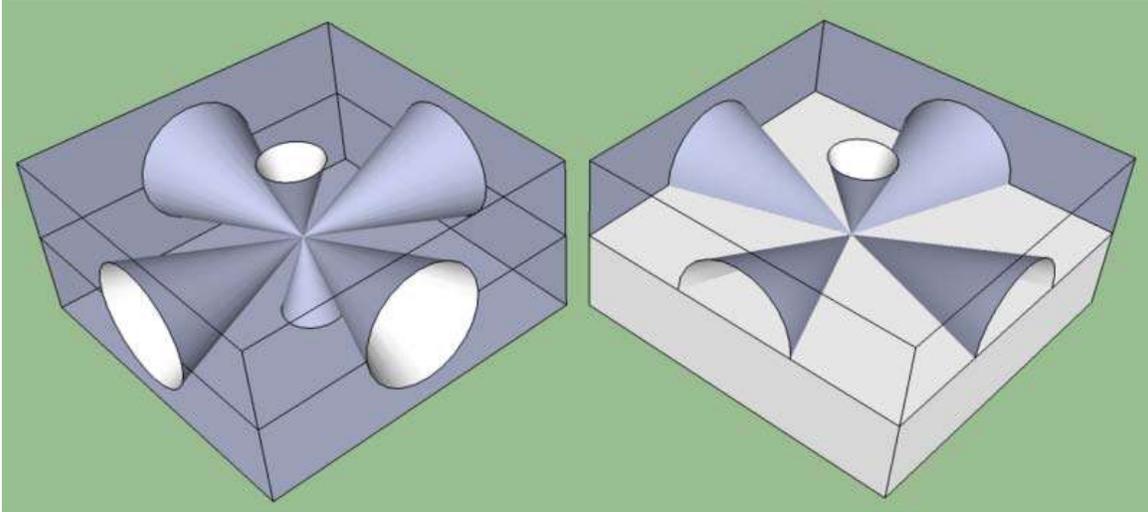
LED development began with infrared and red devices made with gallium arsenide. Advances in materials science have enabled making devices with ever-shorter wavelengths, emitting light in a variety of colors.

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.

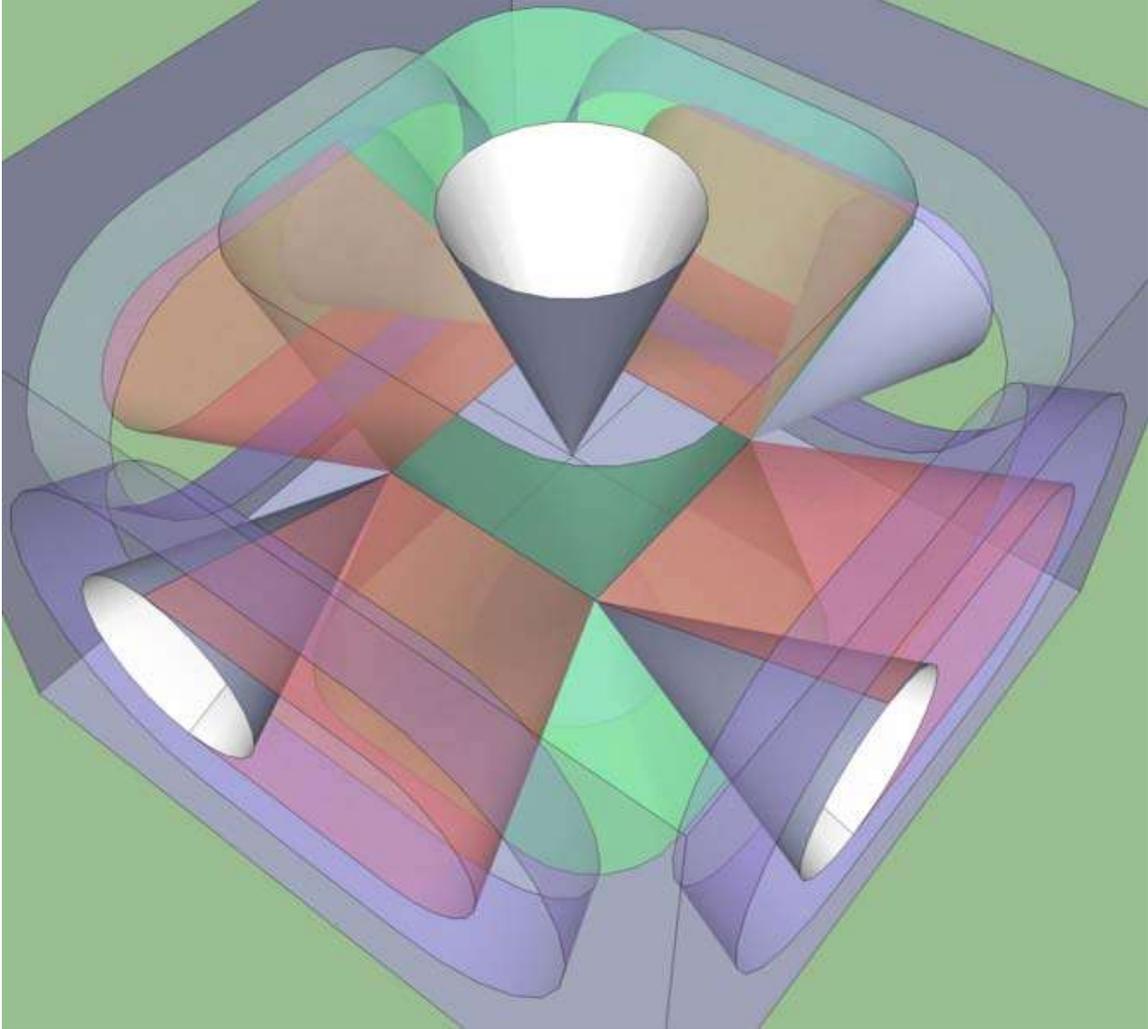
Most materials used for LED production have very high refractive indices. This means that much light will be reflected back into the material at the material/air surface

interface. Thus, light extraction in LEDs is an important aspect of LED production, subject to much research and development.

## Refractive Index



Idealized example of light emission cones in a semiconductor, for a single point-source emission zone. The left illustration is for a fully translucent wafer, while the right illustration shows the half-cones formed when the bottom layer is fully opaque. The light is actually emitted equally in all directions from the point-source, so the areas between the cones shows the large amount of trapped light energy that is wasted as heat.



The light emission cones of a real LED wafer are far more complex than a single point-source light emission. Typically the light emission zone is a 2D plane between the wafers. Across this 2D plane, there is effectively a separate set of emission cones for every atom.

Drawing the billions of overlapping cones is impossible, so this is a simplified diagram showing the extents of all the emission cones combined. The larger side cones are clipped to show the interior features and reduce image complexity; they would extend to the opposite edges of the 2D emission plane.

Bare uncoated semiconductors such as silicon exhibit a very high refractive index relative to open air, which prevents passage of photons at sharp angles relative to the air-contacting surface of the semiconductor. This property affects both the light-emission efficiency of LEDs as well as the light-absorption efficiency of photovoltaic cells. The refractive index of silicon is 4.24, while air is 1.00002926

Generally a flat-surfaced uncoated LED semiconductor chip will only emit light perpendicular to the semiconductor's surface, and a few degrees to the side, in a cone

shape referred to as the *light cone*, *cone of light*, or the *escape cone*. The maximum angle of incidence is referred to as the critical angle. When this angle is exceeded photons no longer penetrate the semiconductor, but are instead reflected both internally inside the semiconductor crystal, and externally off the surface of the crystal as if it were a mirror.

Internal reflections can escape through other crystalline faces, if the incidence angle is low enough and the crystal is sufficiently transparent to not re-absorb the photon emission. But for a simple square LED with 90-degree angled surfaces on all sides, the faces all act as equal angle mirrors. In this case the light can not escape and is lost as waste heat in the crystal.

A convoluted chip surface with angled facets similar to a jewel or fresnel lens can increase light output by allowing light to be emitted perpendicular to the chip surface while far to the sides of the photon emission point.

The ideal shape of a semiconductor with maximum light output would be a microsphere with the photon emission occurring at the exact center, with electrodes penetrating to the center to contact at the emission point. All light rays emanating from the center would be perpendicular to the entire surface of the sphere, resulting in no internal reflections. A hemispherical semiconductor would also work, with the flat back-surface serving as a mirror to back-scattered photons.

### **Transition coatings**

Many LED semiconductor chips are potted in clear or colored molded plastic shells. The plastic shell has three purposes:

1. Mounting the semiconductor chip in devices is easier to accomplish.
2. The tiny fragile electrical wiring is physically supported and protected from damage
3. The plastic acts as a refractive intermediary between the relatively high-index semiconductor and low-index open air.

The third feature helps to boost the light emission from the semiconductor by acting as a diffusing lens, allowing light to be emitted at a much higher angle of incidence from the light cone, than the bare chip is able to emit alone.

### **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.

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 light bulb emits around 15 lm/W, and standard fluorescent lights emit up to 100 lm/W. A recurring problem is that efficiency falls sharply with rising current. This effect is known as droop and effectively limits the light output of a given LED, raising heating more than light output for higher current.

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 plans for 135 lm/W by 2007 and 145 lm/W by 2008, which would be nearing an order of magnitude improvement over standard incandescents and better than even standard fluorescents. Nichia Corporation has developed a white LED with luminous efficacy of 150 lm/W at a forward current of 20 mA.

Practical general lighting needs high-power LEDs, of one watt or more. Typical operating currents for such devices begin at 350 mA.

Note that these efficiencies are for the LED chip only, held at low temperature in a lab. Lighting works at higher temperature and with drive circuit losses, so 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).

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.

### **Lifetime and failure**

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 made 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.

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.

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.

LED light output actually rises at colder temperatures (leveling off depending on type at around -30C). Consequently, LED technology may be a good replacement in uses such as supermarket freezer lighting and will last longer than other technologies. Because LEDs emit less heat than incandescent bulbs, they are an energy-efficient technology for uses such as freezers. However, because they emit little heat, ice and snow may build up on the LED luminaire in colder climates. 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 areas, although some research has been done to try to develop heat sink technologies to transfer heat to other areas of the luminaire.

## 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	$500 < \lambda < 570$	$1.9 < \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP) Zinc selenide (ZnSe)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	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) Boron nitride (215 nm) Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm)
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. These devices had too little light output to be of much practical use. In the late 1980s, key breakthroughs in GaN epitaxial growth and p-type doping ushered in the modern era of GaN-based optoelectronic devices. Building upon this foundation, in 1993 high brightness blue LEDs were demonstrated.

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, instead of 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 AlGaInN 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. 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.

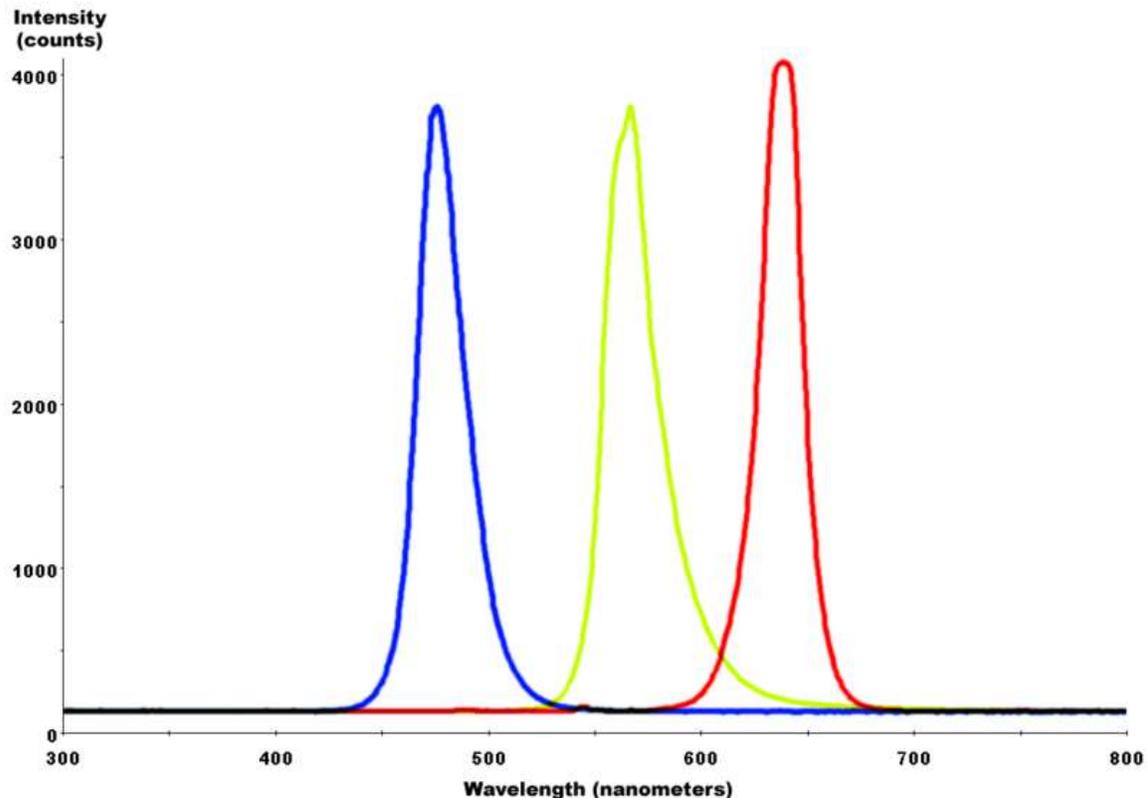
Deep-UV wavelengths were obtained in laboratories using aluminium nitride (210 nm), boron nitride (215 nm) and diamond (235 nm).

### **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—red, green, and blue—and then mix all the colors to form 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



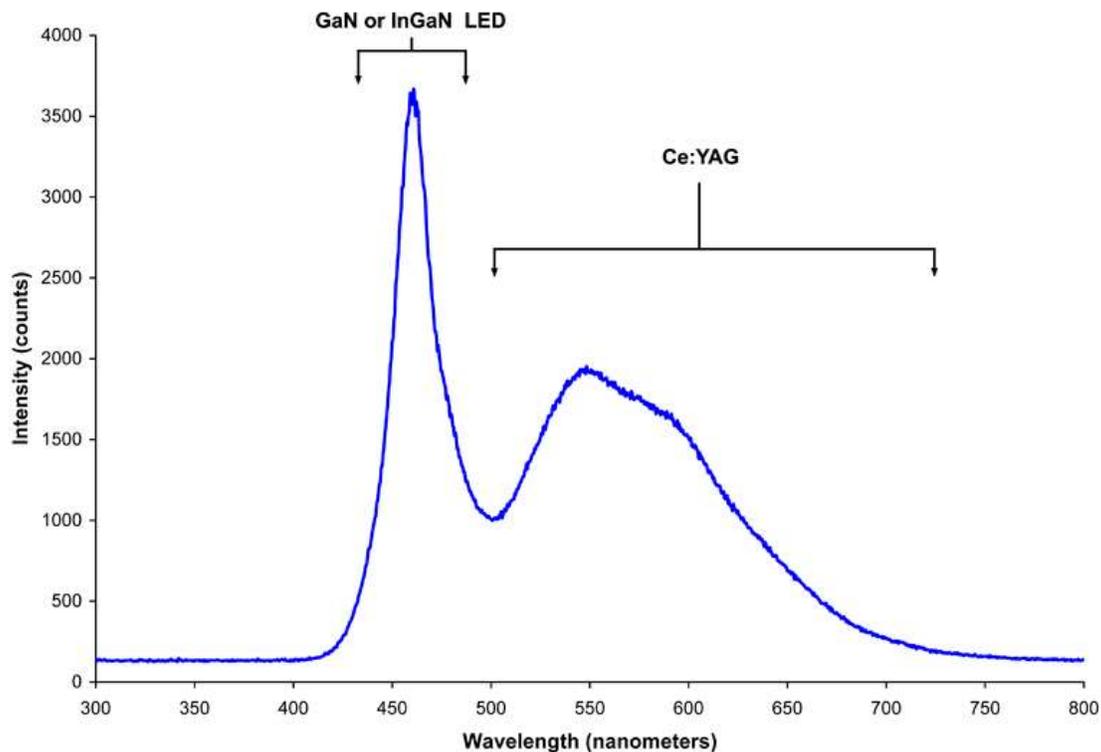
Combined spectral curves for blue, yellow-green, and high brightness red solid-state semiconductor LEDs. FWHM spectral bandwidth is approximately 24–27 nm for all three colors.

White light can be formed by mixing differently colored lights, 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 these need electronic circuits to control the blending and diffusion of different colors, these are seldom used to produce white lighting. Nevertheless, this method is particularly interesting in many uses because of the flexibility of mixing different colors, and, in principle, this mechanism also has higher quantum efficiency in producing white light.

There are several types of multi-colored white LEDs: di-, tri-, and tetrachromatic white LEDs. Several key factors that play among these different methods, 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.

Multi-color LEDs offer not merely another means to form white light, but a new means to form light of different colors. Most perceivable colors can be formed by mixing different amounts of three primary colors. This allows precise dynamic color control. As more effort is devoted to investigating this method, 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 play a role on the market, several technical problems need solving. These include that this type of LED's emission power decays exponentially with rising temperature, resulting in a substantial change in color stability. Such problems inhibit and may preclude industrial use. Thus, 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



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  $\text{Ce}^{3+}$ :YAG phosphor which emits at roughly 500–700 nm.

This method involves coating an LED of one color (mostly blue LED made of InGaN) with phosphor of different colors to form white light; the resultant LEDs are called **phosphor-based white LEDs**. 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 raising the color rendering index (CRI) value of a given LED.

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 method for making 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 raised 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. With development ongoing, the efficiency of phosphor based LEDs generally rises with each new product announcement.

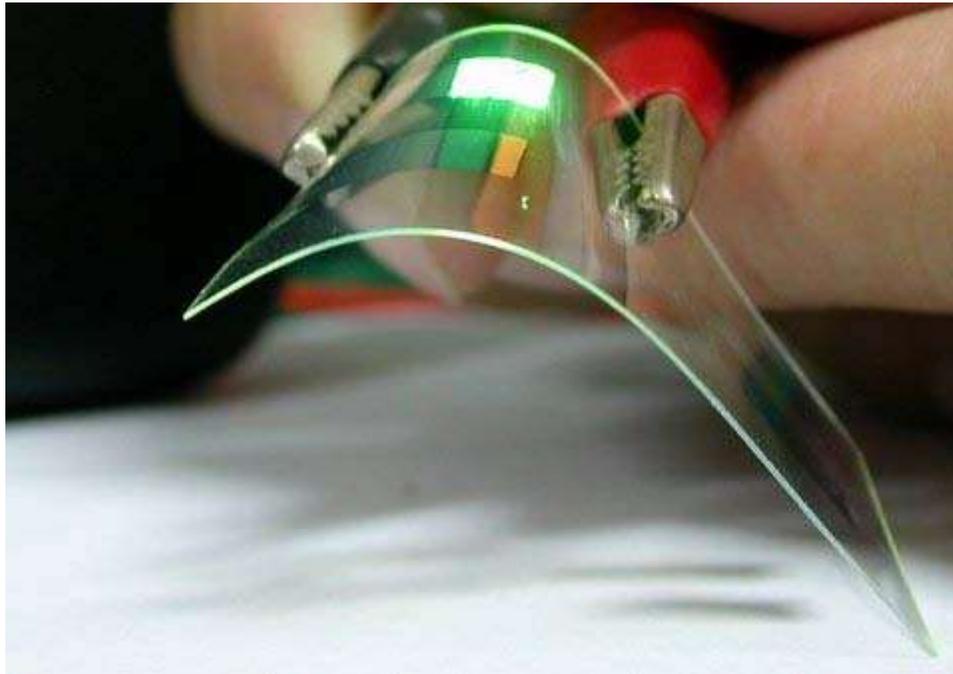
The phosphor based white LEDs encapsulate InGaN blue LEDs inside phosphor coated epoxy. A common yellow phosphor material is cerium-doped yttrium aluminium garnet ( $\text{Ce}^{3+}:\text{YAG}$ ).

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 ( $\text{ZnS}:\text{Cu, Al}$ ). 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, so more energy is 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 methods offer comparable brightness. A 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 ( $\text{ZnSe}$ ) on a  $\text{ZnSe}$  substrate which simultaneously emitted blue light from its active region and yellow light from the substrate.

## Organic light-emitting diodes (OLEDs)



Demonstration of a flexible OLED device

In an organic light emitting diode (OLED), the electroluminescent material comprising the emissive layer of the diode is an organic compound. The organic material is electrically conductive due to the delocalization of pi electrons caused by conjugation over all or part of the molecule, and the material therefore functions as an organic semiconductor. The organic materials can be small organic molecules in a crystalline phase, or polymers.

The potential advantages of OLEDs include thin, low cost displays with a low driving voltage, wide viewing angle and high contrast and colour gamut. Polymer LEDs have the added benefit of printable and flexible displays. OLEDs have been used to make visual displays for portable electronic devices such as cellphones, digital cameras, and MP3 players while possible future uses include lighting and televisions.

### Quantum dot LEDs (experimental)

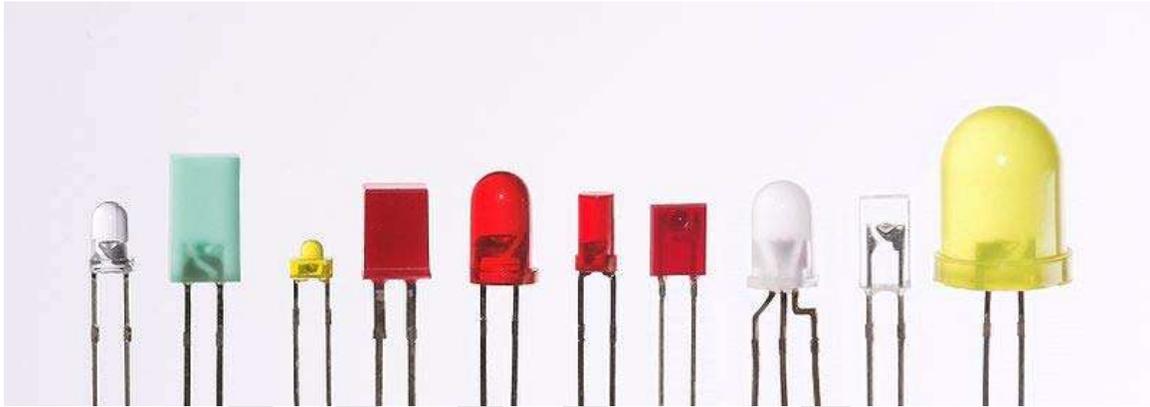
A new method developed by Michael Bowers, a graduate student at Vanderbilt University in Nashville, involves coating a blue LED with quantum dots that glow white in response to the blue light from the LED. This method emits a warm, yellowish-white light similar to that made by incandescent bulbs.

Quantum dots are semiconductor nanocrystals that possess unique optical properties. 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.

## 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. 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).

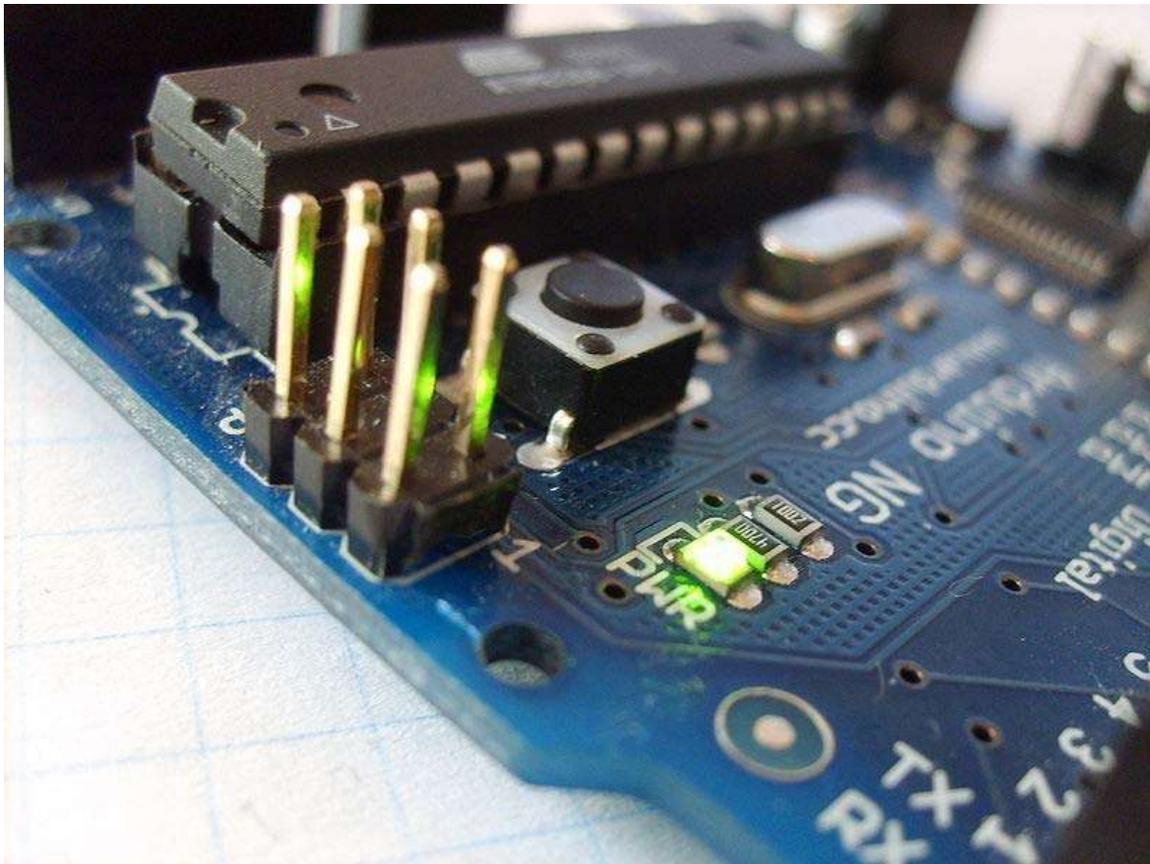
The main types of LEDs are miniature, high power devices and custom designs such as alphanumeric or multi-color.

## Miniature



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. 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.

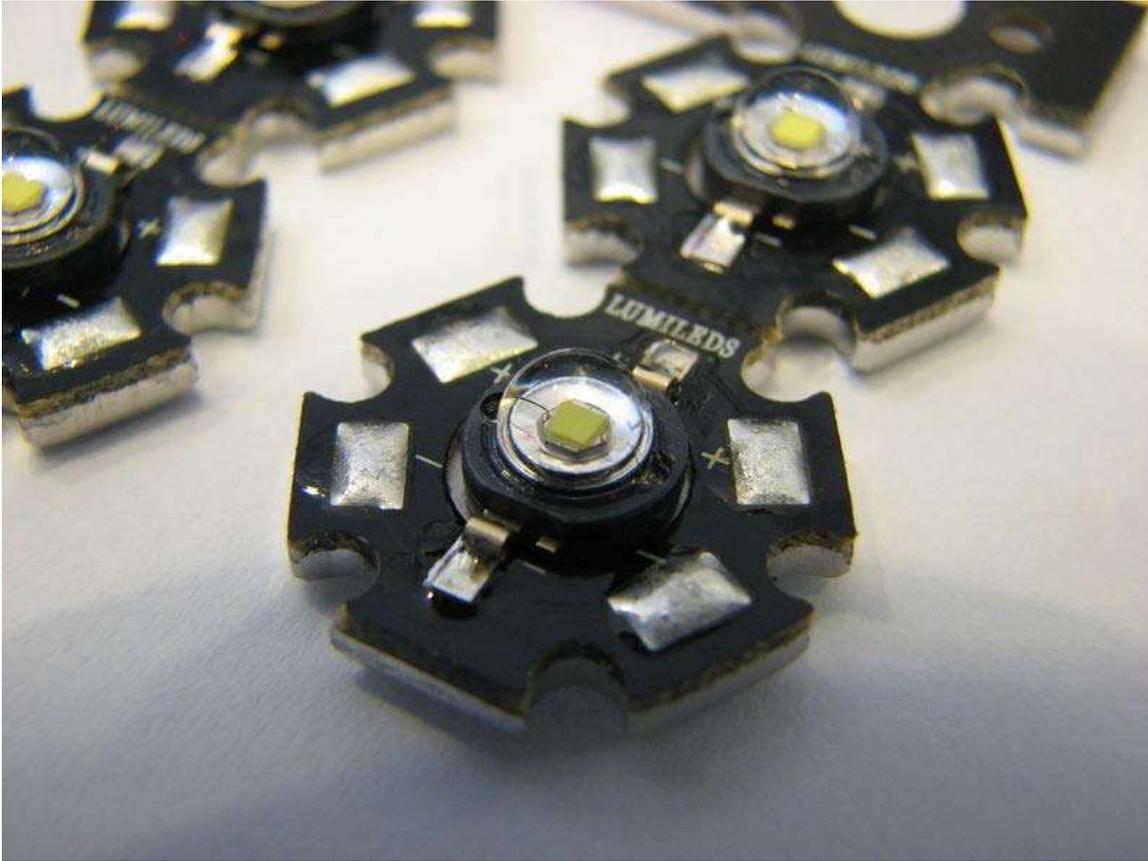


A green surface-mount LED mounted on a circuit board.

### **Mid-range**

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.

## High power



High-power light emitting 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 emit over a thousand 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 fail in seconds. One HPLED can often replace an incandescent bulb in a torch, or be set in an array to form a powerful LED lamp.

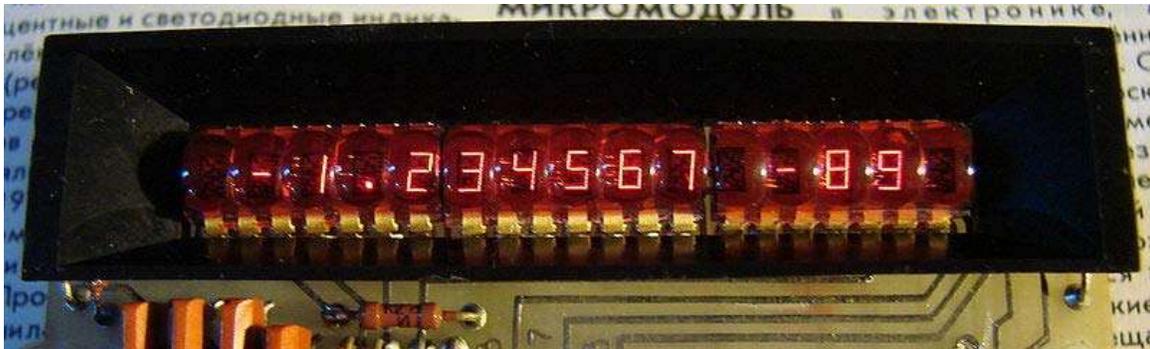
Some well-known HPLEDs in this category are the Lumileds Rebel Led, Osram Opto Semiconductors Golden Dragon and Cree X-lamp. As of September 2009 some HPLEDs manufactured by Cree Inc. now exceed 105 lm/W (e.g. the XLamp XP-G LED chip emitting Cool White light) and are being sold in lamps intended to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

### 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 one 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 emits one color, and current in the opposite direction emits 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 emit 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).
- *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 rising use of liquid crystal displays, with their lower power needs and greater display flexibility, has reduced the popularity of numeric and alphanumeric LED displays.

## Considerations for use

### Power sources

The current/voltage characteristic of an LED is similar to other diodes, in that the current is dependent exponentially on the voltage. This means that a small change in voltage can cause 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 to use constant current power supplies, or driving the LED at a voltage much below the maximum rating. Since most common 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

As with all diodes, current flows easily from p-type to n-type material. However, no current flows and no light is emitted if a small voltage is applied in the reverse direction. If the reverse voltage grows 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  $8^\circ$  or less—could, in theory, cause temporary blindness, and so are classified as "Class 2". In general, laser safety regulations—and the "Class 1", "Class 2", etc. system—also apply to LEDs.

### Advantages

- **Efficiency:** LEDs emit more light per watt than incandescent light bulbs. 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 using any color filters as traditional lighting methods need. This is more efficient and can lower initial costs.

- **Size:** LEDs can be very small (smaller than 2 mm<sup>2</sup>) 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. LEDs used in communications devices can have even faster response times.
- **Cycling:** LEDs are ideal for uses subject to frequent on-off cycling, unlike fluorescent lamps that fail faster when cycled often, 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 failure of incandescent bulbs.
- **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. 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

- **Fluorescent lamps** are typically more efficient than LEDs (for lamps with the same CRI).
- **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 an LED in high ambient temperatures may result in overheating the LED package, eventually leading to device failure. Adequate heat sinking is needed to maintain long life. This is especially important in automotive, medical, and military uses where devices must operate over a wide range of temperatures, and need low failure rates.
- **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.
- **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, 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 apply to uses needing a spherical light field. LEDs cannot provide divergence below a few degrees. In contrast, lasers can emit beams with divergences of 0.2 degrees or less.
- **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.
- **Electrical Polarity:** Unlike incandescent light bulbs, which illuminate regardless of the electrical polarity, LEDs will only light with correct electrical polarity.
- **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 vapor 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 using white light sources with correlated color temperature above 3,000 K.
- **Droop:** The efficiency of LEDs tends to decrease as one increases current.

## Chapter- 2

# Applications of Light Emitting Diodes

LED uses fall into four major categories:

- Visual signals where light goes more or less directly from the source to the human eye, to convey a message or meaning.
- Illumination where light is reflected from objects to give visual response of these objects.
- Measuring and interacting with processes involving no human vision.
- Narrow band light sensors where LEDs operate in a reverse-bias mode and respond to incident light, instead of emitting light.

### Indicators and signs

The low energy consumption, low maintenance and small size of modern LEDs has led to uses 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.

One-color light is well suited for traffic lights and signals, exit signs, emergency vehicle lighting, ships' navigation lights or lanterns (chromacity and luminance standards being set under the Convention on the International Regulations for Preventing Collisions at Sea 1972, Annex I and the CIE) and LED-based Christmas lights. In cold climates, LED traffic lights may remain snow covered. 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.



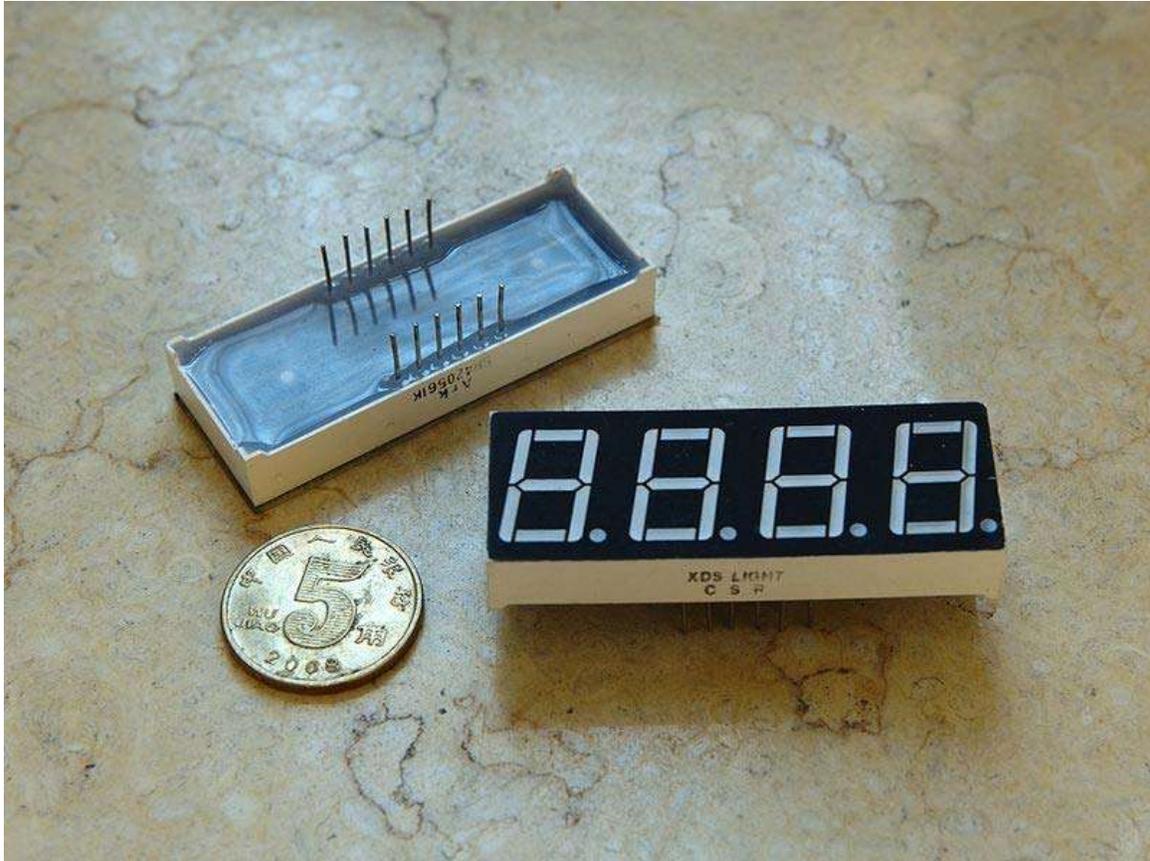
LED lighting in the aircraft cabin of an Airbus A320 Enhanced



A large LED display behind a disc jockey



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



LED digital display that can display 4 digits along with points



Traffic light using LED



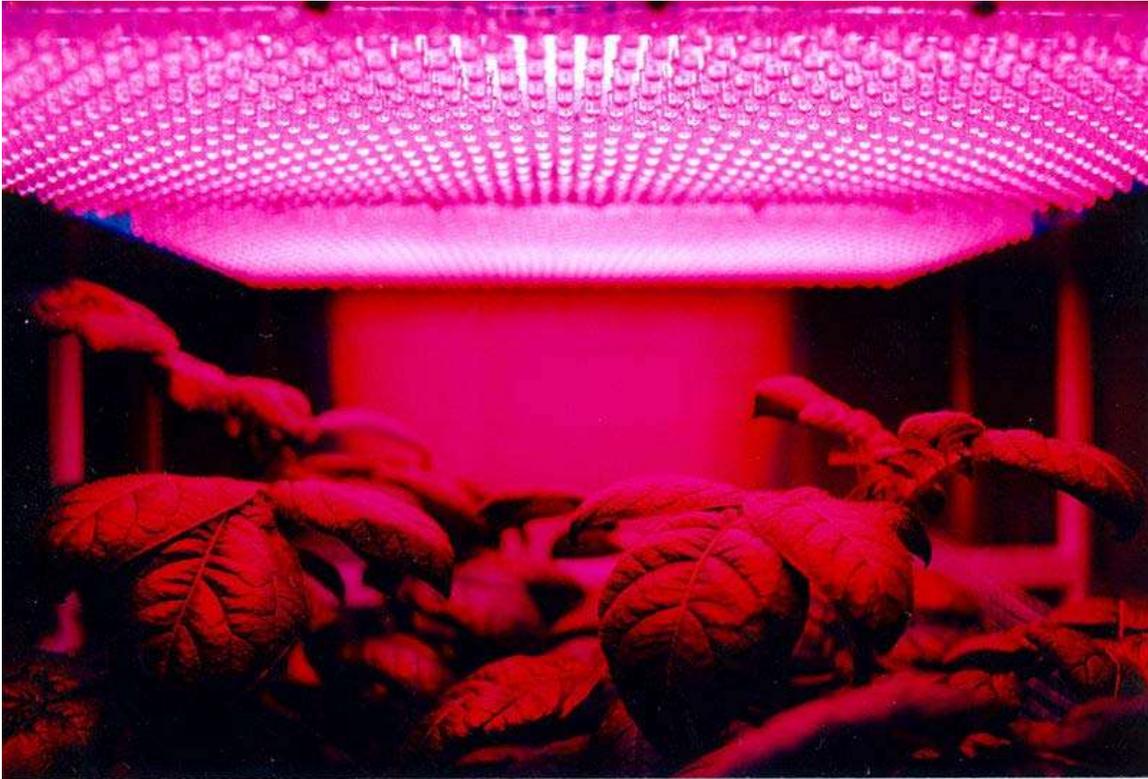
Western Australia Police car using LED



Printhead of an Oki LED printer



LED daytime running lights of Audi A4



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.

Because of their long life and fast switching times, LEDs have been used in brake lights for cars high-mounted brake lights, trucks, and buses, and in turn signals for some time, but many vehicles now use LEDs for their rear light clusters. The use in brakes improves safety, due to a great reduction in the time needed to light fully, or faster rise time, up to 0.5 second faster than an incandescent bulb. This gives drivers behind more time to react. It is reported that at normal highway speeds, this equals one car length equivalent in increased time to react. 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. White LED headlamps are starting to be used. Using LEDs has styling advantages because LEDs can form much thinner lights than incandescent lamps with parabolic reflectors.

Due to the relative cheapness of low output LEDs, they are also used in many temporary uses 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

With the development of high efficiency and high power LEDs it has grown possible to use 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.

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, taxiway centerline & edge lights, guidance signs and obstruction lighting.

LEDs are also suitable for backlighting for LCD televisions and lightweight laptop displays and light source for DLP projectors. RGB LEDs raise the color gamut by as much as 45%. Screens for TV and computer displays can be made thinner using LEDs for backlighting.

LED's can now be used interactively to produce an immersive experience for end users in entertainment mediums such as PC gaming and audio visual platforms via amBX technology

LEDs are used increasingly commonly in aquarium lights. Particularly 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 emit a specific color-spectrum for ideal coloration of corals, fish, and invertebrates while optimizing photosynthetically active radiation (PAR) which raises growth and sustainability of photosynthetic life such as corals, anemones, clams, and macroalgae. These fixtures can be electronically programmed 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.

LEDs are small, durable and need little power, so they are used in hand held devices such as flashlights. LED strobe lights or camera flashes operate at a safe, low voltage, instead of the 250+ volts commonly found in xenon flashlamp-based lighting. This is especially useful in cameras on mobile phones, where space is at a premium and bulky voltage-

raising circuitry is undesirable. LEDs are used for infrared illumination in night vision uses 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 be wireless transmitters and access points for data transport. Lasers can also be modulated in this manner.

### **Sustainable lighting**

Efficient lighting is needed for sustainable architecture. A 13 watt LED lamp emits 450 to 650 lumens, which is equivalent to a standard 40 watt incandescent bulb. 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**

One kilowatt-hour of electricity will cause 1.34 pounds (610 g) of CO<sub>2</sub> emission. Assuming the average light bulb is on for 10 hours a day, one 40-watt incandescent bulb will cause 196 pounds (89 kg) of CO<sub>2</sub> emission per year. The 13-watt LED equivalent will only cause 63 pounds (29 kg) of CO<sub>2</sub> 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 is 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. 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.

## **Non-visual applications**

Light has many other uses besides for seeing. LEDs are used for some of these. 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. Further, its sensors only need be monochromatic, since at any one time the page being scanned is only lit by one 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.

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

Plant growers are interested in LEDs because they are more energy efficient, emit less heat (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. However, LEDs have not replaced these grow lights due to higher price. As mass production and LED kits develop, the LED products 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 useless for this purpose. Although LED forward voltage is far 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 for this purpose, and this is likely to remain one of their major uses until price drops low enough to make signaling and illumination uses more widespread. Barcode scanners are the most common example of machine vision, and many low cost ones use red LEDs instead of lasers. Optical computer mice are also another example of LEDs in machine vision, as it is used to provide an even light source on the surface for the miniature camera within the mouse. 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.

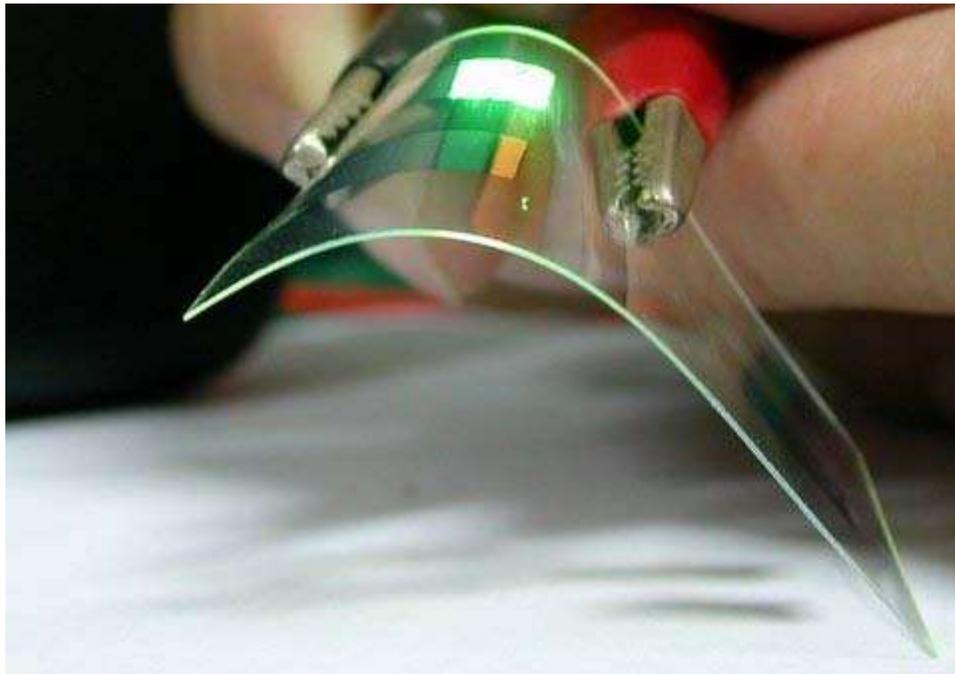
LED elements tend to be small and can be placed with high density over flat or even shaped substrates (PCBs etc.) so that bright and homogeneous sources can be designed which direct light from tightly controlled directions on inspected parts. This can often be obtained with small, low cost lenses and 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 to obtain crisp and sharp “still” images of quickly moving parts.

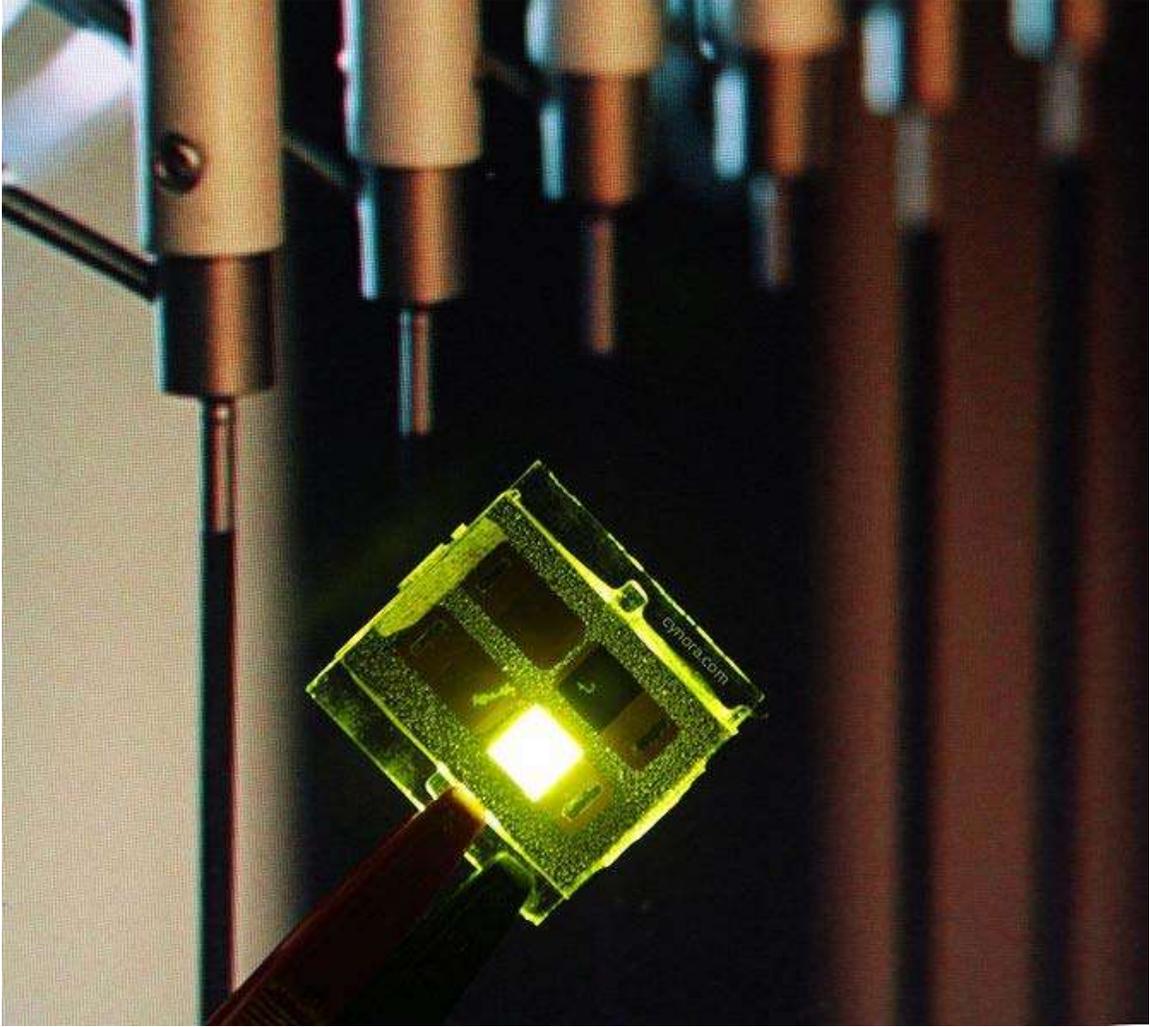
LEDs come in several different colors and wavelengths, allowing easy use of the best color for each need, where different color may provide better visibility of features of interest. Having a precisely known spectrum allows tightly matched filters to be used to separate informative bandwidth or to reduce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

## Chapter- 3

# Organic Light-Emitting Diode



Demonstration of a flexible OLED device



A green emitting OLED device



Sony XEL-1, the world's first OLED TV

An **organic light emitting diode (OLED)** is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compounds which emit light in response to an electric current. This layer of organic semiconductor material is situated between two electrodes. Generally, at least one of these electrodes is transparent.

OLEDs are used in television screens, computer monitors, small, portable system screens such as mobile phones and PDAs, watches, advertising, information and indication. OLEDs are also used in light sources for general space illumination and in large-area light-emitting elements. Due to their comparatively early stage of development, they typically emit less light per unit area than inorganic solid-state based LED point-light sources.

An OLED display functions without a backlight. Thus, it can display deep black levels and can also be thinner and lighter than established liquid crystal displays. Similarly, in low ambient light conditions such as dark rooms, an OLED screen can achieve a higher contrast ratio than an LCD using either cold cathode fluorescent lamps or the more recently developed LED backlight.

There are two main families of OLEDs: those based upon small molecules and those employing polymers. Adding mobile ions to an OLED creates a Light-emitting Electrochemical Cell or LEC, which has a slightly different mode of operation.

OLED displays can use either passive-matrix (PMOLED) or active-matrix addressing schemes. Active-matrix OLEDs (AMOLED) require a thin-film transistor backplane to switch each individual pixel on or off, and can make higher resolution and larger size displays possible.

## History

The first observations of electroluminescence in organic materials were in the early 1950s by A. Bernanose and co-workers at the Nancy-Université, France. They applied high-voltage alternating current (AC) fields in air to materials such as acridine orange, either deposited on or dissolved in cellulose or cellophane thin films. The proposed mechanism was either direct excitation of the dye molecules or excitation of electrons.

In 1960, Martin Pope and co-workers at New York University developed ohmic dark-injecting electrode contacts to organic crystals. They further described the necessary energetic requirements (work functions) for hole and electron injecting electrode contacts. These contacts are the basis of charge injection in all modern OLED devices. Pope's group also first observed direct current (DC) electroluminescence under vacuum on a pure single crystal of anthracene and on anthracene crystals doped with tetracene in 1963 using a small area silver electrode at 400V. The proposed mechanism was field-accelerated electron excitation of molecular fluorescence.

Pope's group reported in 1965 that in the absence of an external electric field, the electroluminescence in anthracene crystals is caused by the recombination of a thermalized electron and hole, and that the conducting level of anthracene is higher in energy than the exciton energy level. Also in 1965, W. Helfrich and W. G. Schneider of the National Research Council in Canada produced double injection recombination electroluminescence for the first time in an anthracene single crystal using hole and electron injecting electrodes, the forerunner of modern double injection devices. In the same year, Dow Chemical researchers patented a method of preparing electroluminescent cells using high voltage (500–1500 V) AC-driven (100–3000 Hz) electrically-insulated one millimetre thin layers of a melted phosphor consisting of ground anthracene powder, tetracene, and graphite powder. Their proposed mechanism involved electronic excitation at the contacts between the graphite particles and the anthracene molecules.

Device performance was limited by the poor electrical conductivity of contemporary organic materials. However this was overcome by the discovery and development of highly conductive polymers.

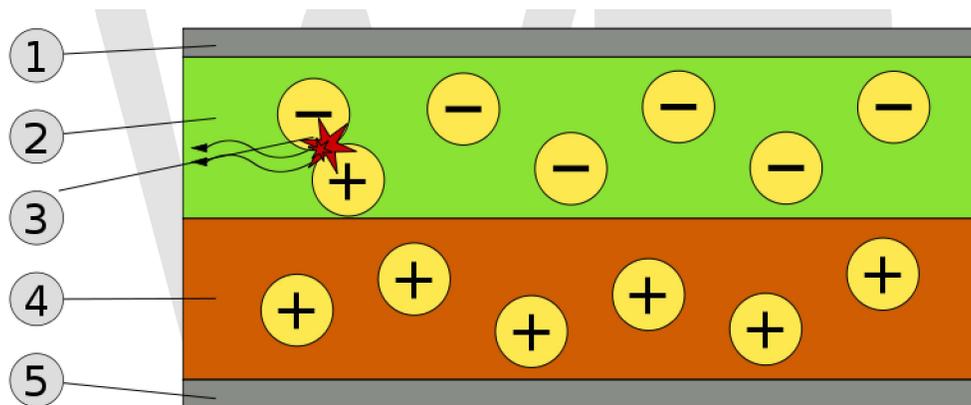
Electroluminescence from polymer films was first observed by Roger Partridge at the National Physical Laboratory in the United Kingdom. The device consisted of a film of

poly(n-vinylcarbazole) up to 2.2 micrometres thick located between two charge injecting electrodes. The results of the project were patented in 1975 and published in 1983.

The first diode device was reported at Eastman Kodak by Ching W. Tang and Steven Van Slyke in 1987. This device used a novel two-layer structure with separate hole transporting and electron transporting layers such that recombination and light emission occurred in the middle of the organic layer. This resulted in a reduction in operating voltage and improvements in efficiency and led to the current era of OLED research and device production.

Research into polymer electroluminescence culminated in 1990 with J. H. Burroughes *et al.* at the Cavendish Laboratory in Cambridge reporting a high efficiency green light-emitting polymer based device using 100 nm thick films of poly(p-phenylene vinylene).

## Working principle



Schematic of a bilayer OLED: 1. Cathode (-), 2. Emissive Layer, 3. Emission of radiation, 4. Conductive Layer, 5. Anode (+)

A typical OLED is composed of a layer of organic materials situated between two electrodes, the anode and cathode, all deposited on a substrate. The organic molecules are electrically conductive as a result of delocalization of pi electrons caused by conjugation over all or part of the molecule. These materials have conductivity levels ranging from insulators to conductors, and therefore are considered organic semiconductors. The highest occupied and lowest unoccupied molecular orbitals (HOMO and LUMO) of organic semiconductors are analogous to the valence and conduction bands of inorganic semiconductors.

Originally, the most basic polymer OLEDs consisted of a single organic layer. One example was the first light-emitting device synthesised by J. H. Burroughes *et al.*, which involved a single layer of poly(p-phenylene vinylene). However multilayer OLEDs can be fabricated with two or more layers in order to improve device efficiency. As well as conductive properties, different materials may be chosen to aid charge injection at

electrodes by providing a more gradual electronic profile, or block a charge from reaching the opposite electrode and being wasted. Many modern OLEDs incorporate a simple bilayer structure, consisting of a conductive layer and an emissive layer.

During operation, a voltage is applied across the OLED such that the anode is positive with respect to the cathode. A current of electrons flows through the device from cathode to anode, as electrons are injected into the LUMO of the organic layer at the cathode and withdrawn from the HOMO at the anode. This latter process may also be described as the injection of electron holes into the HOMO. Electrostatic forces bring the electrons and the holes towards each other and they recombine forming an exciton, a bound state of the electron and hole. This happens closer to the emissive layer, because in organic semiconductors holes are generally more mobile than electrons. The decay of this excited state results in a relaxation of the energy levels of the electron, accompanied by emission of radiation whose frequency is in the visible region. The frequency of this radiation depends on the band gap of the material, in this case the difference in energy between the HOMO and LUMO.

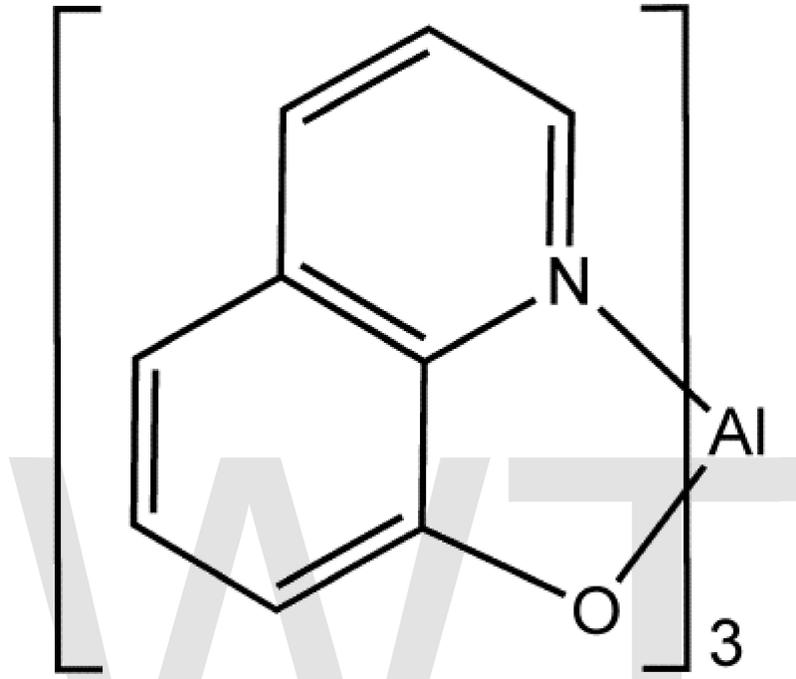
As electrons and holes are fermions with half integer spin, an exciton may either be in a singlet state or a triplet state depending on how the spins of the electron and hole have been combined. Statistically three triplet excitons will be formed for each singlet exciton. Decay from triplet states (phosphorescence) is spin forbidden, increasing the timescale of the transition and limiting the internal efficiency of fluorescent devices. Phosphorescent organic light-emitting diodes make use of spin-orbit interactions to facilitate intersystem crossing between singlet and triplet states, thus obtaining emission from both singlet and triplet states and improving the internal efficiency.

Indium tin oxide (ITO) is commonly used as the anode material. It is transparent to visible light and has a high work function which promotes injection of holes into the HOMO level of the organic layer. A typical conductive layer may consist of PEDOT:PSS as the HOMO level of this material generally lies between the workfunction of ITO and the HOMO of other commonly used polymers, reducing the energy barriers for hole injection. Metals such as barium and calcium are often used for the cathode as they have low work functions which promote injection of electrons into the LUMO of the organic layer. Such metals are reactive, so require a capping layer of aluminium to avoid degradation.

Single carrier devices are typically used to study the kinetics and charge transport mechanisms of an organic material and can be useful when trying to study energy transfer processes. As current through the device is composed of only one type of charge carrier, either electrons or holes, recombination does not occur and no light is emitted. For example, electron only devices can be obtained by replacing ITO with a lower work function metal which increases the energy barrier of hole injection. Similarly, hole only devices can be made by using a cathode comprised solely of aluminium, resulting in an energy barrier too large for efficient electron injection.

# Material technologies

## Small molecules



Alq<sub>3</sub>, commonly used in small molecule OLEDs.

Efficient OLEDs using small molecules were first developed by Dr. Ching W. Tang *et al.* at Eastman Kodak. The term OLED traditionally refers specifically to this type of device, though the term SM-OLED is also in use.

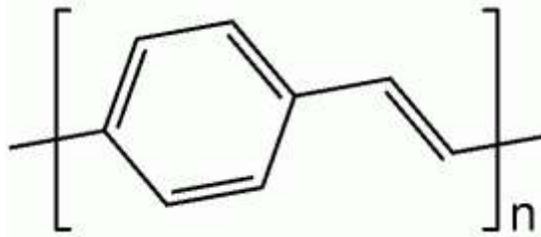
Molecules commonly used in OLEDs include organometallic chelates (for example Alq<sub>3</sub>, used in the organic light-emitting device reported by Tang *et al.*), fluorescent and phosphorescent dyes and conjugated dendrimers. A number of materials are used for their charge transport properties, for example triphenylamine and derivatives are commonly used as materials for hole transport layers. Fluorescent dyes can be chosen to obtain light emission at different wavelengths, and compounds such as perylene, rubrene and quinacridone derivatives are often used. Alq<sub>3</sub> has been used as a green emitter, electron transport material and as a host for yellow and red emitting dyes.

The production of small molecule devices and displays usually involves thermal evaporation in a vacuum. This makes the production process more expensive and of limited use for large-area devices than other processing techniques. However, contrary to polymer-based devices, the vacuum deposition process enables the formation of well controlled, homogeneous films, and the construction of very complex multi-layer structures. This high flexibility in layer design, enabling distinct charge transport and

charge blocking layers to be formed, is the main reason for the high efficiencies of the small molecule OLEDs.

Coherent emission from a laser dye-doped tandem SM-OLED device, excited in the pulsed regime, has been demonstrated. The emission is nearly diffraction limited with a spectral width similar to that of broadband dye lasers.

### **Polymer light-emitting diodes**



poly(*p*-phenylene vinylene), used in the first PLED.

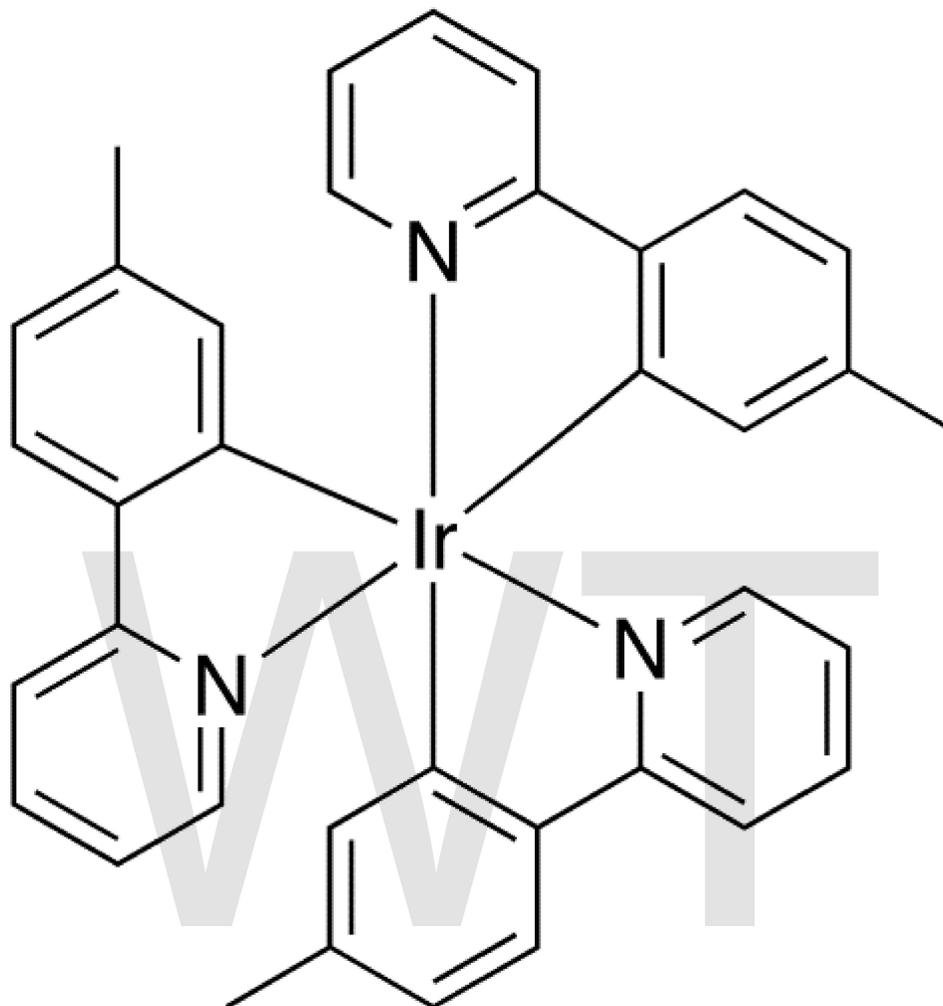
Polymer light-emitting diodes (PLED), also light-emitting polymers (LEP), involve an electroluminescent conductive polymer that emits light when connected to an external voltage. They are used as a thin film for full-spectrum colour displays. Polymer OLEDs are quite efficient and require a relatively small amount of power for the amount of light produced.

Vacuum deposition is not a suitable method for forming thin films of polymers. However, polymers can be processed in solution, and spin coating is a common method of depositing thin polymer films. This method is more suited to forming large-area films than thermal evaporation. No vacuum is required, and the emissive materials can also be applied on the substrate by a technique derived from commercial inkjet printing. However, as the application of subsequent layers tends to dissolve those already present, formation of multilayer structures is difficult with these methods. The metal cathode may still need to be deposited by thermal evaporation in vacuum.

Typical polymers used in PLED displays include derivatives of poly(*p*-phenylene vinylene) and polyfluorene. Substitution of side chains onto the polymer backbone may determine the colour of emitted light or the stability and solubility of the polymer for performance and ease of processing.

While unsubstituted poly(*p*-phenylene vinylene) (PPV) is typically insoluble, a number of PPVs and related poly(naphthalene vinylene)s (PNVs) that are soluble in organic solvents or water have been prepared via ring opening metathesis polymerization.

## Phosphorescent materials



$\text{Ir}(\text{mppy})_3$ , a phosphorescent dopant which emits green light.

Phosphorescent organic light emitting diodes use the principle of electrophosphorescence to convert electrical energy in an OLED into light in a highly efficient manner, with the internal quantum efficiencies of such devices approaching 100%.

Typically, a polymer such as poly(n-vinylcarbazole) is used as a host material to which an organometallic complex is added as a dopant. Iridium complexes such as  $\text{Ir}(\text{mppy})_3$  are currently the focus of research, although complexes based on other heavy metals such as platinum have also been used.

The heavy metal atom at the centre of these complexes exhibits strong spin-orbit coupling, facilitating intersystem crossing between singlet and triplet states. By using these phosphorescent materials, both singlet and triplet excitons will be able to decay

radiatively, hence improving the internal quantum efficiency of the device compared to a standard PLED where only the singlet states will contribute to emission of light.

Applications of OLEDs in solid state lighting require the achievement of high brightness with good CIE coordinates (for white emission). The use of macromolecular species like polyhedral oligomeric silsesquioxanes (POSS) in conjunction with the use of phosphorescent species such as Ir for printed OLEDs have exhibited brightnesses as high as 10,000 cd/m<sup>2</sup>.

## Device Architectures

### Structure

- **Bottom or top emission:** Bottom emission devices use a transparent or semi-transparent bottom electrode to get the light through a transparent substrate. Top emission devices use a transparent or semi-transparent top electrode emitting light directly. Top-emitting OLEDs are better suited for active-matrix applications as they can be more easily integrated with a non-transparent transistor backplane.
- **Transparent OLEDs** use transparent or semi-transparent contacts on both sides of the device to create displays that can be made to be both top and bottom emitting (transparent). TOLEDs can greatly improve contrast, making it much easier to view displays in bright sunlight. This technology can be used in Head-up displays, smart windows or augmented reality applications. Novaled's OLED panel presented in Finetech Japan 2010, boasts a transparency of 60–70%.
- **Stacked OLEDs** use a pixel architecture that stacks the red, green, and blue subpixels on top of one another instead of next to one another, leading to substantial increase in gamut and color depth, and greatly reducing pixel gap. Currently, other display technologies have the RGB (and RGBW) pixels mapped next to each other decreasing potential resolution.
- **Inverted OLED:** In contrast to a conventional OLED, in which the anode is placed on the substrate, an Inverted OLED uses a bottom cathode that can be connected to the drain end of an n-channel TFT especially for the low cost amorphous silicon TFT backplane useful in the manufacturing of AMOLED displays.

### Patterning technologies

Patternable organic light-emitting devices use a light or heat activated electroactive layer. A latent material (PEDOT-TMA) is included in this layer that, upon activation, becomes highly efficient as a hole injection layer. Using this process, light-emitting devices with arbitrary patterns can be prepared.

Colour patterning can be accomplished by means of laser, such as radiation-induced sublimation transfer (RIST).

Organic vapour jet printing (OVJP) uses an inert carrier gas, such as argon or nitrogen, to transport evaporated organic molecules (as in Organic Vapor Phase Deposition). The gas is expelled through a micron sized nozzle or nozzle array close to the substrate as it is being translated. This allows printing arbitrary multilayer patterns without the use of solvents.

Conventional OLED displays are formed by vapor thermal evaporation (VTE) and are patterned by shadow-mask. A mechanical mask has openings allowing the vapor to pass only on the desired location.

### **Backplane technologies**

For a high resolution display like a TV, a TFT backplane is necessary to drive the pixels correctly. Currently, Low Temperature Polycrystalline silicon LTPS-TFT is used for commercial AMOLED displays. LTPS-TFT has variation of the performance in a display, so various compensation circuits have been reported. Due to the size limitation of the excimer laser used for LTPS, the AMOLED size was limited. To cope with the hurdle related to the panel size, amorphous-silicon/microcrystalline-silicon backplanes have been reported with large display prototype demonstrations.

### **Advantages**

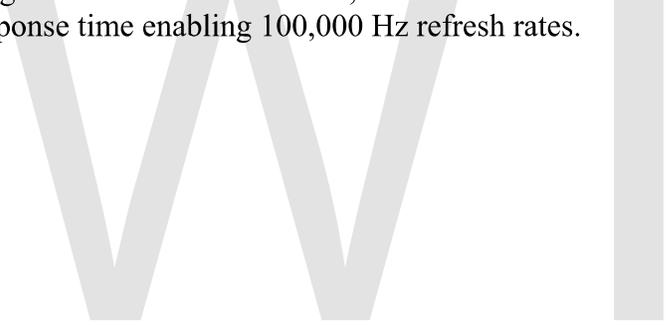


Demonstration of a 4.1" prototype flexible display from Sony

The different manufacturing process of OLEDs lends itself to several advantages over flat-panel displays made with LCD technology.

- **Lower cost in the future:** OLEDs can be printed onto any suitable substrate by an inkjet printer or even by screen printing, theoretically making them cheaper to produce than LCD or plasma displays. However, fabrication of the OLED substrate is more costly than that of a TFT LCD, until mass production methods lower cost through scalability.

- **Light weight & flexible plastic substrates:** OLED displays can be fabricated on flexible plastic substrates leading to the possibility of Organic light-emitting diode roll-up display being fabricated or other new applications such as roll-up displays embedded in fabrics or clothing. As the substrate used can be flexible such as PET., the displays may be produced inexpensively.
- **Wider viewing angles & improved brightness:** OLEDs can enable a greater artificial contrast ratio (both dynamic range and static, measured in purely dark conditions) and viewing angle compared to LCDs because OLED pixels directly emit light. OLED pixel colours appear correct and unshifted, even as the viewing angle approaches 90° from normal.
- **Better power efficiency:** LCDs filter the light emitted from a backlight, allowing a small fraction of light through so they cannot show true black, while an inactive OLED element does not produce light or consume power.
- **Response time:** OLEDs can also have a faster response time than standard LCD screens. Whereas LCD displays are capable of between 2 and 8 ms response time offering a frame rate of +/-200 Hz, an OLED can theoretically have less than 0.01 ms response time enabling 100,000 Hz refresh rates.



## Disadvantages



LEP display showing partial failure



An old OLED display showing wear

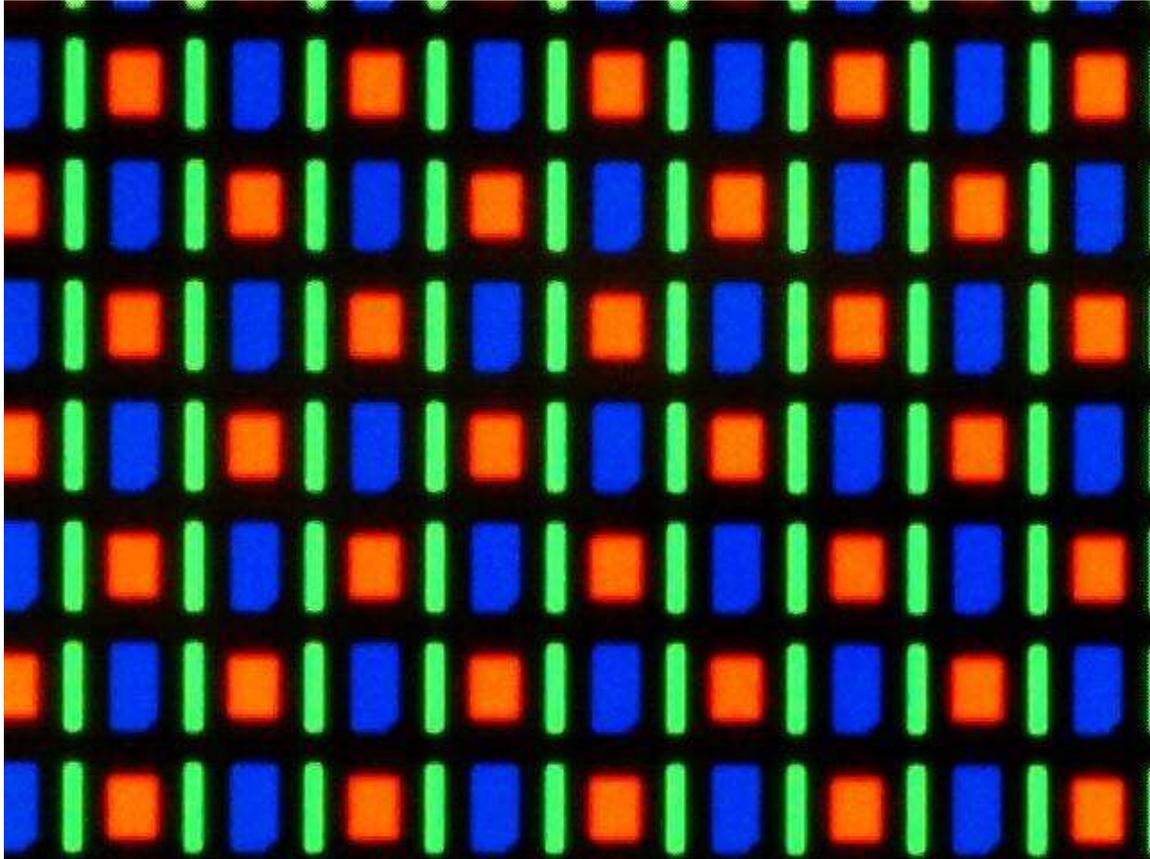
- **Lifespan:** The biggest technical problem for OLEDs was the limited lifetime of the organic materials. In particular, blue OLEDs historically have had a lifetime of around 14,000 hours to half original brightness (five years at 8 hours a day) when used for flat-panel displays. This is lower than the typical lifetime of LCD, LED or PDP technology—each currently rated for about 25,000 – 40,000 hours to half brightness, depending on manufacturer and model. However, some manufacturers' displays aim to increase the lifespan of OLED displays, pushing their expected life past that of LCD displays by improving light outcoupling, thus achieving the same brightness at a lower drive current. In 2007, experimental OLEDs were created which can sustain  $400 \text{ cd/m}^2$  of luminance for over 198,000 hours for green OLEDs and 62,000 hours for blue OLEDs.
- **Color balance issues:** Additionally, as the OLED material used to produce blue light degrades significantly more rapidly than the materials that produce other colors, blue light output will decrease relative to the other colors of light. This differential color output change will change the color balance of the display and is much more noticeable than a decrease in overall luminance. This can be partially avoided by adjusting colour balance but this may require advanced control circuits and interaction with the user, which is unacceptable for some users. In order to delay the problem, manufacturers bias the colour balance towards blue so that the display initially has an artificially blue tint, leading to complaints of artificial-looking, over-saturated colors. More commonly, though, manufacturers optimize the size of the R, G and B subpixels to reduce the current density

through the subpixel in order to equalize lifetime at full luminance. For example, a blue subpixel may be 100% larger than the green subpixel. The red subpixel may be 10% smaller than the green.

- **Efficiency of blue OLEDs:** Improvements to the efficiency and lifetime of blue OLEDs is vital to the success of OLEDs as replacements for LCD technology. Considerable research has been invested in developing blue OLEDs with high external quantum efficiency as well as a deeper blue color. External quantum efficiency values of 20% and 19% have been reported for red (625 nm) and green (530 nm) diodes, respectively. However, blue diodes (430 nm) have only been able to achieve maximum external quantum efficiencies in the range between 4% to 6%.
- **Water damage:** Water can damage the organic materials of the displays. Therefore, improved sealing processes are important for practical manufacturing. Water damage may especially limit the longevity of more flexible displays.
- **Outdoor performance:** As an emissive display technology, OLEDs rely completely upon converting electricity to light, unlike most LCDs which are to some extent reflective; e-ink leads the way in efficiency with ~ 33% ambient light reflectivity, enabling the display to be used without any internal light source. The metallic cathode in an OLED acts as a mirror, with reflectance approaching 80%, leading to poor readability in bright ambient light such as outdoors. However, with the proper application of a circular polarizer and anti-reflective coatings, the diffuse reflectance can be reduced to less than 0.1%. With 10,000 fc incident illumination (typical test condition for simulating outdoor illumination), that yields an approximate photopic contrast of 5:1.
- **Power consumption:** While an OLED will consume around 40% of the power of an LCD displaying an image which is primarily black, for the majority of images it will consume 60–80% of the power of an LCD – however it can use over three times as much power to display an image with a white background such as a document or website. This can lead to disappointing real-world battery life in mobile devices. You may balance this however, by setting your background to black, and your characters to any actual color.
- **Screen burn-in:** Unlike displays with a common light source, the brightness of each OLED pixel fades depending on the content displayed. The varied lifespan of the organic dyes can cause a discrepancy between red, green, and blue intensity. This leads to image persistence, also known as burn-in.
- **UV sensitivity:** OLED displays can be damaged by prolonged exposure to UV light. The most pronounced example of this can be seen with a near UV laser (such as a Blu-ray pointer) and can damage the display almost instantly with more than 20mW leading to dim or dead spots where the beam is focused. This is usually avoided by installing a UV blocking filter over the panel and this can

easily be seen as a clear plastic layer on the glass. Removal of this filter can lead to severe damage and an unusable display after only a few months of room light exposure.

## **Manufacturers and Commercial Uses**



Magnified image of the AMOLED screen on the Google Nexus One smartphone using the RGBG system of the PenTile Matrix Family.



A 3.8 cm (1.5 in) OLED display from a Creative ZEN V media player

OLED technology is used in commercial applications such as displays for mobile phones and portable digital media players, car radios and digital cameras among others. Such portable applications favor the high light output of OLEDs for readability in sunlight and their low power drain. Portable displays are also used intermittently, so the lower lifespan of organic displays is less of an issue. Prototypes have been made of flexible and rollable displays which use OLEDs' unique characteristics. Applications in flexible signs and lighting are also being developed. Philips Lighting have made OLED lighting samples under the brand name 'Lumiblade' available online.

OLEDs have been used in most Motorola and Samsung colour cell phones, as well as some HTC, LG and Sony Ericsson models. Nokia has also recently introduced some OLED products including the N85 and the N86 8MP, both of which feature an AMOLED display. OLED technology can also be found in digital media players such as the Creative ZEN V, the iriver clix, the Zune HD and the Sony Walkman X Series.

The Google and HTC Nexus One smartphone includes an AMOLED screen, as does HTC's own Desire and Legend phones. However due to supply shortages of the Samsung-produced displays, certain HTC models will use Sony's SLCD displays in the future, while the Google and Samsung Nexus S smartphone will use "Super Clear LCD" instead in some countries.

Other manufacturers of OLED panels include Anwell Technologies Limited, Chi Mei Corporation, LG, and others.

DuPont stated in a press release in May 2010 that they can produce a 50-inch OLED TV in two minutes with a new printing technology. If this can be scaled up in terms of manufacturing, then the total cost of OLED TVs would be greatly reduced. Dupont also states that OLED TVs made with this less expensive technology can last up to 15 years if left on for a normal eight hour day.

Handheld computer manufacturer OQO introduced the smallest Windows netbook computer, including an OLED display, in 2009.

The use of OLEDs may be subject to patents held by Eastman Kodak, DuPont, General Electric, Royal Philips Electronics, numerous universities and others. There are by now literally thousands of patents associated with OLEDs, both from larger corporations and smaller technology companies .

### **Samsung applications**

By 2004 Samsung, South Korea's largest conglomerate, was the world's largest OLED manufacturer, producing 40% of the OLED displays made in the world, and as of 2010 has a 98% share of the global AMOLED market. The company is leading the world OLED industry, generating \$100.2 million out of the total \$475 million revenues in the global OLED market in 2006. As of 2006, it held more than 600 American patents and more than 2800 international patents, making it the largest owner of AMOLED technology patents.

Samsung SDI announced in 2005 the world's largest OLED TV at the time, at 21 inches (53 cm). This OLED featured the highest resolution at the time, of 6.22 million pixels. In addition, the company adopted active matrix based technology for its low power consumption and high-resolution qualities. This was exceeded in January 2008, when Samsung showcased the world's largest and thinnest OLED TV at the time, at 31 inches and 4.3 mm.

In May 2008, Samsung unveiled an ultra-thin 12.1 inch laptop OLED display concept, with a 1,280×768 resolution with infinite contrast ratio. According to Woo Jong Lee, Vice President of the Mobile Display Marketing Team at Samsung SDI, the company expected OLED displays to be used in notebook PCs as soon as 2010.

In October 2008, Samsung showcased the world's thinnest OLED display, also the first to be 'flappable' and bendable. It measures just 0.05 mm (thinner than paper), yet a Samsung staff member said that it is "technically possible to make the panel thinner". To achieve this thickness, Samsung etched an OLED panel that uses a normal glass substrate. The drive circuit was formed by low-temperature polysilicon TFTs. Also, low-molecular organic EL materials were employed. The pixel count of the display is 480 × 272. The

contrast ratio is 100,000:1, and the luminance is 200 cd/m<sup>2</sup>. The colour reproduction range is 100% of the NTSC standard.

In the same month, Samsung unveiled what was then the world's largest OLED Television at 40-inch with a Full HD resolution of 1920×1080 pixel. In the FPD International, Samsung stated that its 40-inch OLED Panel is the largest size currently possible. The panel has a contrast ratio of 1,000,000:1, a colour gamut of 107% NTSC, and a luminance of 200 cd/m<sup>2</sup> (peak luminance of 600 cd/m<sup>2</sup>).

At the Consumer Electronics Show (CES) in January 2010, Samsung demonstrated a laptop computer with a large, transparent OLED display featuring up to 40% transparency and an animated OLED display in a photo ID card.

Samsung's latest AMOLED smartphones use their Super AMOLED trademark, with the Samsung Wave S8500 and Samsung i9000 Galaxy S being launched in June 2010.

### **Sony applications**



Sony XEL-1, the world's first OLED TV. (front)



Sony XEL-1 (side)

The Sony CLIÉ PEG-VZ90 was released in 2004, being the first PDA to feature an OLED screen. Other Sony products to feature OLED screens include the MZ-RH1 portable minidisc recorder, released in 2006 and the Walkman X Series.

At the Las Vegas CES 2007, Sony showcased 11-inch (28 cm, resolution 960×540) and 27-inch (68.5 cm, full HD resolution at 1920×1080) OLED TV models. Both claimed 1,000,000:1 contrast ratios and total thicknesses (including bezels) of 5 mm. In April 2007, Sony announced it would manufacture 1000 11-inch OLED TVs per month for market testing purposes. On October 1, 2007, Sony announced that the 11-inch model, now called the XEL-1, would be released commercially; the XEL-1 was first released in Japan in December 2007.

In May 2007, Sony publicly unveiled a video of a 2.5-inch flexible OLED screen which is only 0.3 millimeters thick. At the Display 2008 exhibition, Sony demonstrated a 0.2 mm thick 3.5 inch display with a resolution of 320×200 pixels and a 0.3 mm thick 11 inch display with 960×540 pixels resolution, one-tenth the thickness of the XEL-1.

In July 2008, a Japanese government body said it would fund a joint project of leading firms, which is to develop a key technology to produce large, energy-saving organic displays. The project involves one laboratory and 10 companies including Sony Corp.

NEDO said the project was aimed at developing a core technology to mass-produce 40 inch or larger OLED displays in the late 2010s.

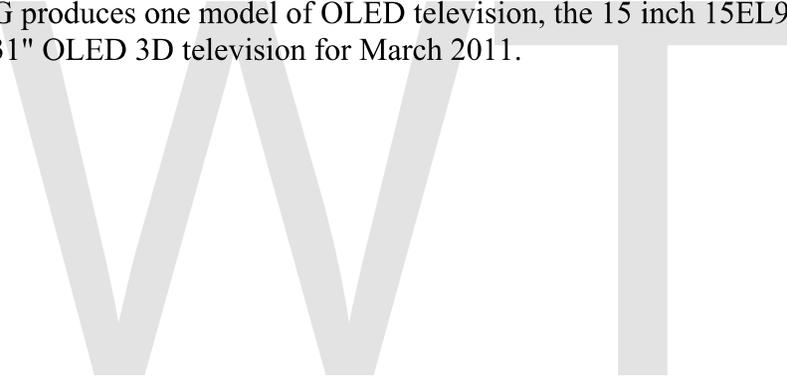
In October 2008, Sony published results of research it carried out with the Max Planck Institute over the possibility of mass-market bending displays, which could replace rigid LCDs and plasma screens. Eventually, bendable, transparent OLED screens could be stacked to produce 3D images with much greater contrast ratios and viewing angles than existing products.

Sony exhibited a 24.5" prototype OLED 3D television during the Consumer Electronics Show in January 2010.

In January 2011, Sony announced the NGP handheld game console (the successor to the PSP) will feature a 5-inch OLED screen.

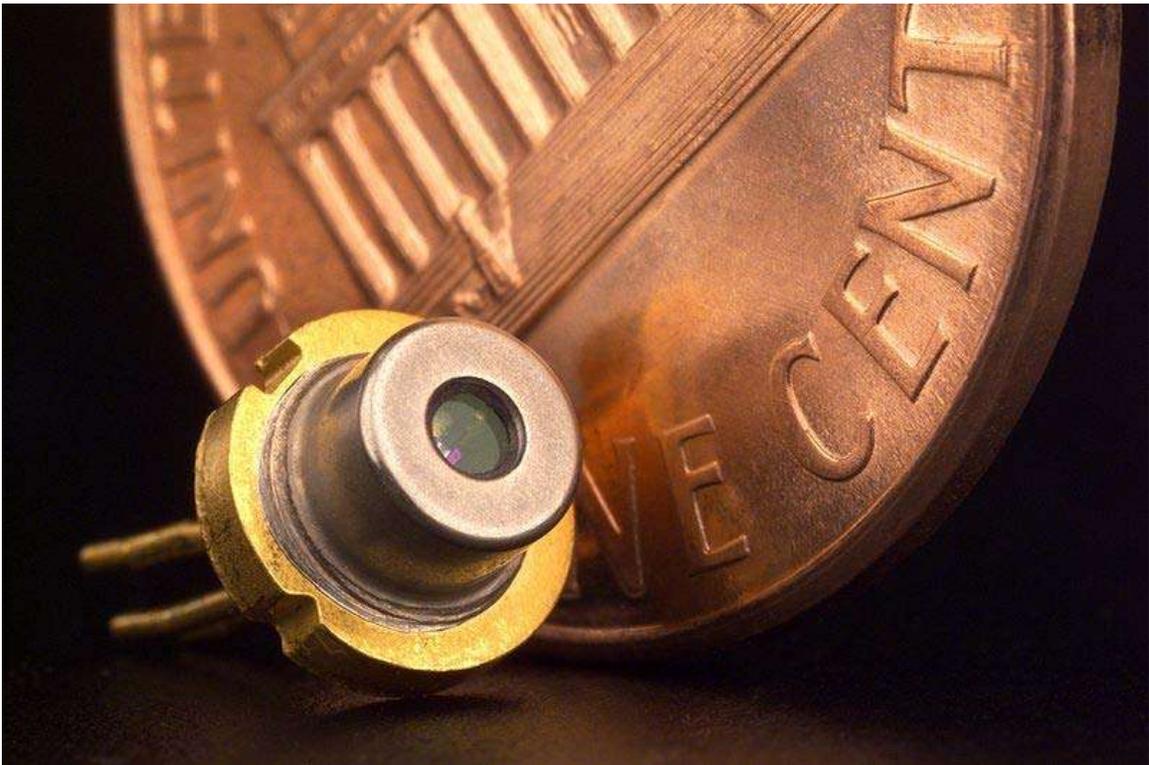
### **LG applications**

As of 2010 LG produces one model of OLED television, the 15 inch 15EL9500 and has announced a 31" OLED 3D television for March 2011.



## Chapter- 4

# Laser Diode



A packaged laser diode with penny for scale

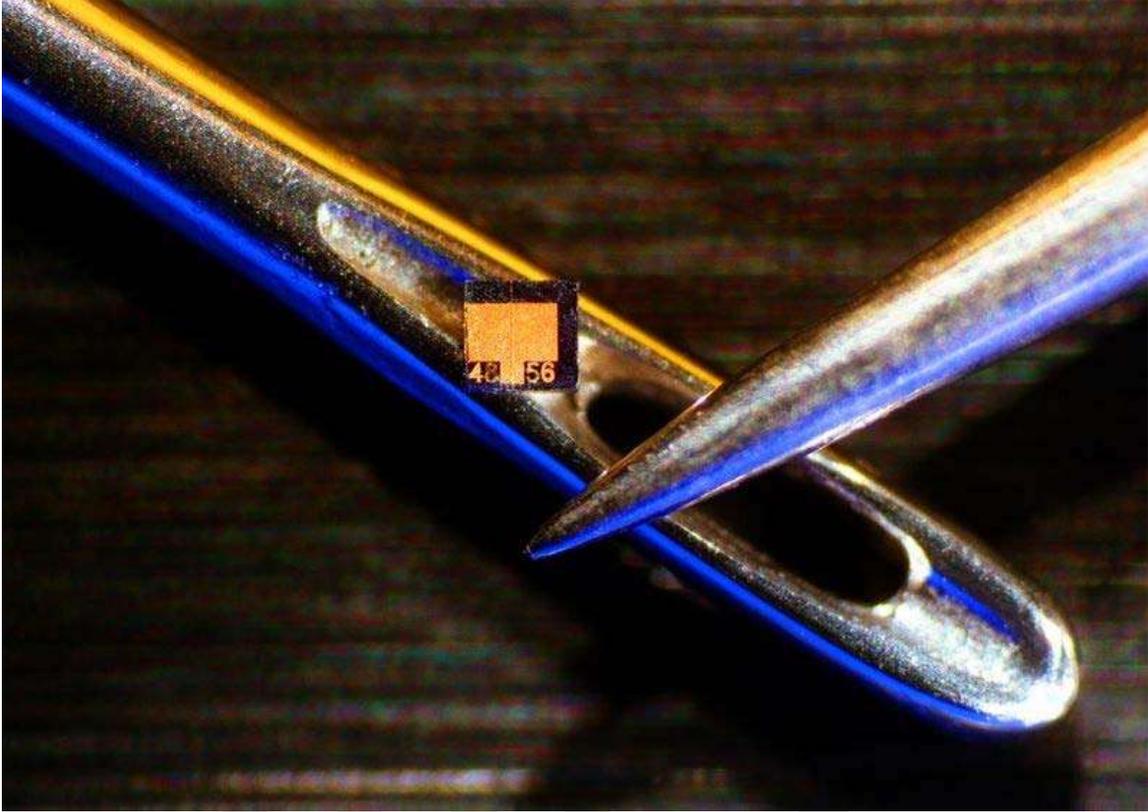
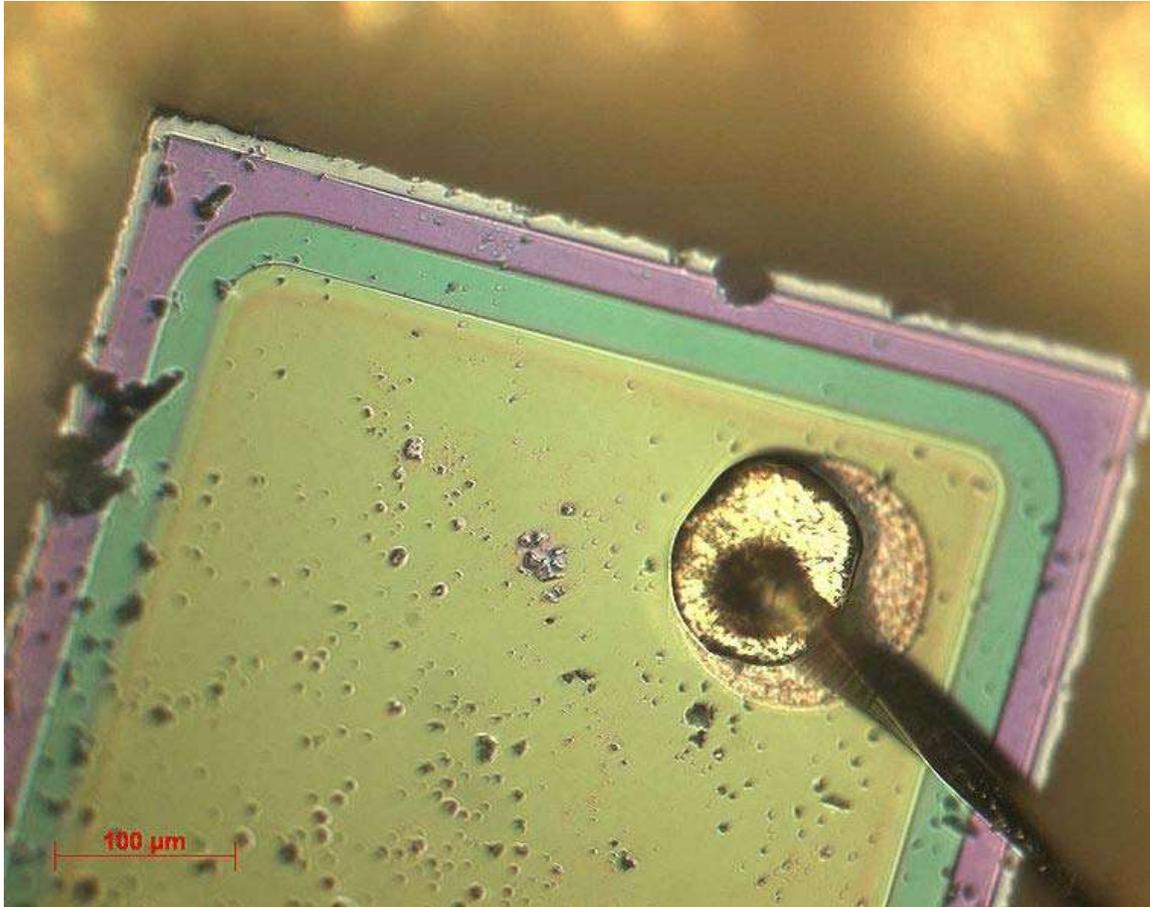


Image of the actual laser diode chip (shown on the eye of a needle for scale) contained within the package shown in the above image.



This is a visible light micrograph of a laser diode taken from a CD-ROM drive. Visible are the P and N layers distinguished by different colours. Also visible are scattered glass fragments from a broken collimating lens.

A **laser diode** is a laser where the active medium is a semiconductor similar to that found in a light-emitting diode. The most common type of laser diode is formed from a p-n junction and powered by injected electric current. The former devices are sometimes referred to as *injection laser diodes* to distinguish them from *optically pumped laser diodes*.

## Theory of operation

A laser diode is formed by doping a very thin layer on the surface of a crystal wafer. The crystal is doped to produce an n-type region and a p-type region, one above the other, resulting in a *p-n* junction, or diode.

Laser diodes form a subset of the larger classification of semiconductor *p-n* junction diodes. Forward electrical bias across the laser diode causes the two species of charge carrier – holes and electrons – to be "injected" from opposite sides of the *p-n* junction into the depletion region. Holes are injected from the *p*-doped, and electrons from the *n*-

doped, semiconductor. (A depletion region, devoid of any charge carriers, forms as a result of the difference in electrical potential between *n*- and *p*-type semiconductors wherever they are in physical contact.) Due to the use of charge injection in powering most diode lasers, this class of lasers is sometimes termed "injection lasers," or "injection laser diode" (ILD). As diode lasers are semiconductor devices, they may also be classified as semiconductor lasers. Either designation distinguishes diode lasers from solid-state lasers.

Another method of powering some diode lasers is the use of optical pumping. Optically Pumped Semiconductor Lasers (OPSL) use a III-V semiconductor chip as the gain media, and another laser (often another diode laser) as the pump source. OPSL offer several advantages over ILDs, particularly in wavelength selection and lack of interference from internal electrode structures.

When an electron and a hole are present in the same region, they may recombine or "annihilate" with the result being spontaneous emission — i.e., the electron may re-occupy the energy state of the hole, emitting a photon with energy equal to the difference between the electron and hole states involved. (In a conventional semiconductor junction diode, the energy released from the recombination of electrons and holes is carried away as phonons, i.e., lattice vibrations, rather than as photons.) Spontaneous emission gives the laser diode below lasing threshold similar properties to an LED. Spontaneous emission is necessary to initiate laser oscillation, but it is one among several sources of inefficiency once the laser is oscillating.

The difference between the photon-emitting semiconductor laser and conventional phonon-emitting (non-light-emitting) semiconductor junction diodes lies in the use of a different type of semiconductor, one whose physical and atomic structure confers the possibility for photon emission. These photon-emitting semiconductors are the so-called "direct bandgap" semiconductors. The properties of silicon and germanium, which are single-element semiconductors, have bandgaps that do not align in the way needed to allow photon emission and are not considered "direct." Other materials, the so-called compound semiconductors, have virtually identical crystalline structures as silicon or germanium but use alternating arrangements of two different atomic species in a checkerboard-like pattern to break the symmetry. The transition between the materials in the alternating pattern creates the critical "direct bandgap" property. Gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride are all examples of compound semiconductor materials that can be used to create junction diodes that emit light.

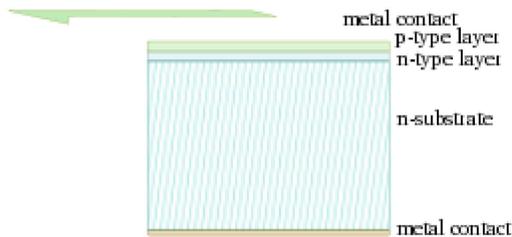


Diagram (not to scale) of a simple laser diode, such as shown above.

In the absence of stimulated emission (e.g., lasing) conditions, electrons and holes may coexist in proximity to one another, without recombining, for a certain time, termed the "upper-state lifetime" or "recombination time" (about a nanosecond for typical diode laser materials), before they recombine. Then a nearby photon with energy equal to the recombination energy can cause recombination by stimulated emission. This generates another photon of the same frequency, travelling in the same direction, with the same polarization and phase as the first photon. This means that stimulated emission causes gain in an optical wave (of the correct wavelength) in the injection region, and the gain increases as the number of electrons and holes injected across the junction increases. The spontaneous and stimulated emission processes are vastly more efficient in direct bandgap semiconductors than in indirect bandgap semiconductors; therefore silicon is not a common material for laser diodes.

As in other lasers, the gain region is surrounded with an optical cavity to form a laser. In the simplest form of laser diode, an optical waveguide is made on that crystal surface, such that the light is confined to a relatively narrow line. The two ends of the crystal are cleaved to form perfectly smooth, parallel edges, forming a Fabry–Pérot resonator. Photons emitted into a mode of the waveguide will travel along the waveguide and be reflected several times from each end face before they are emitted. As a light wave passes through the cavity, it is amplified by stimulated emission, but light is also lost due to absorption and by incomplete reflection from the end facets. Finally, if there is more amplification than loss, the diode begins to "lase".

Some important properties of laser diodes are determined by the geometry of the optical cavity. Generally, in the vertical direction, the light is contained in a very thin layer, and the structure supports only a single optical mode in the direction perpendicular to the layers. In the lateral direction, if the waveguide is wide compared to the wavelength of light, then the waveguide can support multiple lateral optical modes, and the laser is known as "multi-mode". These laterally multi-mode lasers are adequate in cases where one needs a very large amount of power, but not a small diffraction-limited beam; for example in printing, activating chemicals, or pumping other types of lasers.

In applications where a small focused beam is needed, the waveguide must be made narrow, on the order of the optical wavelength. This way, only a single lateral mode is supported and one ends up with a diffraction-limited beam. Such single spatial mode devices are used for optical storage, laser pointers, and fiber optics. Note that these lasers may still support multiple longitudinal modes, and thus can lase at multiple wavelengths simultaneously.

The wavelength emitted is a function of the band-gap of the semiconductor and the modes of the optical cavity. In general, the maximum gain will occur for photons with energy slightly above the band-gap energy, and the modes nearest the gain peak will lase most strongly. If the diode is driven strongly enough, additional *side modes* may also lase. Some laser diodes, such as most visible lasers, operate at a single wavelength, but that wavelength is unstable and changes due to fluctuations in current or temperature.

Due to diffraction, the beam diverges (expands) rapidly after leaving the chip, typically at 30 degrees vertically by 10 degrees laterally. A lens must be used in order to form a collimated beam like that produced by a laser pointer. If a circular beam is required, cylindrical lenses and other optics are used. For single spatial mode lasers, using symmetrical lenses, the collimated beam ends up being elliptical in shape, due to the difference in the vertical and lateral divergences. This is easily observable with a red laser pointer.

The simple diode described above has been heavily modified in recent years to accommodate modern technology, resulting in a variety of types of laser diodes, as described below.

## Types

The simple laser diode structure, described above, is extremely inefficient. Such devices require so much power that they can only achieve pulsed operation without damage. Although historically important and easy to explain, such devices are not practical.

## Double heterostructure lasers

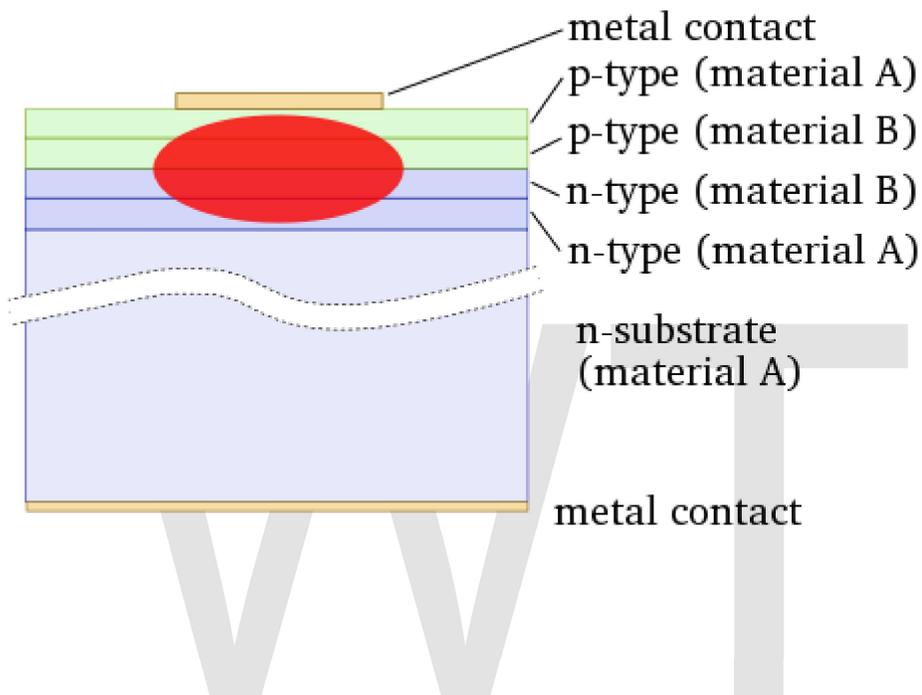


Diagram of front view of a double heterostructure laser diode (not to scale)

In these devices, a layer of low bandgap material is sandwiched between two high bandgap layers. One commonly-used pair of materials is gallium arsenide (GaAs) with aluminium gallium arsenide ( $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$ ). Each of the junctions between different bandgap materials is called a *heterostructure*, hence the name "double heterostructure laser" or *DH* laser.

The advantage of a DH laser is that the region where free electrons and holes exist simultaneously—the active region—is confined to the thin middle layer. This means that many more of the electron-hole pairs can contribute to amplification—not so many are left out in the poorly amplifying periphery. In addition, light is reflected from the heterojunction; hence, the light is confined to the region where the amplification takes place.

## Quantum well lasers

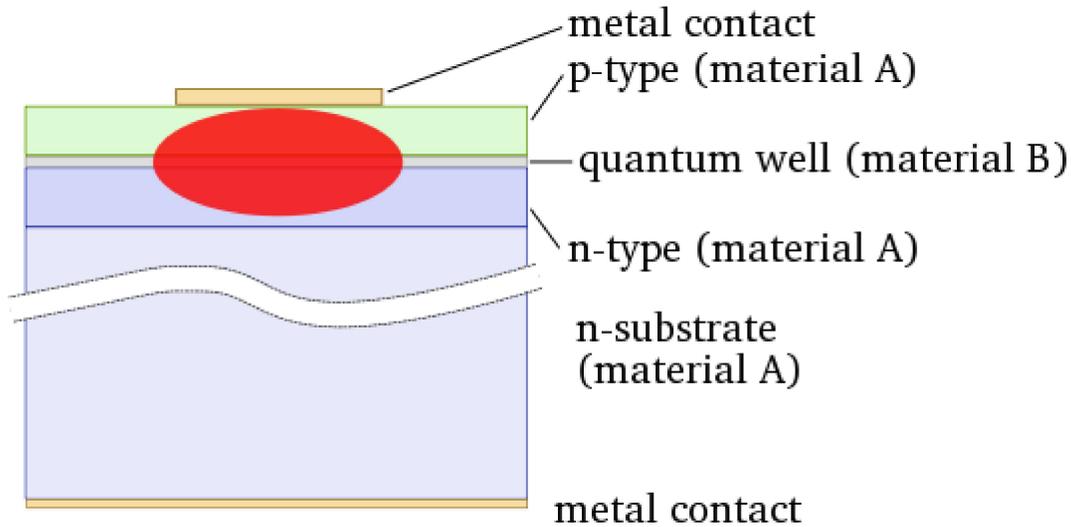


Diagram of front view of a simple quantum well laser diode (not to scale)

If the middle layer is made thin enough, it acts as a quantum well. This means that the vertical variation of the electron's wavefunction, and thus a component of its energy, is quantized. The efficiency of a quantum well laser is greater than that of a bulk laser because the density of states function of electrons in the quantum well system has an abrupt edge that concentrates electrons in energy states that contribute to laser action.

Lasers containing more than one quantum well layer are known as *multiple quantum well* lasers. Multiple quantum wells improve the overlap of the gain region with the optical waveguide mode.

Further improvements in the laser efficiency have also been demonstrated by reducing the quantum well layer to a quantum wire or to a "sea" of quantum dots.

## Quantum cascade lasers

In a quantum cascade laser, the difference between quantum well energy levels is used for the laser transition instead of the bandgap. This enables laser action at relatively long wavelengths, which can be tuned simply by altering the thickness of the layer. They are heterojunction lasers.

## Separate confinement heterostructure lasers

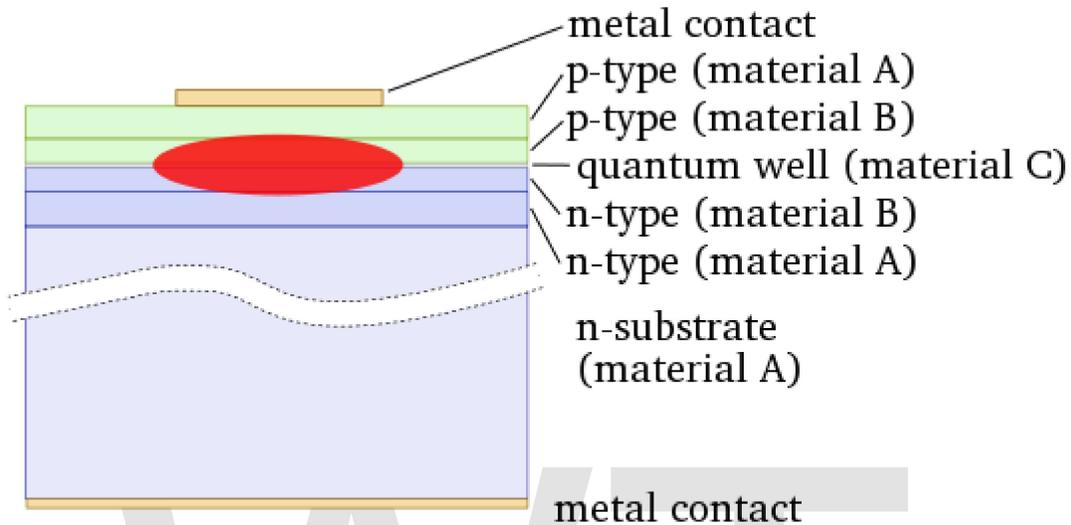


Diagram of front view of a separate confinement heterostructure quantum well laser diode

The problem with the simple quantum well diode described above is that the thin layer is simply too small to effectively confine the light. To compensate, another two layers are added on, outside the first three. These layers have a lower refractive index than the centre layers, and hence confine the light effectively. Such a design is called a separate confinement heterostructure (SCH) laser diode.

Almost all commercial laser diodes since the 1990s have been SCH quantum well diodes.

## Distributed feedback lasers

Distributed feedback lasers (DFB) are the most common transmitter type in DWDM-systems. To stabilize the lasing wavelength, a diffraction grating is etched close to the p-n junction of the diode. This grating acts like an optical filter, causing a single wavelength to be fed back to the gain region and lase. Since the grating provides the feedback that is required for lasing, reflection from the facets is not required. Thus, at least one facet of a DFB is anti-reflection coated. The DFB laser has a stable wavelength that is set during manufacturing by the pitch of the grating, and can only be tuned slightly with temperature. DFB lasers are widely used in optical communication applications where a precise and stable wavelength is critical.

## VCSELs

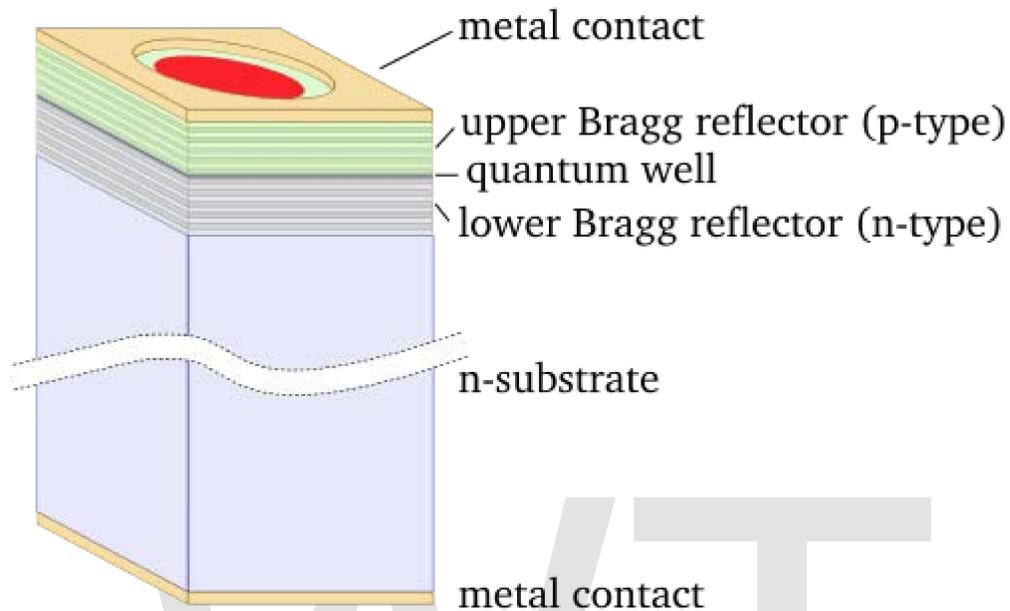


Diagram of a simple VCSEL structure

Vertical-cavity surface-emitting lasers (VCSELs) have the optical cavity axis along the direction of current flow rather than perpendicular to the current flow as in conventional laser diodes. The active region length is very short compared with the lateral dimensions so that the radiation emerges from the surface of the cavity rather than from its edge as shown in the figure. The reflectors at the ends of the cavity are dielectric mirrors made from alternating high and low refractive index quarter-wave thick multilayer.

Such dielectric mirrors provide a high degree of wavelength-selective reflectance at the required free surface wavelength  $\lambda$  if the thicknesses of alternating layers  $d_1$  and  $d_2$  with refractive indices  $n_1$  and  $n_2$  are such that  $n_1d_1 + n_2d_2 = \lambda/2$  which then leads to the constructive interference of all partially reflected waves at the interfaces. But there is a disadvantage: because of the high mirror reflectivities, VCSELs have lower output powers when compared to edge-emitting lasers.

There are several advantages to producing VCSELs when compared with the production process of edge-emitting lasers. Edge-emitters cannot be tested until the end of the production process. If the edge-emitter does not work, whether due to bad contacts or poor material growth quality, the production time and the processing materials have been wasted. Additionally, because VCSELs emit the beam perpendicular to the active region of the laser as opposed to parallel as with an edge emitter, tens of thousands of VCSELs can be processed simultaneously on a three inch Gallium Arsenide wafer. Furthermore,

even though the VCSEL production process is more labor and material intensive, the yield can be controlled to a more predictable outcome. However, they normally show a lower power output level.

## **VECSELS**

Vertical external-cavity surface-emitting lasers, or VECSELS, are similar to VCSELs. In VCSELs, the mirrors are typically grown epitaxially as part of the diode structure, or grown separately and bonded directly to the semiconductor containing the active region. VECSELS are distinguished by a construction in which one of the two mirrors is external to the diode structure. As a result, the cavity includes a free-space region. A typical distance from the diode to the external mirror would be 1 cm.

One of the most interesting features of any VECSEL is the small thickness of the semiconductor gain region in the direction of propagation, less than 100 nm. In contrast, a conventional in-plane semiconductor laser entails light propagation over distances of from 250  $\mu\text{m}$  upward to 2 mm or longer. The significance of the short propagation distance is that it causes the effect of "antiguiding" nonlinearities in the diode laser gain region to be minimized. The result is a large-cross-section single-mode optical beam which is not attainable from in-plane ("edge-emitting") diode lasers.

Several workers demonstrated optically pumped VECSELS, and they continue to be developed for many applications including high power sources for use in industrial machining (cutting, punching, etc.) because of their unusually high power and efficiency when pumped by multi-mode diode laser bars.

Electrically pumped VECSELS have also been demonstrated. Applications for electrically pumped VECSELS include projection displays, served by frequency doubling of near-IR VECSEL emitters to produce blue and green light.

## **External-cavity diode lasers**

External-cavity diode lasers are tunable lasers which use mainly double heterostructures diodes of the  $\text{Al}_x\text{Ga}_{(1-x)}\text{As}$  type. The first external-cavity diode lasers used intracavity etalons and simple tuning Littrow gratings. Other designs include gratings in grazing-incidence configuration and multiple-prism grating configurations.

## **Failure modes**

Laser diodes have the same reliability and failure issues as light emitting diodes. In addition they are subject to *catastrophic optical damage* (COD) when operated at higher power.

Many of the advances in reliability of diode lasers in the last 20 years remain proprietary to their developers. The reliability of a laser diode can make or break a product line.

Moreover, "reverse engineering" is not always able to reveal the differences between more-reliable and less-reliable diode laser products.

At the edge of a diode laser, where light is emitted, a mirror is traditionally formed by cleaving the semiconductor wafer to form a specularly reflecting plane. This approach is facilitated by the weakness of the crystallographic plane in III-V semiconductor crystals (such as GaAs, InP, GaSb, etc.) compared to other planes. A scratch made at the edge of the wafer and a slight bending force causes a nearly atomically perfect mirror-like cleavage plane to form and propagate in a straight line across the wafer.

But it so happens that the atomic states at the cleavage plane are altered (compared to their bulk properties within the crystal) by the termination of the perfectly periodic lattice at that plane. Surface states at the cleaved plane, have energy levels within the (otherwise forbidden) bandgap of the semiconductor.

Essentially, as a result when light propagates through the cleavage plane and transits to free space from within the semiconductor crystal, a fraction of the light energy is absorbed by the surface states whence it is converted to heat by phonon-electron interactions. This heats the cleaved mirror. In addition the mirror may heat simply because the edge of the diode laser—which is electrically pumped—is in less-than-perfect contact with the mount that provides a path for heat removal. The heating of the mirror causes the bandgap of the semiconductor to shrink in the warmer areas. The bandgap shrinkage brings more electronic band-to-band transitions into alignment with the photon energy causing yet more absorption. This is thermal runaway, a form of positive feedback, and the result can be melting of the facet, known as *catastrophic optical damage*, or COD.

In the 1970s this problem, which is particularly nettlesome for GaAs-based lasers emitting between 1  $\mu\text{m}$  and 0.630  $\mu\text{m}$  wavelengths (less so for InP based lasers used for long-haul telecommunications which emit between 1.3  $\mu\text{m}$  and 2  $\mu\text{m}$ ), was identified. Michael Ettenberg, a researcher and later Vice President at RCA Laboratories' David Sarnoff Research Center in Princeton, New Jersey, devised a solution. A thin layer of aluminum oxide was deposited on the facet. If the aluminum oxide thickness is chosen correctly it functions as an anti-reflective coating, reducing reflection at the surface. This alleviated the heating and COD at the facet.

Since then, various other refinements have been employed. One approach is to create a so-called non-absorbing mirror (NAM) such that the final 10  $\mu\text{m}$  or so before the light emits from the cleaved facet are rendered non-absorbing at the wavelength of interest.

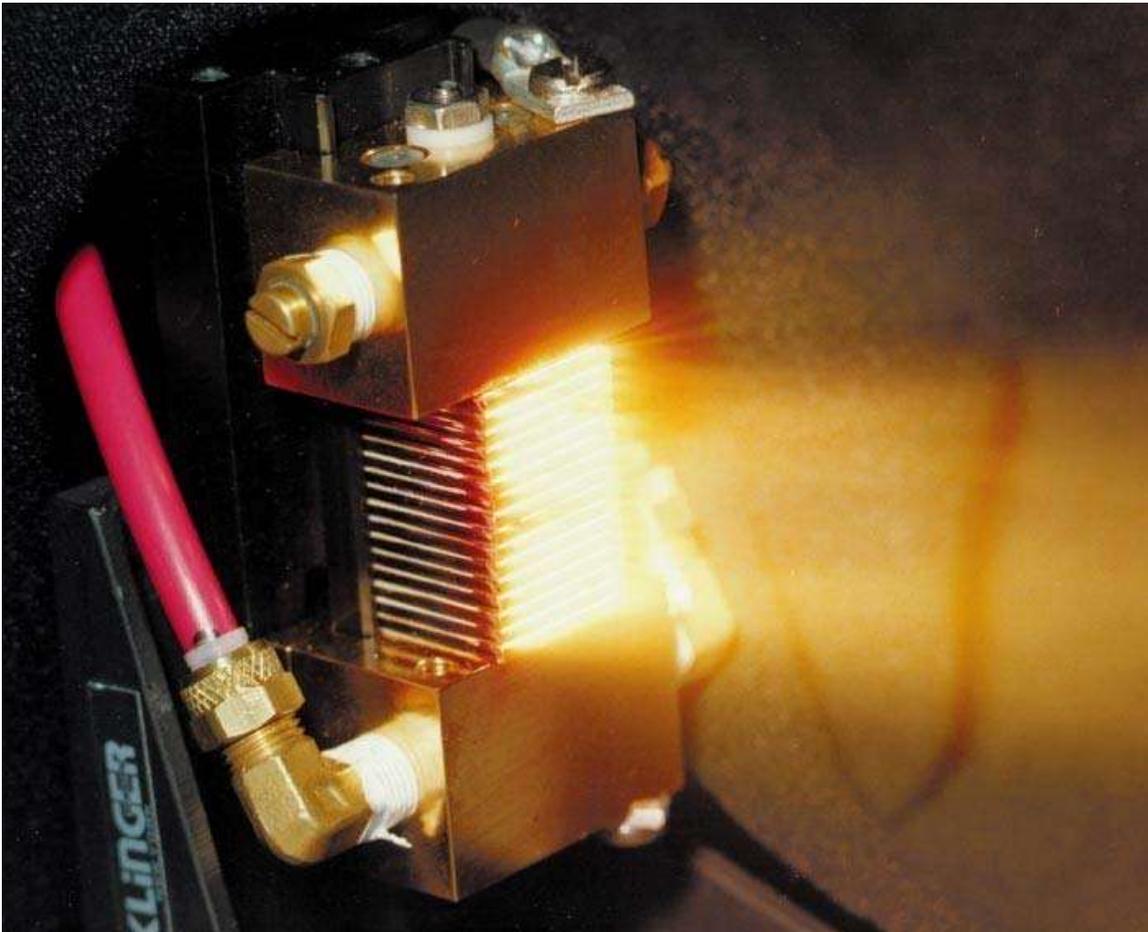
In the very early 1990s, SDL, Inc. began supplying high power diode lasers with good reliability characteristics. CEO Donald Scifres and CTO David Welch presented new reliability performance data at, e.g., SPIE Photonics West conferences of the era. The methods used by SDL to defeat COD were considered to be highly proprietary and have still not been disclosed publicly as of June, 2006.

In the mid-1990s IBM Research (Ruschlikon, Switzerland) announced that it had devised its so-called "E2 process" which conferred extraordinary resistance to COD in GaAs-based lasers. This process, too, has never been disclosed as of June, 2006.

Reliability of high-power diode laser pump bars (employed to pump solid state lasers) remains a difficult problem in a variety of applications, in spite of these proprietary advances. Indeed, the physics of diode laser failure is still being worked out and research on this subject remains active, if proprietary.

Extension of the lifetime of laser diodes is critical to their continued adaptation to a wide variety of applications.

## **Applications of laser diodes**



Laser diodes can be arrayed to produce very high power (continuous wave or pulsed) outputs. Such arrays may be used to efficiently pump solid state lasers for inertial confinement fusion or high average power drilling or burning applications.

Laser diodes are numerically the most common type of laser, with 2004 sales of approximately 733 million diode lasers, as compared to 131,000 of other types of lasers.

Laser diodes find wide use in telecommunication as easily modulated and easily coupled light sources for fiber optics communication. They are used in various measuring instruments, such as rangefinders. Another common use is in barcode readers. Visible lasers, typically red but later also green, are common as laser pointers. Both low and high-power diodes are used extensively in the printing industry both as light sources for scanning (input) of images and for very high-speed and high-resolution printing plate (output) manufacturing. Infrared and red laser diodes are common in CD players, CD-ROMs and DVD technology. Violet lasers are used in HD DVD and Blu-ray technology. Diode lasers have also found many applications in laser absorption spectrometry (LAS) for high-speed, low-cost assessment or monitoring of the concentration of various species in gas phase. High-power laser diodes are used in industrial applications such as heat treating, cladding, seam welding and for pumping other lasers, such as diode pumped solid state lasers.

Applications of laser diodes can be categorized in various ways. Most applications could be served by larger solid state lasers or optical parametric oscillators, but the low cost of mass-produced diode lasers makes them essential for mass-market applications. Diode lasers can be used in a great many fields; since light has many different properties (power, wavelength and spectral quality, beam quality, polarization, etc.) it is interesting to classify applications by these basic properties.

Many applications of diode lasers primarily make use of the "directed energy" property of an optical beam. In this category one might include the laser printers, bar-code readers, image scanning, illuminators, designators, optical data recording, combustion ignition, laser surgery, industrial sorting, industrial machining, and directed energy weaponry. Some of these applications are emerging while others are well-established.

Laser medicine: medicine and especially dentistry have found many new applications for diode lasers. The shrinking size of the units and their increasing user friendliness makes them very attractive to clinicians for minor soft tissue procedures. The 800 nm – 980 nm units have a high absorption rate for hemoglobin and thus make them ideal for soft tissue applications, where good hemostasis is necessary.

Applications which may make use of the coherence of diode-laser-generated light include interferometric distance measurement, holography, coherent communications, and coherent control of chemical reactions.

Applications which may make use of "narrow spectral" properties of diode lasers include range-finding, telecommunications, infra-red countermeasures, spectroscopic sensing, generation of radio-frequency or terahertz waves, atomic clock state preparation, quantum key cryptography, frequency doubling and conversion, water purification (in the UV), and photodynamic therapy (where a particular wavelength of light would cause a

substance such as porphyrin to become chemically active as an anti-cancer agent only where the tissue is illuminated by light).

Applications where the desired quality of laser diodes is their ability to generate ultra-short pulses of light by the technique known as "mode-locking" include clock distribution for high-performance integrated circuits, high-peak-power sources for laser-induced breakdown spectroscopy sensing, arbitrary waveform generation for radio-frequency waves, photonic sampling for analog-to-digital conversion, and optical code-division-multiple-access systems for secure communication.

## Common wavelengths

- **375 nm** – excitation of Hoechst stain, Calcium Blue, and other fluorescent dyes in fluorescence microscopy
- **405 nm** – InGaN blue-violet laser, in Blu-ray Disc and HD DVD drives
- **445 nm** – InGaN Deep blue laser multimode diode recently introduced (2010) for use in mercury free high brightness data projectors
- **473 nm** – Bright blue laser pointers, still very expensive, output of DPSS systems
- **485 nm** – excitation of GFP and other fluorescent dyes
- **510 nm** - Green diodes recently (2010) developed by Nichia for laser projectors.
- **532 nm** – AlGaAs-pumped bright green laser pointers, frequency doubled 1064 nm Nd:YAG laser or (more commonly in laser pointers) Nd:YVO<sub>4</sub> IR lasers (SHG)
- **593 nm** – Yellow-Orange laser pointers, DPSS
- **635 nm** – AlGaInP better red laser pointers, same power subjectively 5 times as bright as 670 nm one
- **640 nm** – High brightness red DPSS laser pointers
- **657 nm** – AlGaInP DVD drives, laser pointers
- **670 nm** – AlGaInP cheap red laser pointers
- **760 nm** – AlGaInP gas sensing: O<sub>2</sub>
- **785 nm** – GaAlAs Compact Disc drives
- **808 nm** – GaAlAs pumps in DPSS Nd:YAG lasers (e.g. in green laser pointers or as arrays in higher-powered lasers)
- **848 nm** – laser mice
- **980 nm** – InGaAs pump for optical amplifiers, for Yb:YAG DPSS lasers
- **1064 nm** – AlGaAs fiber-optic communication
- **1310 nm** – InGaAsP fiber-optic communication
- **1480 nm** – InGaAsP pump for optical amplifiers
- **1512 nm** – InGaAsP gas sensing: NH<sub>3</sub>
- **1550 nm** – InGaAsP fiber-optic communication
- **1625 nm** – InGaAsP fiber-optic communication, service channel
- **1654 nm** – InGaAsP gas sensing: CH<sub>4</sub>
- **1877 nm** – GaSbAs gas sensing: H<sub>2</sub>O
- **2004 nm** – GaSbAs gas sensing: CO<sub>2</sub>
- **2330 nm** – GaSbAs gas sensing: CO
- **2680 nm** – GaSbAs gas sensing: CO<sub>2</sub>

# History

The first to demonstrate coherent light emission from a semiconductor diode (the first *laser* diode), is widely acknowledged to have been Robert N. Hall and his team at the General Electric research center in 1962. The first visible wavelength laser diode was demonstrated by Nick Holonyak, Jr. later in 1962.

Other teams at IBM, MIT Lincoln Laboratory, Texas Instruments, and RCA Laboratories were also involved in and received credit for their historic initial demonstrations of efficient light emission and lasing in semiconductor diodes in 1962 and thereafter. GaAs lasers were also produced in early 1963 in the Soviet Union by the team led by Nikolay Basov.

In the early 1960s liquid phase epitaxy (LPE) was invented by Herbert Nelson of RCA Laboratories. By layering the highest quality crystals of varying compositions, it enabled the demonstration of the highest quality heterojunction semiconductor laser materials for many years. LPE was adopted by all the leading laboratories, worldwide and used for many years. It was finally supplanted in the 1970s by molecular beam epitaxy and organometallic chemical vapor deposition.

Diode lasers of that era operated with threshold current densities of  $1000 \text{ A/cm}^2$  at 77 K temperatures. Such performance enabled continuous-lasing to be demonstrated in the earliest days. However, when operated at room temperature, about 300 K, threshold current densities were two orders of magnitude greater, or  $100,000 \text{ A/cm}^2$  in the best devices. The dominant challenge for the remainder of the 1960s was to obtain low threshold current density at 300 K and thereby to demonstrate continuous-wave lasing at room temperature from a diode laser.

The first diode lasers were homojunction diodes. That is, the material (and thus the bandgap) of the waveguide core layer and that of the surrounding clad layers, were identical. It was recognized that there was an opportunity, particularly afforded by the use of liquid phase epitaxy using aluminum gallium arsenide, to introduce heterojunctions. Heterostructures consist of layers of semiconductor crystal having varying bandgap and refractive index. Heterojunctions (formed from heterostructures) had been recognized by Herbert Kroemer, while working at RCA Laboratories in the mid-1950s, as having unique advantages for several types of electronic and optoelectronic devices including diode lasers. LPE afforded the technology of making heterojunction diode lasers.

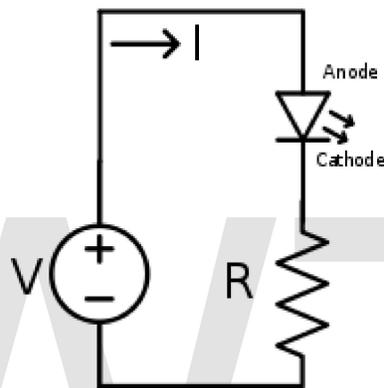
The first heterojunction diode lasers were single-heterojunction lasers. These lasers utilized aluminum gallium arsenide *p*-type injectors situated over *n*-type gallium arsenide layers grown on the substrate by LPE. An admixture of aluminum replaced gallium in the semiconductor crystal and raised the bandgap of the *p*-type injector over that of the *n*-type layers beneath. It worked; the 300 K threshold currents went down by  $10\times$  to 10,000 amperes per square centimeter. Unfortunately, this was still not in the needed range and these single-heterostructure diode lasers did not function in continuous wave operation at room temperature.

The innovation that met the room temperature challenge was the double heterostructure laser. The trick was to quickly move the wafer in the LPE apparatus between different "melts" of aluminum gallium arsenide (*p*- and *n*-type) and a third melt of gallium arsenide. It had to be done rapidly since the gallium arsenide core region needed to be significantly under 1  $\mu\text{m}$  in thickness. This may have been the earliest true example of "nanotechnology." The first laser diode to achieve *continuous wave* operation was a double heterostructure demonstrated in 1970 essentially simultaneously by Zhores Alferov and collaborators (including Dmitri Z. Garbuzov) of the Soviet Union, and Morton Panish and Izuo Hayashi working in the United States. However, it is widely accepted that Zhores I. Alferov and team reached the milestone first.

WWT

## Chapter- 5

# LED Circuit



Simple LED circuit diagram

In electronics, the basic **LED circuit** is an electric power circuit used to power a light-emitting diode or LED. The simplest such circuit consists of a voltage source powering two components connected in series: A current limiting resistor (sometimes called the ballast resistor), and an LED. Optionally, a switch may be introduced to open and close the circuit. The switch may be replaced with another component or circuit to form a continuity tester.

(Although simple, this circuit is not necessarily the most energy efficient circuit to drive an LED, since energy is lost in the resistor. More complicated circuits may be used to improve energy efficiency).

The LED used will have a voltage drop, specified at the intended operating current. Ohm's law and Kirchhoff's circuit laws are used to calculate the resistor that is used to attain the correct current. The resistor value is computed by subtracting the LED voltage drop from the supply voltage, and then dividing by the desired LED operating current. If the supply voltage is equal to the LED's voltage drop, no resistor is needed.

This basic circuit is used in a wide range of applications, including many consumer appliances.

# Simple resistance formula for optimum brightness of the LED

The formula to calculate the correct resistance to use is:

$$\text{resistance}(R) = \frac{\text{power supply voltage}(V_s) - \text{LED voltage drop}(V_f)}{\text{LED current rating}(I_f)}$$

where:

- **Power supply voltage** ( $V_s$ ) is the voltage of the power supply: e.g. a 9 volt battery.
- **LED voltage drop** ( $V_f$ ) is the voltage drop across the LED. Typically, this is about 1.8 – 3.3 volts; it varies by the color of the LED. A *red* LED typically drops 1.8 volts, but voltage drop normally rises as the light frequency increases, so a *blue* LED may drop around 3.3 volts.
- **LED current rating** ( $I_f$ ) is the manufacturer rating of the LED (usually given in milliamperes, such as 20 mA).

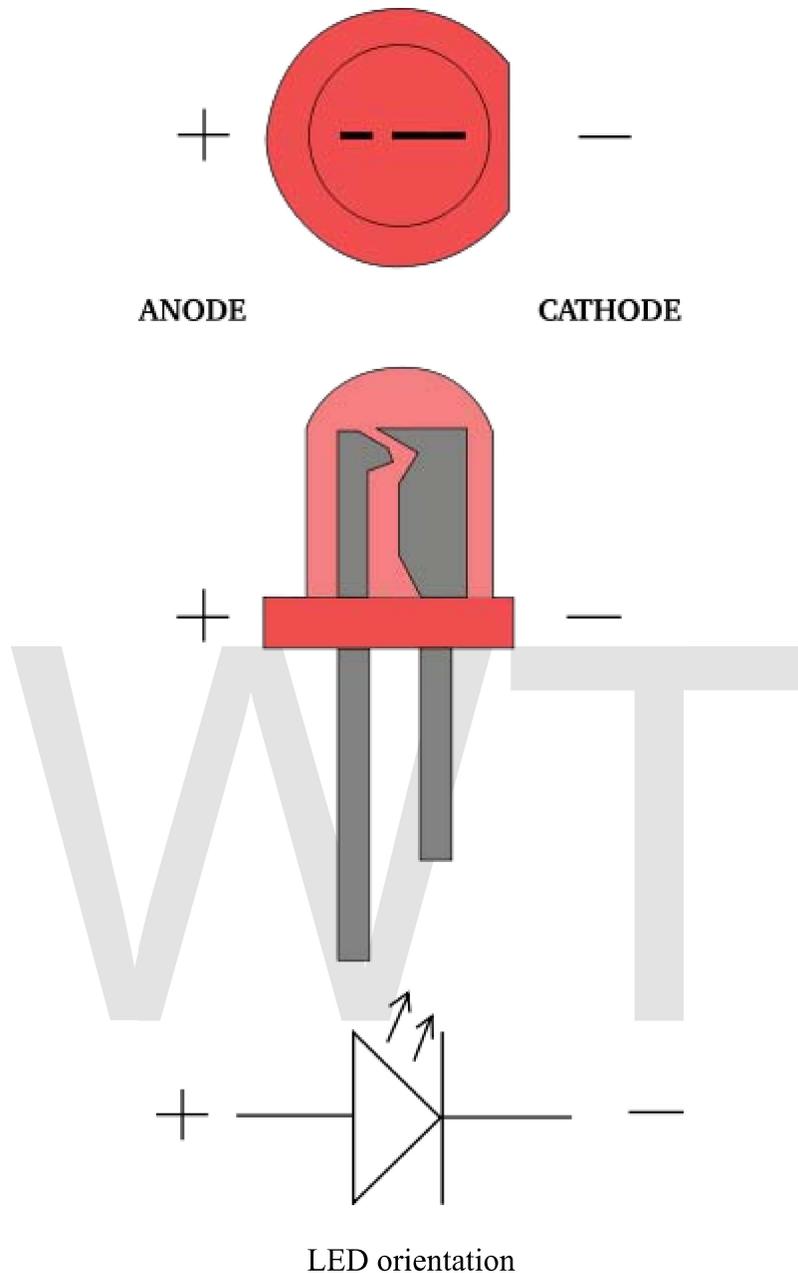
## Analysis using Kirchhoff's Laws

The formula can be explained considering the LED as a  $\frac{V_f}{I_f} \Omega$  resistance, and applying the KVL ( $R$  is the unknown quantity):

$$V_s = V_r + V_f = RI_f + \frac{V_f}{I_f}I_f$$

$$RI_f = V_s - V_f$$

$$R = \frac{V_s - V_f}{I_f}$$



LED orientation

## Polarity

Unlike incandescent light bulbs, which illuminate regardless of the electrical polarity, LEDs will only light with correct 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.

Most LEDs have low reverse breakdown voltage ratings, so they will also be damaged by an applied reverse voltage above this threshold. The cause of damage is overcurrent resulting from the diode breakdown, not the voltage itself. LEDs driven directly from an AC supply of more than the reverse breakdown voltage may be protected by placing a diode (or another LED) in inverse parallel.

The manufacturer will normally advise how to determine the polarity of the LED in the product datasheet. However, these methods may also be used:

<b>sign:</b>	+	-
terminal:	anode (A)	cathode (K)
leads:	long	short
exterior:	round	flat
wiring:	red	black
marking:*	none	stripe
pin:*	1	2
PCB:*	round	square

(\* )Less reliable methods of determining polarity

## Power sources

The voltage versus current characteristics of an **LED** are much like any diode. Current is approximately an exponential function of voltage, so a small voltage change results in a large change in current. It is therefore important that the power source gives the right voltage.

If the voltage is below the threshold or on-voltage no current will flow and the result is an unlit LED. If the voltage is too high the current will go above the maximum rating, heating and potentially destroying the LED. As the LED heats, its voltage drop decreases (band gap decrease), further increasing current. Consequently, LEDs should only be connected directly to constant-voltage sources if special care is taken. Series resistors are a simple way to stabilize the LED current, but wastes energy in the resistor. A constant current regulator is commonly used for high power LEDs. Low drop-out (LDO) constant current regulators also allow the total LED string voltage to be a higher percentage of the power supply voltage, resulting in improved efficiency and reduced power use. Switched-mode power supplies are used in some LED flashlights, stabilizing light output over a wide range of battery voltages and increasing the useful life of the batteries.

Miniature indicator LEDs are normally driven from low voltage DC via a current limiting resistor. Currents of 2 mA, 10 mA and 20 mA are common. Sub-mA indicators may be made by driving ultrabright LEDs at very low current. Efficiency tends to reduce at low currents, but indicators running on 100  $\mu$ A are still practical. The cost of ultrabright LEDs is higher than that of 2 mA indicator LEDs.

Strings of LEDs are normally operated in series LEDs, with the total LED voltage typically adding up to around two-thirds of the supply voltage, with resistor current control for each string. In disposable coin cell powered keyring type LED lights, the resistance of the cell itself is usually the only current limiting device. The cell should not therefore be replaced with a lower resistance type.

LEDs can be purchased with built in series resistors. These can save printed circuit board space and are especially useful when building prototypes or populating a PCB in a way other than its designers intended. However, the resistor value is set at the time of manufacture, removing one of the key methods of setting the LED's intensity. Alphanumeric LEDs use the same drive strategy as indicator LEDs, the only difference being the larger number of channels, each with its own resistor. Seven-segment and starburst LED arrays are available in both common-anode and common-cathode form.

## **Lighting LEDs on mains**

LEDs, by nature, require direct current (DC) with low voltage, as opposed to the mains electricity from the electrical grid which supplies a high voltage with an alternating current (AC).

A CR dropper (capacitor and resistor) followed by full-wave rectification is the usual electrical ballast with series-parallel LED clusters. A single series string minimizes dropper losses, while paralleled strings increase reliability. In practice usually three strings or more are used. An advantage of a capacitor is that it can reduce the high line voltage to an appropriate low voltage, without wasting power, with a very simple circuit; a disadvantage is that there may be a high surge of current for a short time when it is first turned on.

Operation on square wave and modified sine wave (MSW) sources, such as many inverters, causes heavily-increased resistor dissipation in CR dropper, and LED ballasts designed for sine wave use tend to burn on non-sine waveforms. The non-sine waveform also causes high peak LED currents, heavily shortening LED life. An inductor and rectifier make a more suitable ballast for such use, and other options are also possible. Dedicated integrated circuits are available that provide optimal drive for LEDs and maximum overall efficiency.

Multiple LEDs can be connected in series with a single current limiting resistor provided the source voltage is greater than the sum of the individual LED threshold voltages. Parallel operation is also possible but can be more problematic. Parallel LEDs must have closely matched forward voltages (Vf) in order to have equal branch currents and, therefore, equal light output. Variations in the manufacturing process can make it difficult to obtain satisfactory operation when connecting some types of LEDs in parallel.

To increase efficiency (or to allow intensity control without the complexity of a DAC), the power may be applied periodically or intermittently; so long as the flicker rate is

greater than the human flicker fusion threshold, the LED will appear to be continuously lit.

## **Resonant asymmetric inductive supply (RAIS)**

RAIS is an off-line LED driver topology with TRIAC dimmer compatibility and near unity power factor with no loss in efficiency.

This LED driver technology is especially suited to use with domestic TRIAC dimmers. Resonant asymmetric inductive supply (RAIS) sits between the mains and the LED. Report L10270 from the Lighting Association Laboratories found that the technology would work across different dimmer types while still maintaining a power factor of 0.96, and with an input to output system efficiency of 91 per cent. As the light is dimmed, the system is able to hold a significantly higher efficiency than a Buck converter as RAIS draws a continuous current without using bleed resistors. RAIS is a single stage supply that also delivers a constant current output to the LED with no sense resistor. The report also found that RAIS technology fitted into the dimensions of a standard GU10 lampholder (bayonet mount).

LED lighting typically involves LEDs connected in series. The resultant forward voltage may be in the region of 10 to 20V. In such cases, the ratio between the mains voltage and the voltage required to drive the load is between 10 and 20. With such a large ratio, conventional circuits used to drive LEDs become very inefficient because the switching will be operating at extremes of duty ratio with very short conduction times and high peak currents. This inevitably means that extra components, such as a common mode choke, need to be used. It is therefore common to include a magnetic or piezoelectric (ceramic) transformer with an input-to-output ratio suitable to create a step down in voltage and a corresponding step up in current, introducing further efficiency loss, cost and bulk.

In contrast, the RAIS technology can drive high current, low voltage LED strings from a 240V AC mains supply without high peak currents, a transformer, or common mode choke, and still achieve the turns ratio.

**Typical Use:** Between the mains and the LED within retro fit lamps, such as a GU10, where small size and use with conventional TRIAC dimmers is required.

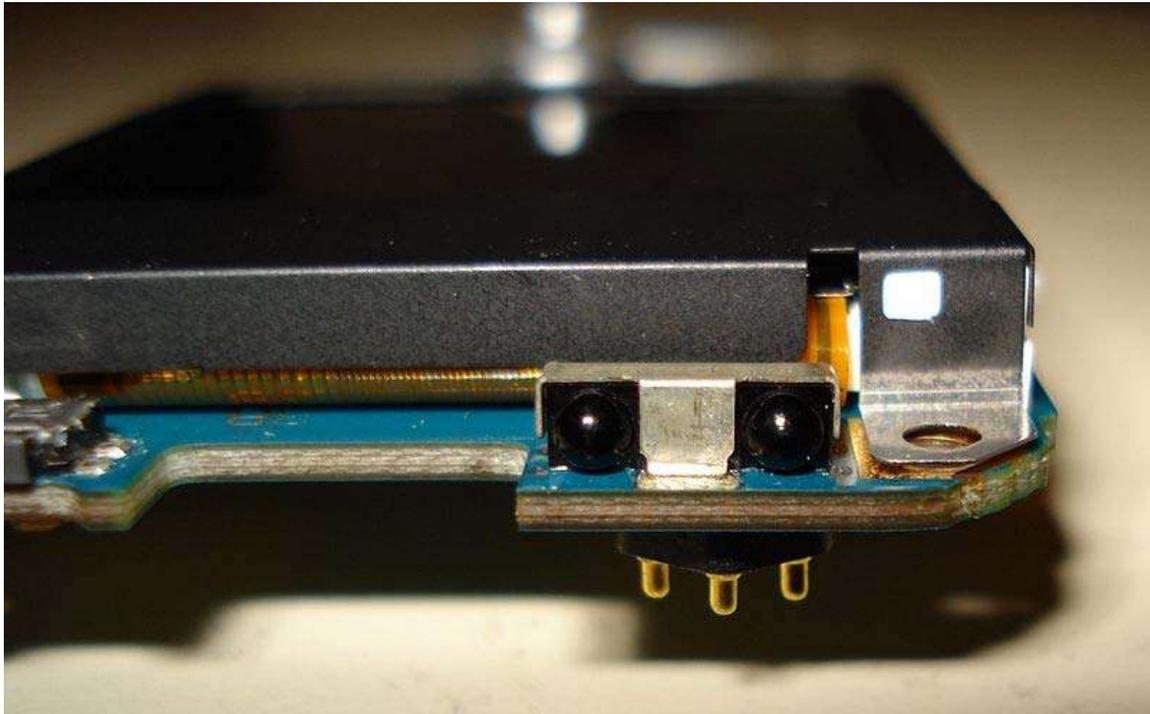
**Special Features :** Inherent compatibility with a TRIAC dimmers through continuous current draw in the same way as a conventional lamp, in other words it looks like a resistor to the mains. This also has an impact on the efficiency as it does not require a bleeder circuit or holding current resistor to ensure proper TRIAC operation that can cause efficiency loss during dimming.

The topology is inherently constant current. There is no need for a second stage, current sensing, feedback or short circuit protection.

Typical performance of a TRIAC dimmable LED retrofit lamp, Power Factor 0.96, efficiency > 90%.

The RAIS technology has now been granted UK patent # GB2449616 dated 17th February 09 and is applied for in most other world-wide territories.

## **LED as light sensor**



Mobile phone IrDA

An LED can be used as a photodiode used for light detection as well as emission. This capability has been demonstrated and used in a variety of applications including ambient light detection and bidirectional communications. This implementation of LEDs is important because functionality can be added to designs with only minor modifications, usually at little or no cost.

An LED is simply a diode that has been doped specifically for efficient light emission and has been packaged in a transparent case. Therefore, if inserted into a circuit in the same way as a photodiode, which is essentially the same thing, the LED will perform the same function. As a photodiode, it is sensitive to wavelengths equal to or shorter than the predominant wavelength it emits. For example, a green LED will be sensitive to blue light and to some green light, but not to yellow or red light. Additionally, the LED can be multiplexed in such a circuit, such that it can be used for both light emission and sensing at different times.

Several applications for this technology have been suggested and/or implemented, ranging from use as simple ambient light sensors to full bidirectional communications using a single LED. Most of these applications benefit from this technology because of the cost reduction of using the same component for multiple functions.

### **Ambient light sensors**

LEDs have been used as ambient light sensors. For example, a remote control keypad backlight would be turned on by capacitive proximity sensors only in the absence of ambient light. The LED used for the backlight was also used as the ambient light sensor. This resulted in increased functionality for no increase in manufacturing costs.

### **Bidirectional communications**

LEDs can be used as both emitters and detectors of light, which means that a device having only a single LED can be used to achieve bidirectional communications with another device meeting these requirements. Using this technology, any of the ubiquitous LEDs connected to household appliances, computers and other electronic devices can be used as a bidirectional communications port.

One application for bidirectional communication with a single LED is fiber optic communications. In typical plastic optical fiber communications, a single optical fiber is used only for communication in one direction. This is because a single LED transmitter is placed at one end of the fiber, and a photodiode receiver is placed at the other end. Thus, two fibers are needed for bidirectional communication. However, if a single LED is placed at each end of a fiber, then the optical fiber can carry information in both directions using half the number of components as a typical system. This reduces system weight, cost and complexity.

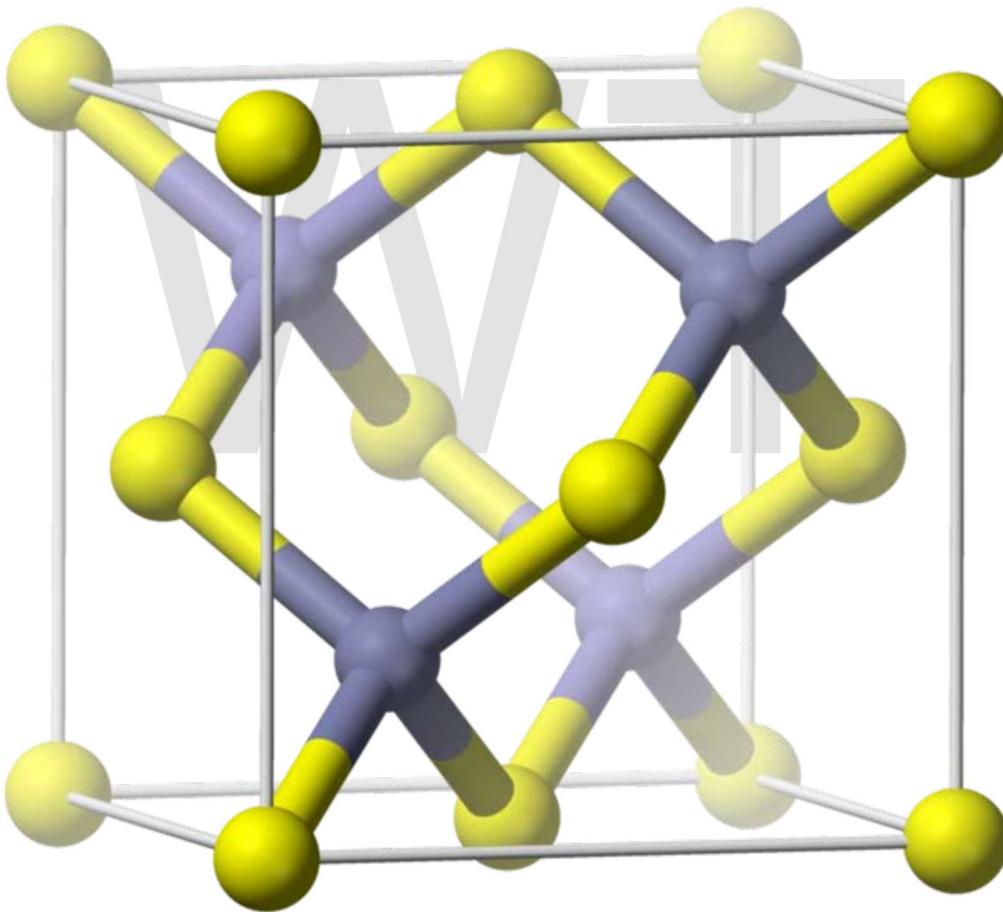
Another application of this use of LEDs is a proposed alternative to RFID tags called the iDropper, developed by Mitsubishi Electric Research Laboratories in 2003. The iDropper is a small device that consists of a microcontroller, a battery, an LED, and a single push-button. The device records or transmits a small amount of data upon command from the user. Compared to RFID tags, the iDropper is more secure because the user must press a button to reveal personal information, and is similar in cost.

One major limitation of this scheme is the fact that a single LED can only operate as a half-duplex transceiver. A single LED can either transmit or receive information at one time, not both simultaneously. A simple way to put this is that an LED transceiver behaves like a walkie-talkie, in contrast to a telephone. This means that it takes a considerable time for two devices to "talk" to each other.

## Chapter- 6

# Light-Emitting Diode Materials

## Aluminium gallium arsenide



The crystal structure of aluminium gallium arsenide is zincblende.

**Aluminium gallium arsenide** (also **aluminum gallium arsenide**) ( $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ) is a semiconductor material with very nearly the same lattice constant as GaAs, but a larger

bandgap. The  $x$  in the formula above is a number between 0 and 1 - this indicates an arbitrary alloy between GaAs and AlAs.

The bandgap varies between 1.42 eV (GaAs) and 2.16 eV (AlAs). For  $x < 0.4$ , the bandgap is direct.

The formula *AlGaAs* should be considered an abbreviated form of the above, rather than any particular ratio.

Aluminium gallium arsenide is used as a barrier material in GaAs based heterostructure devices. The AlGaAs layer confines the electrons to a gallium arsenide region. An example of such a device is a quantum well infrared photodetector (QWIP).

It can also be used in 1064 nm (Infra-red) laser diodes.

## Safety and toxicity aspects

The toxicology of AlGaAs has not been fully investigated. The dust is an irritant to skin, eyes and lungs. The environment, health and safety aspects of aluminium gallium arsenide sources (such as trimethylgallium and arsine) and industrial hygiene monitoring studies of standard MOVPE sources have been reported recently in a review .

## Aluminium gallium indium phosphide

**Aluminium gallium indium phosphide** (AlGaInP, also AlInGaP, InGaAlP, etc.) is a semiconductor material.

AlGaInP is used in manufacture of light-emitting diodes of high-brightness red, orange, green, and yellow color, to form the heterostructure emitting light. It is also used to make diode lasers.

AlGaInP layer is often grown by heteroepitaxy on gallium arsenide or gallium phosphide in order to form a quantum well structure.

## Safety and toxicity aspects

The toxicology of AlInGaP has not been fully investigated. The dust is an irritant to skin, eyes and lungs. The environment, health and safety aspects of aluminium indium gallium phosphide sources (such as trimethylgallium, trimethylindium and phosphine) and industrial hygiene monitoring studies of standard MOVPE sources have been reported recently in a review

# Aluminium gallium nitride

**Aluminium gallium nitride (AlGaN)** is a semiconductor material. It is an alloy of aluminium nitride and gallium nitride.

AlGaN is used to manufacture light-emitting diodes operating in blue to ultraviolet region, where wavelengths down to 250 nm (far UV) were achieved. It is also used in blue semiconductor lasers. It is also used in detectors of ultraviolet radiation, and in AlGaN/GaN HEMT transistors.

AlGaN is often used together with gallium nitride or aluminium nitride, forming heterojunctions.

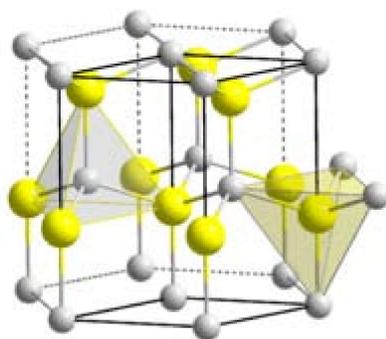
AlGaN layers can be also grown on sapphire.

## Safety and toxicity aspects

The toxicology of AlGaN has not been fully investigated. The AlGaN dust is an irritant to skin, eyes and lungs. The environment, health and safety aspects of aluminium gallium nitride sources (such as trimethylgallium and ammonia) and industrial hygiene monitoring studies of standard MOVPE sources have been reported recently in a review .

# Aluminium nitride

## Aluminium nitride



**Other names**  
Aluminum nitride

### Identifiers

CAS number	24304-00-5 ✓
PubChem	90455
ChemSpider	81668 ✓

### Properties

Molecular formula	AlN
Molar mass	40.9882 g/mol
Appearance	white to pale-yellow solid
Density	3.260 g/cm <sup>3</sup>
Melting point	2200 °C
Boiling point	2517 °C (decomp)
Solubility in water	decomposes
Band gap	6.2 eV (direct)
Electron mobility	~300 cm <sup>2</sup> /(V·s)
Thermal conductivity	285 W/(m·K)
Refractive index ( <i>n<sub>D</sub></i> )	1.9–2.2

### Structure

Crystal structure	Wurtzite
Space group	$C_{6v}^4-P6_3mc$
Coordination geometry	Tetrahedral

## Thermochemistry

Specific heat capacity,  $C$  740 J·Kg<sup>-1</sup> K<sup>-1</sup>

**Aluminium nitride** (AlN) is a nitride of aluminium. Its wurtzite phase (w-AlN) is a wide band gap (6.2 eV) semiconductor material, giving it potential application for deep ultraviolet optoelectronics.

## History

AlN was first synthesized in 1877, but it was not until the middle of the 1980s that its potential for application in microelectronics was realized due to its relative high thermal conductivity for an electrical insulating ceramic (70–210 W·m<sup>-1</sup>·K<sup>-1</sup> for polycrystalline material, and as high as 285 W·m<sup>-1</sup>·K<sup>-1</sup> for single crystals).

## Stability and chemical properties

Aluminium nitride is stable at high temperatures in inert atmospheres and melts at 2800 °C. In a vacuum, AlN decomposes at ~1800 °C. In the air, surface oxidation occurs above 700°C, and even at room temperature, surface oxide layers of 5-10 nm have been detected. This oxide layer protects the material up to 1370°C. Above this temperature bulk oxidation occurs. Aluminium nitride is stable in hydrogen and carbon dioxide atmospheres up to 980°C.

The material dissolves slowly in mineral acids through grain boundary attack, and in strong alkalis through attack on the aluminium nitride grains. The material hydrolyzes slowly in water. Aluminium nitride is resistant to attack from most molten salts, including chlorides and cryolite.

## Manufacture

AlN is synthesized by the carbothermal reduction of alumina or by direct nitridation of aluminium. The use of sintering aids and hot pressing is required to produce a dense technical grade material.

## Applications

Metallization methods are available to allow AlN to be used in electronics applications similar to those of alumina and beryllium oxide.

Currently there is much research into developing light-emitting diodes to operate in the ultraviolet using the gallium nitride based semiconductors and, using the alloy aluminum gallium nitride, wavelengths as short as 250 nm have been achieved. In May 2006, an inefficient AlN LED emission at 210 nm has been reported.

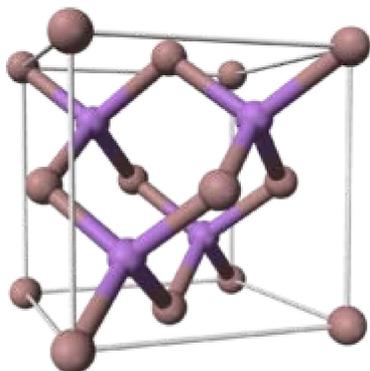
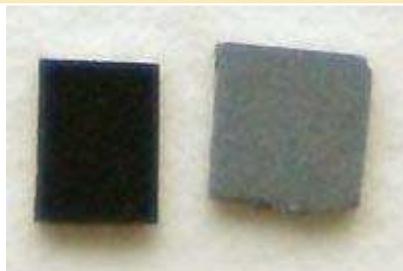
Among the applications of AlN are

- opto-electronics,
- dielectric layers in optical storage media,
- electronic substrates, chip carriers where high thermal conductivity is essential,
- military applications,
- as a crucible to grow crystals of gallium arsenide,
- steel and semiconductor manufacturing.

Epitaxially grown thin film crystalline aluminium nitride is also used for surface acoustic wave sensors (SAW's) deposited on silicon wafers because of the AlN's piezoelectric properties. One application is an RF filter used in mobile phones called a thin film bulk acoustic resonator (FBAR). This is a MEMS device that uses aluminium nitride sandwiched between two metal layers.

## Gallium arsenide

### Gallium arsenide



IUPAC name  
Gallium arsenide

#### Identifiers

CAS number	1303-00-0 ✓
PubChem	14770
ChemSpider	14087 ✓

RTECS number LW8800000

### Properties

Molecular formula GaAs  
Molar mass 144.645 g/mol  
Appearance Gray cubic crystals  
Density 5.316 g/cm<sup>3</sup>  
Melting point 1238 °C (1511 K)  
Solubility in water < 0.1 g/100 mL (20 °C)  
Band gap 1.424 eV (300 K)  
Electron mobility 8500 cm<sup>2</sup>/(V·s) (300 K)  
Thermal conductivity 0.55 W/(cm·K) (300 K)  
Refractive index (*n<sub>D</sub>*) 3.0 - 5.0

### Structure

Crystal structure Zinc blende  
Space group *T<sub>d</sub><sup>2</sup>-F-43m*  
Coordination geometry Tetrahedral  
Molecular shape Linear

### Hazards

MSDS External MSDS  
EU classification Toxic (T)  
Dangerous for the environment (N)  
R-phrases R23/25, R50/53  
S-phrases (S1/2), S20/21, S28, S45, S60, S61

**Gallium arsenide (GaAs)** is a compound of the elements gallium and arsenic. It is a III/V semiconductor, and is used in the manufacture of devices such as microwave frequency integrated circuits, monolithic microwave integrated circuits, infrared light-emitting diodes, laser diodes, solar cells, and optical windows.

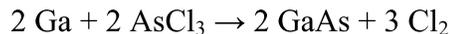
## Preparation and chemistry

In the compound, gallium has a +3 oxidation state. Gallium arsenide can be prepared by direct reaction from the elements which is used in a number of industrial processes:

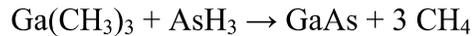
- Crystal growth using a horizontal zone furnace in the Bridgman-Stockbarger technique, in which gallium and arsenic vapors react and free molecules deposit on a seed crystal at the cooler end of the furnace.
- Liquid encapsulated Czochralski (LEC) growth is used for producing high purity single crystals that exhibit semi-insulating characteristics.

Alternative methods for producing films of GaAs include:

- VPE reaction of gaseous gallium metal and arsenic trichloride:



- MOCVD reaction of trimethylgallium and arsine:



Wet etching of GaAs industrially uses an oxidizing agent, for example hydrogen peroxide or bromine water, and the same strategy has been described in a patent relating to processing scrap components containing GaAs where the  $\text{Ga}^{3+}$  is complexed with a hydroxamic acid ("HA"), for example::



Oxidation of GaAs occurs in air and degrades performance of the semiconductor. The surface can be passivated by depositing a cubic gallium(II) sulfide layer using a tert-butyl gallium sulfide compound such as  $(t\text{BuGaS})_7$ .

## Comparison with silicon

### GaAs advantages

GaAs has some electronic properties which are superior to those of silicon. It has a higher saturated electron velocity and higher electron mobility, allowing transistors made from it to function at frequencies in excess of 250 GHz. Unlike silicon junctions, GaAs devices are relatively insensitive to heat. Also, GaAs devices generate less noise than silicon devices when operated at high frequencies. They can also be operated at higher power levels than the equivalent silicon device because they have higher breakdown voltages. These properties recommend GaAs circuitry in mobile phones, satellite communications, microwave point-to-point links, and some radar systems. It is used in the manufacture of Gunn diodes for generation of microwaves.

Another advantage of GaAs is that it has a direct band gap, which means that it can be used to emit light efficiently. Silicon has an indirect bandgap and so is very poor at emitting light. Nonetheless, recent advances may make silicon LEDs and lasers possible. As a wide direct band gap material with high breakdown voltage, and resulting resistance to radiation damage, GaAs is an excellent material for space and optical windows in high power applications.

Because of its wide bandgap, pure GaAs is highly resistive. Combined with the high dielectric constant, this property makes GaAs a very good electrical substrate and unlike Si provides natural isolation between devices and circuits. This has made it an ideal material for microwave and millimeter wave integrated circuits, MMICs, where active and essential passive components can readily be produced on a single slice of GaAs.

One of the first GaAs microprocessors was developed in the early 1980s by the RCA corporation and was considered for the Star Wars program of the United States Department of Defense. Those processors were several times faster and several orders of magnitude more radiation hard than silicon counterparts, but they were rather expensive.

Other GaAs processors were implemented by the supercomputer vendors Cray Computer Corporation, Convex, and Alliant in an attempt to stay ahead of the ever-improving CMOS microprocessor. Cray eventually built one GaAs-based machine in the early 1990s, the Cray-3, but the effort was not adequately capitalized, and the company filed for bankruptcy in 1995.

Complex layered structures of gallium arsenide in combination with aluminium arsenide (AlAs) or the alloy  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  can be grown using molecular beam epitaxy (MBE) or using metalorganic vapor phase epitaxy (MOVPE). Because GaAs and AlAs have almost the same lattice constant, the layers have very little induced strain, which allows them to be grown almost arbitrarily thick. This allows for extremely high performance high electron mobility, HEMT transistors and other quantum well devices.

### **Silicon advantages**

Silicon has three major advantages over GaAs for integrated circuit manufacture. First, silicon is abundant and cheap to process. Si is highly abundant in the Earth's crust, in the form of silicate minerals. The economy of scale available to the silicon industry has also reduced the adoption of GaAs.

In addition, Si crystal has an extremely stable structure mechanically and it can be grown to very large diameter boules and can be processed with very high yields. It is also a decent thermal conductor thus enable very dense packing of transistors, all very desirable for design and manufacturing of very large ICs. Such good mechanical characteristics also makes it a suitable material for the rapidly developing field of nanoelectronics.

The second major advantage of Si is the existence of silicon dioxide—one of the best insulators. Silicon dioxide can easily be incorporated onto silicon circuits, and such layers are adherent to the underlying Si. GaAs does not easily form such a stable adherent insulating layer and does not have stable oxide either.

The third, and perhaps most important, advantage of silicon is that it possesses a much higher hole mobility. This high mobility allows the fabrication of higher-speed P-channel field effect transistors, which are required for CMOS logic. Because they lack a fast CMOS structure, GaAs logic circuits have much higher power consumption, which has made them unable to compete with silicon logic circuits.

Silicon has relatively low absorptivity for the sunlight meaning about 100 micrometers of Si is needed to absorb most sunlight. Such layer is relatively robust and easy to handle. On the contrary, the absorptivity of GaAs is so high that a corresponding layer would be only a few micrometers thick and mechanically unstable.

Silicon is a pure element, avoiding the problems of stoichiometric imbalance and thermal unmixing of GaAs.

Silicon has a nearly perfect lattice, impurity density is very low and allows to build very small structures (currently down to 25 nm). GaAs in contrast has a very high impurity density, which makes it difficult to build ICs with small structures, so the 500 nm process is a common process for GaAs.

## Other applications

### Solar cells and detectors

Another important application of GaAs is for high efficiency solar cells. Gallium arsenide (GaAs) is also known as single-crystalline thin film and are high cost high efficiency solar cells.

In 1970, the first GaAs heterostructure solar cells were created by the team led by Zhores Alferov in the USSR. In the early 1980s, the efficiency of the best GaAs solar cells surpassed that of silicon solar cells, and in the 1990s GaAs solar cells took over from silicon as the cell type most commonly used for Photovoltaic arrays for satellite applications. Later, dual- and triple-junction solar cells based on GaAs with germanium and indium gallium phosphide layers were developed as the basis of a triple junction solar cell which held a record efficiency of over 32% and can operate also with light as concentrated as 2,000 suns. This kind of solar cell powers the rovers Spirit and Opportunity, which are exploring Mars' surface. Also many solar cars utilize GaAs in solar arrays.

Complex designs of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ -GaAs devices can be sensitive to infrared radiation (QWIP).

GaAs diodes can be used for the detection of X-rays.

### Light emission devices

GaAs has been used to produce (near-infrared) laser diodes since 1962.

Single crystals of gallium arsenide can be manufactured by the Bridgeman technique, as the Czochralski process is difficult for this material due to its mechanical properties. However, an encapsulated Czochralski method is used to produce ultra-high purity GaAs for semi-insulators.

GaAs is often used a substrate material for the epitaxial growth of other III-V semiconductors including: InGaAs and GaInNAs.

## Safety

The toxicological properties of gallium arsenide have not been thoroughly investigated. On one hand, due to its arsenic content, it is considered highly toxic and carcinogenic. On

the other hand, the crystal is stable enough that ingested pieces may be passed with negligible absorption by the body. When ground into very fine particles, such as in wafer-polishing processes, the high surface area enables more reaction with water releasing some arsine and/or dissolved arsenic. The environment, health and safety aspects of gallium arsenide sources (such as trimethylgallium and arsine) and industrial hygiene monitoring studies of metalorganic precursors have been reported. California lists gallium arsenide as a carcinogen.

## Gallium arsenide phosphide

**Gallium arsenide phosphide** ( $\text{GaAs}_{1-x}\text{P}_x$ ) is a semiconductor material, an alloy of gallium arsenide and gallium phosphide. It exists in various composition ratios indicated in its formula by the fraction  $x$ .

Gallium arsenide phosphide is used for manufacturing red, orange and yellow light-emitting diodes. It is often grown on gallium phosphide substrates to form a GaP/GaAsP heterostructure. In order to tune its electronic properties, it may be doped with nitrogen (GaAsP:N).

## Chapter- 7

# LED Display and LED Headliner

## LED display



The 1,500-foot (460 m) long LED display on the Fremont Street Experience is currently the largest in the world.



The 40m large LED display at the Armin Only event on 19/20 apr 2008 in the Jaarbeurs Utrecht



The LED Display at the Taipei Arena displays commercials and movie trailers



A city bus with LED destination signs

An **LED display** is a video display which uses light-emitting diodes. A **LED panel** is a small display, or a component of a larger display. They are typically used outdoors in store signs and billboards, and in recent years have also become commonly used in destination signs on public transport vehicles or even as part of transparent glass area. LED panels are sometimes used as form of lighting, for the purpose of general illumination, task lighting, or even stage lighting rather than display.

## Types

There are two types of LED panels: conventional (using discrete LEDs) and surface-mounted device (SMD) panels. Most outdoor screens and some indoor screens are built around discrete LEDs, also known as individually mounted LEDs. A cluster of red, green, and blue diodes is driven together to form a full-color pixel, usually square in shape. These pixels are spaced evenly apart and are measured from center to center for absolute pixel resolution. The largest LED display in the world is over 1,500 ft (457.2 m) long and is located in Las Vegas, Nevada covering the Fremont Street Experience. The largest LED television in the world is the Center Hung Video Display at Cowboys Stadium, which is  $160 \times 72$  ft ( $49 \times 22$  m), 11,520 square feet ( $1,070 \text{ m}^2$ ).

Most indoor screens on the market are built using SMD technology—a trend that is now extending to the outdoor market. A SMD pixel consists of red, green, and blue diodes mounted in a single package, which is then mounted on the driver PC board. The individual diodes are smaller than a pinhead and are set very close together. The difference is that the maximum viewing distance is reduced by 25% from the discrete diode screen with the same resolution.

Indoor use generally requires a screen that is based on SMD technology and has a minimum brightness of 600 candelas per square meter ( $\text{cd}/\text{m}^2$ , sometimes informally called *nits*). This will usually be more than sufficient for corporate and retail applications, but under high ambient-brightness conditions, higher brightness may be required for visibility. Fashion and auto shows are two examples of high-brightness stage lighting that may require higher LED brightness. Conversely, when a screen may appear in a shot on a television studio set, the requirement will often be for lower brightness levels with lower color temperatures; common displays have a white point of 6500–9000 K, which is much bluer than the common lighting on a television production set.

For outdoor use, at least  $2,000 \text{ cd}/\text{m}^2$  is required for most situations, whereas higher-brightness types of up to  $5,000 \text{ cd}/\text{m}^2$  cope even better with direct sunlight on the screen. (The brightness of LED panels can be reduced from the designed maximum, if required.)

Suitable locations for large display panels are identified by factors such as line of sight, local authority planning requirements (if the installation is to become semi-permanent), vehicular access (trucks carrying the screen, truck-mounted screens, or cranes), cable runs for power and video (accounting for both distance and health and safety requirements), power, suitability of the ground for the location of the screen (if there are no pipes, shallow drains, caves, or tunnels that may not be able to support heavy loads), and overhead obstructions.

### Flat Panel LED Television Display

Possibly the first true all LED flat panel television TV screen was developed, demonstrated and documented by J. P. Mitchell in 1977. The modular, scalable display was initially designed with hundreds of MV50 LEDs and a newly available TTL memory

addressing circuit from National Semiconductor. The ¼ in thin flat panel prototype and the scientific paper were displayed at the 29th ISEF expo sponsored by the Society for Science and the Public in Washington D.C. May 1978. The technical display received awards and recognition. Awards included NASA, General Motors Corporation, and recognition from faculty and area Universities and the IEEE. The monochromatic LED prototype remains operational. An LCD (liquid crystal display) matrix design was also cited in the LED paper as an alternative x-y scan technology and as a future alternate television display method. The replacement of the 70 year+ high-voltage analog system (cathode-ray tube technology) with a digital x-y scan system has been significant. Displacement of the electromagnetic scan systems included the removal of inductive deflection, electron beam and color convergence circuits. The digital x-y scan system has helped the modern television to “collapse” into its current thin form factor.

In 1978, Mitchell also submitted his paper to the Westinghouse Science Talent Search contest, where he received an Honorable Mention.

Mitchell also presented his paper at the 90th Session of The Iowa Academy of Science April 21–22, 1978, at the University of Northern Iowa, Cedar Falls, Iowa.

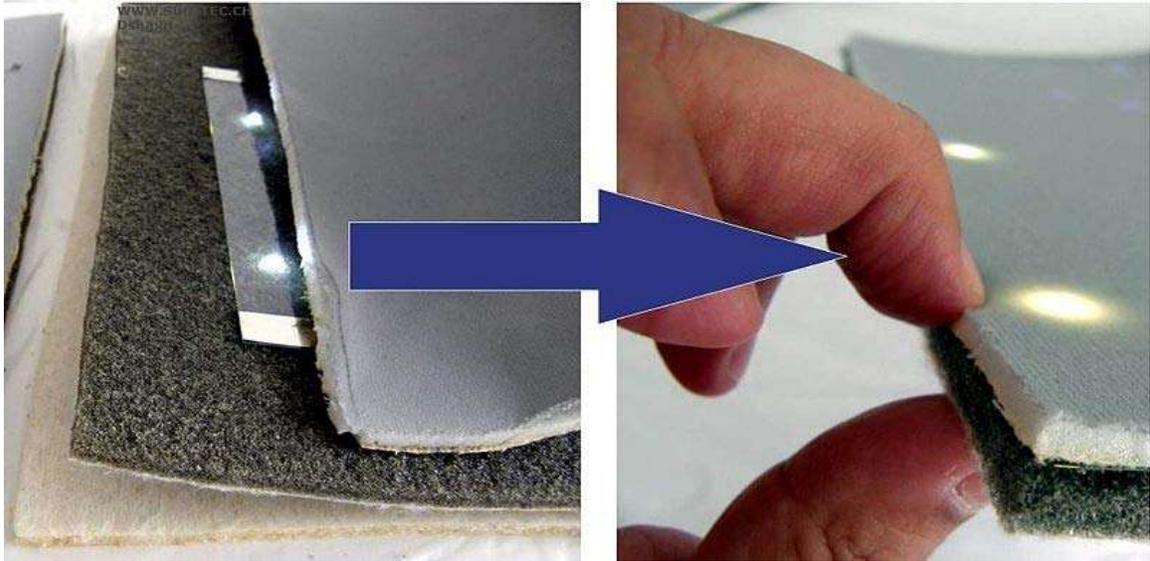
The 1977 model was monochromatic by design. Efficient blue LEDs did not arrive for another decade. Large displays now use high-brightness diodes to generate a wide spectrum color palette. It took three decades and organic electroluminescent materials for Sony to introduce an LED TV: the Sony XEL-1.

## **LED Headliner**

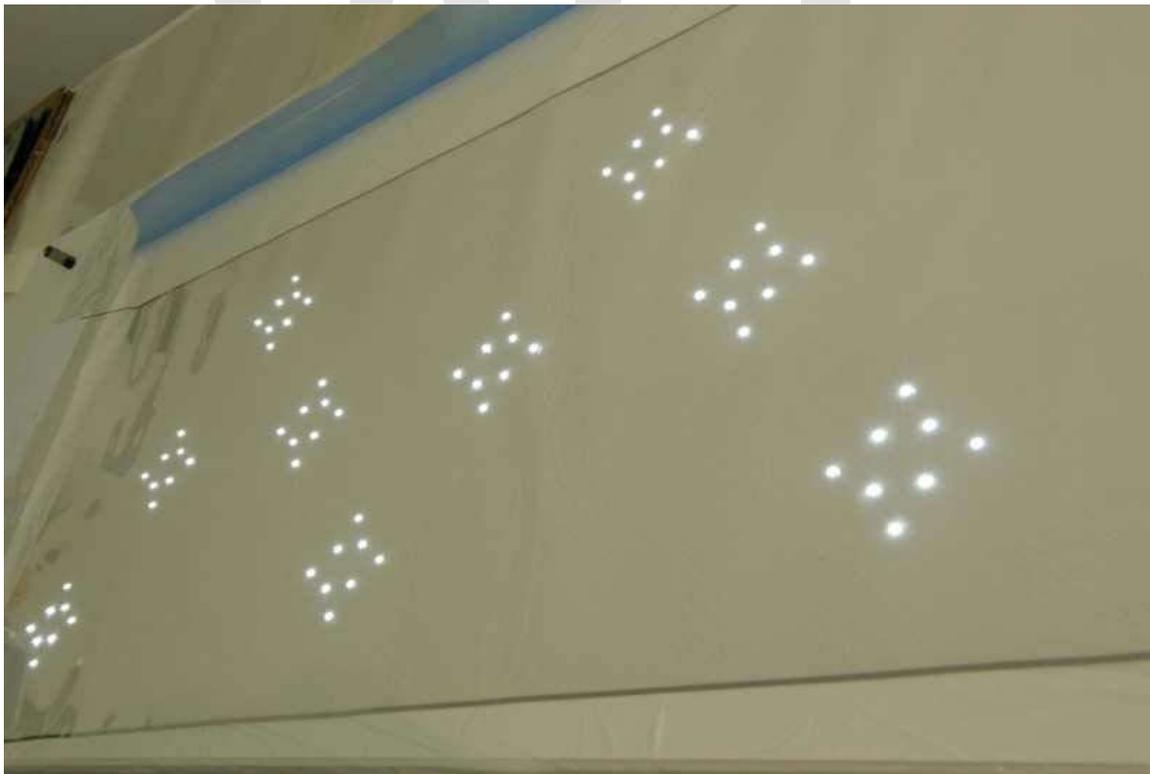
### **Introduction**

The Dictionary of Automotive Terms defines Headliners "as fabric or vinyl upholstery on the interior of the roof of a vehicle". Lighting is a functionality, which is getting more important today. A well known starlight Headliner was produced 2009 for the Rolls-Royce Phantom Sedan. Its starlight consisted of multiple illuminating glass fibers, all connected separately. In other words, the Lighting functionality was not part of the initial composite layers. Automotive companies, have realized the integration of electroluminescent light panels as dome light behind fabrics. Today, surface mount technology (SMT/SMD) may use 0603 or 0402 SMD LEDs (< 0,3 mm thickness) enabling the production of flexible electronic circuits below 1 mm thickness. As headliner interlayers, they are nearly as thin as electroluminescent panels mentioned above, but they may work with simple 12 VDC without need for electroluminescent inverters. The literature, describes precisely the hot vacuum-lamination of these thin LED Interlayers between glass and polymer composites. A LED Headliner describes a

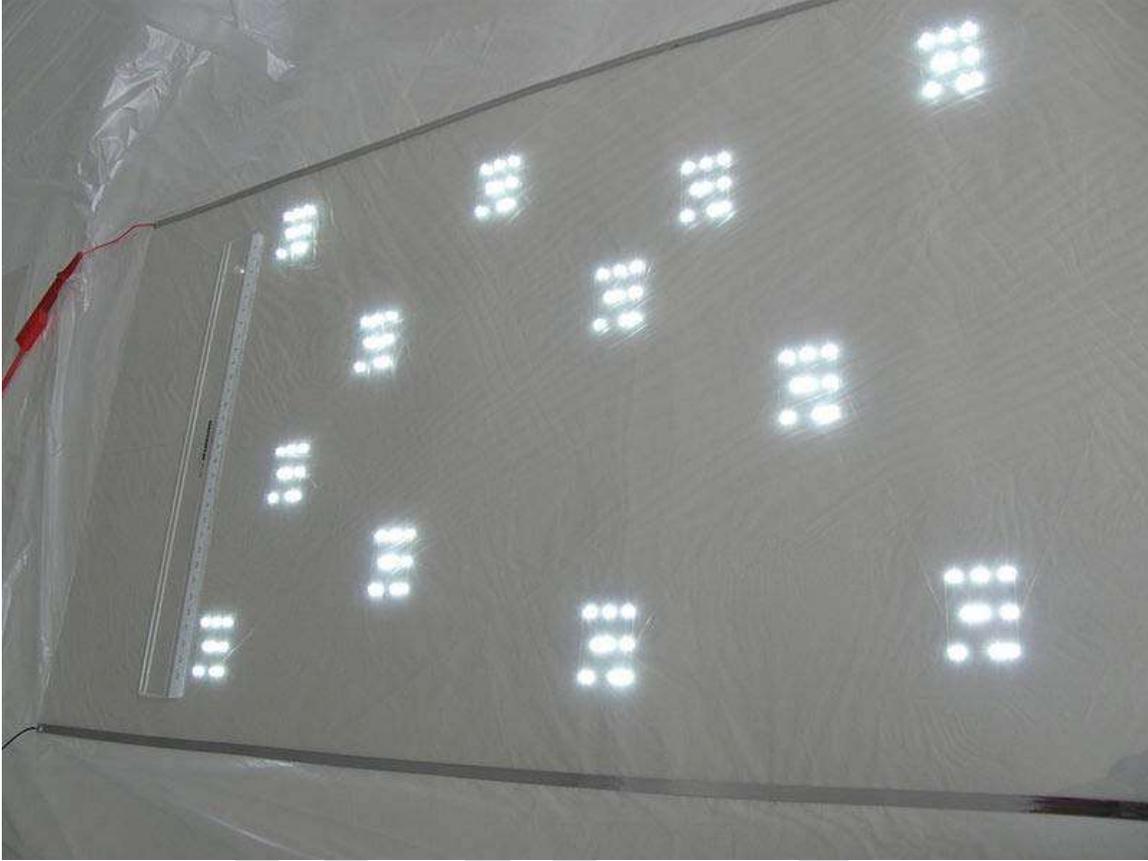
composite Headliner specification containing such an SMD LED Film for lighting purposes.



LED Headliner composite material



Big sized transparent conductive LED Film



Big sized transparent conductive LED Film



Cuttable LED Strips

## Technology

Purchasers of middleclass automobiles also have preferences for vehicle exteriors with hidden or concealed light sources as a distinguishing decorative appearance for the vehicle. Big efforts are done to provide a lighting arrangement for the interior of an automotive vehicle in which the light source, such as LED, is recessed into the interior structure of the vehicle and covered with a layer of fabric. Providing invisible light

sources when not in use, but enough light through the fabric/foam layer when illuminated, is the main goal of any lighting Headliner.

Since 2006, the Stella Consortium, a group of 12 companies and universities to develop stretchable electronics mounted on fabrics. This solution may open an option for electronics mounted in the last layer of headliners.

LED Headliner consist of multiple layer composite material containing light emitting diode (LED) mounted on electro conductive Films. These films based on printed or transparent conductive Polyester will substitute wires and transport electricity into the roof area of the vehicle, where other overhead systems may be powered. Thermoplastics like Polyester and Polypropylene are already in use in Headliner composites for optimised head impact countermeasure (HIC),. LEDFilm embedded in LED Headliner may be perforated to enable a well define placement of these films on or to mounting elements within the composite. Perforation may contain Thermoplastic or Adhesive, in different shapes. Example of a shape would be the one of a connecting plug, which is present on both sides of the LED film. This type of connecting plug will reduce vibrations within the LED Film and the LED headliner, which is supposed to absorb noise within its composite. Topview LED will produce small lighting area, starlike, in the Headliner fabric. Sideview LED, with a beam parallel to the substrate surface, will enable bigger area as well as pseudo-homogenous lighting if used in bigger quantities. The best pseudo-homogenous lighting is achieved by embedding side view LED films into transparent polymeric layers, which will act as lightguide materials.

Special interlayers of electroconductive LED Films based on flexible conductive polymers, on flexible printed circuit board or on transparent conductive metals & oxides sputtered on polymer films which will be laminated between some layers of the composite Headliners.

New automotive composite Headliner base material are disclosed by many different companies,, allows sound waves originating within a vehicle to penetrate deeply into the headliner where a significant portion of their energy is absorbed rather than reflected back into the vehicle. One possible production process disclosed for producing a composite headliner will comprise: Applying adhesive to the top surface and bottom surface of a foam core; placing a fibrous layer to the adhesive coated surface of the foam core; placing a scrim layer next to the lower porous fiber layers; preparing a coverstock sheet comprising a coverstock material layer and an adhesive barrier; and applying heat (100 - 160 °C) and pressure to the layered materials with a hot press.

The pressures and temperatures of the lamination process mentioned above are quite similar to glass laminating temperatures. Consequently not only flexilble printed circuit boards, but also LED embedded films, which are also laminated as inserts at 120 °C to produce transparent LED embedded Glass and dichroic LED Glass are integrated in LED Headliner lamination process.

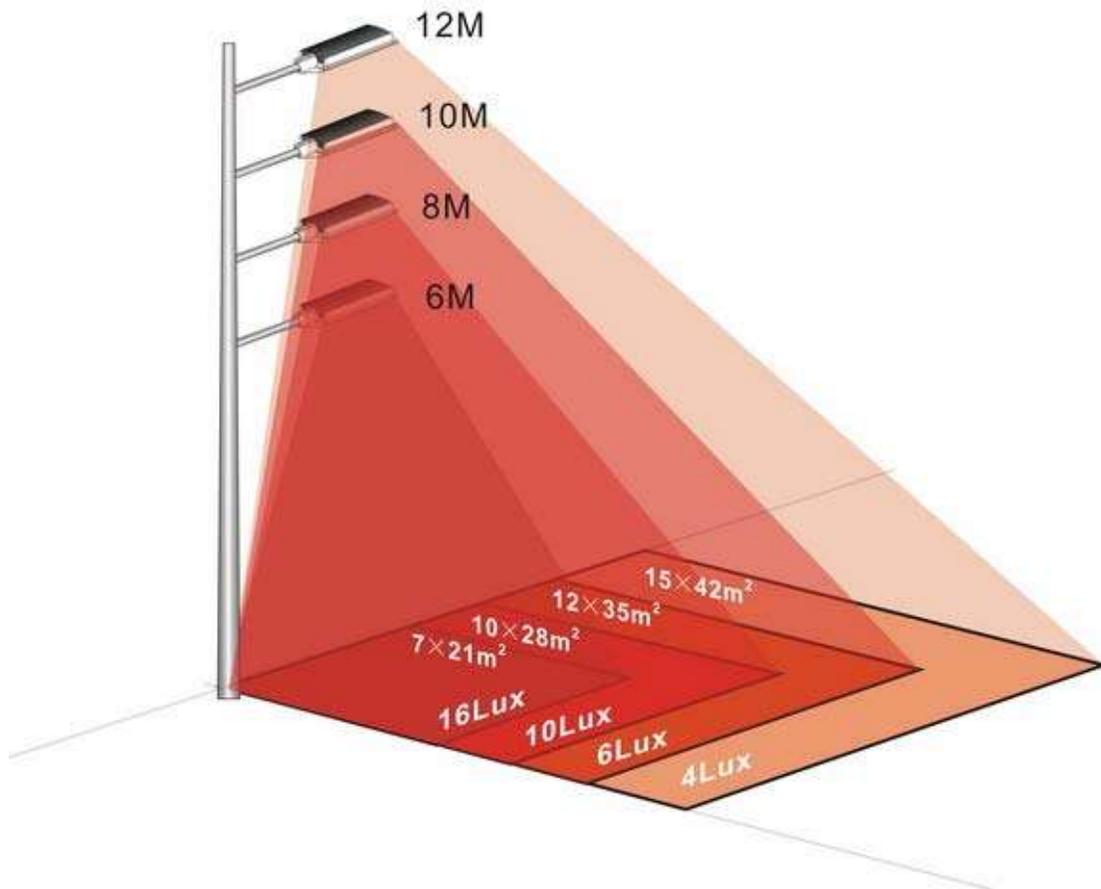
## Chapter- 8

# LED Street Light, LED Anti-Collision Light and LED Art

## LED street light



LED street light



LED street light beam pattern

An **LED street light** (also called **LED road lighting**) is an integrated LED (Light Emitting Diode) light fixture that is used as street lighting. Because they are more energy efficient than other technologies used for street lighting, LED street lights can save on the cost of keeping streets well lit during the night.

## Overview

An LED street light is an integrated light that uses LEDs as its light source. These are considered integrated lights because in most of the cases the luminaire and the fixture are not separate parts (except LEDGine based luminaires). New in manufacturing, the LED light cluster is sealed on a panel and then assembled to the LED panel with a heat sink to become an integrated lighting fixture.

## Installations

LED street lights have been installed or announced for installation in several large cities as well as smaller cities throughout the world. The United States Department of Energy

has available a number of reports on the results of many pilot projects for municipal outdoor lighting.

Some cities that have announced their intention to install LED street lights include:

- Boston
- Worcester
- Cleveland

Cities that have installed at least some LED street lights include:

- Varna, Bulgaria, A2 Highway
- Toronto
- Budapest
- New York City
- Mesa, Arizona
- St. John's, Newfoundland and Labrador
- Halifax, Amherst, Annapolis Royal, Wolfville, Halifax International Airport, Truro, Antigonish, and many other smaller towns in Nova Scotia have installed fixtures manufactured and designed by a company in that province.

## Energy efficiency



The life span of an LED as compared to other light sources

The primary appeal of LED street lighting is energy efficiency compared to incandescent bulbs of the same luminance. Research continues to improve the efficiency of newer models. One such advance can be found in a street light product created by Lighting

Science Group. One model of LED street lights produced by this group is up to 60% more efficient than previous models, lasts for 12 years and allows for cost recovery through energy savings in only three years.

An LED street light based on a 901 milliwatt output LED can normally produce the same amount of (or higher) luminance as a traditional light, but requires only half of the power consumption.

Many cities misrepresent the efficiency and economy of LED lighting. Replacement LED lamps usually generate less light than the ones they replace. LED lamp installations require more lamp posts closer together to maintain midpoint illumination. LED lamps generate less UV light, meaning CCTV's performance is degraded. In foggy areas, LED light spectrum is inferior. Heat, Cold, Moisture, salt and UV shorten LED lifespans, and usually not up to suppliers claims. After National subsidy schemes, LED lighting can be cost effective, and without the RF issues of Sulfur lamps.

## **Design and style**

Different designs have been created that incorporate various types of LEDs into a light fixture. The trend in the world is to use high power 1 watt LEDs, but some companies use low power LEDs in their products, including several low power LEDs packed together to perform the same purpose as a single high power LED. The shape of the LED street light depends on several factors, including: LED configuration; the heat sink used with the LEDs; or, aesthetic design preference.

Heat sinks for LED street lights are similar in design to heat sinks used to cool other electronics such as computers. Heat sinks tend to have as many grooves as possible to facilitate the flow of hot air away from the LEDs. The area of heat exchange will directly effect the lifespan of the LED street light.

The lifespan of LED street lights is determined by its light output compared to its original design specification. Once its brightness decreases by 70%, an LED street light is considered to be at the end of its life.

Most LED street lights have a lens on the LED panel, that is designed to cast its light in a rectangular pattern, an advantage compared to traditional street lights, which typically have a reflector on the back side of a high-pressure sodium lamp. In this case much of the luminance of the light is lost and produces light pollution in the air and surrounding environment. Such street lights also can cause glare for drivers and pedestrians.

A drawback of LED focus panels is that most light is directed to the road, and less light to the footpaths and other areas.

# LED anti-collision light

The **LED anti-collision light** refers primarily to a flashing LED light assembly installed on the upper and lower fuselage of aircraft. Historically, this item employed rotating incandescent bulbs or flashing xenon flashtubes in order to meet the Federal Aviation Administration requirement for 400 candela output.

## Development

Talon Aerospace in Helena, Alabama began a program to develop and certify an LED equivalent in 2004. Due to relatively low light output and excessive heat, a reliable substitute was not produced and certified until 2008.

Since that time, numerous other companies have produced LED Anti-Collision lights. Units produced by Goodrich Hella, Whelen, and other companies meet the requirements of TSO C96.

## Other applications

Talon Aerospace has gone on to produce LED replacements for many other aircraft lighting assemblies, saving the airlines huge sums due to the lighter weight and higher reliability of LED equipped assemblies.

## LED art

**LED Art** is form of light art constructed from light-emitting diodes. Many artists that use LEDs are guerilla artists, incorporating LEDs to produce temporary pieces in public places. LEDs are very inexpensive to purchase and have become a new way to make street art. LEDs are, among others, used in installation art, sculptural pieces and interactive artworks.



LED Based Sculpture in which LEDs are integrated within steel sculpture

## **Infamous LED Art**

In early 2007, there was a bomb scare in Boston, Massachusetts in the United States caused by a guerilla marketing campaign. An advertising firm working for Turner Broadcasting System Inc. to promote Aqua Teen Hunger Force, one of the networks television shows, hired two artists to produce art for the ad campaign. The artists used a character from the television show (a cartoon) referred to as a Mooninite as their imagery. The Mooninite was turned into an LED sign and was stuck to many locations in 10 cities. However, Boston was the only city that reacted by shutting down bridges and bringing in bomb squads to remove the LEDs. The majority of the light boards were removed and the artists were arrested. The artists were not charged.

## Artists incorporating LEDs

- Jenny Holzer - One of the most well known artists who incorporates LEDs into her work. She uses familiar statements and reinterprets them to alter their meanings.
- Cell Phone Disco is an installation that uses the electromagnetic spectrum emitted by the viewer's cell phone and creates a visual interpretation. The LEDs are attached to large grids and when a phone is activated in a section of the room, the lights turn on. They make the invisible environments around us visible.
- Kevin McCormick – an artist who incorporated LEDs into large spheres emulating disco balls.
- GreenPix – Zero Energy Media Wall – created as an environmentally friendly art space. It acts as a low resolution screen for artists to show their work.
- Liu Dao - an art collective in China that uses actors and filmmakers to make animated LED portraits. The group also combines traditional Chinese arts like papercutting with LEDs to highlight China's journey from tradition and modernity, and is directed by Thomas Charvériat to find originality through international collaboration.

## LED throwies



LED throwies

A **LED throwie** is a small LED attached to a coin battery and a rare earth magnet (usually with conductive epoxy or electrical tape), used for the purpose of creating non-destructive graffiti and light displays. Artists use them by throwing individual LEDs onto metallic objects, like public sculpture or road infrastructure. By throwing LEDs onto an object, the object itself acts as a canvas. LED Throwies were devised by James Powderly and Evan Roth working together at the Graffiti Research Lab during a fellowship at Eyebeam OpenLab in 2006.

## Chapter- 9

# LED Lamp

An **LED lamp** is a solid-state lamp that uses light-emitting diodes (LEDs) as the source of light. The term *LED lightbulb* is also colloquially used. *LED lamp* may in general refer to conventional semiconductor light-emitting diodes, to organic LEDs (OLED), or polymer light-emitting diodes (PLED) devices, although OLED and PLED technologies are not commercially available in 2010.

Since the light output of individual light-emitting diodes is small compared to incandescent and compact fluorescent lamps, multiple diodes are often used together. In recent years, as diode technology has improved, high power light-emitting diodes with higher lumen output are making it possible to replace other lamps with LED lamps. One high power LED chip used in some commercial LED lights can emit 7,527 lumens while using only 100 watts. LED lamps can be made interchangeable with other types of lamps.

Diodes use direct current (DC) electrical power, so LED lamps must also include internal circuits to operate from standard AC voltage. LEDs are damaged by being run at higher temperatures, so LED lamps typically include heat management elements such as heat sinks and cooling fins. LED lamps offer long service life and high energy efficiency, but initial costs are higher than those of fluorescent lamps.



An assortment of LED lightbulbs that are commercially available as of 2010 as replacements for screw-in bulbs, including floodlight fixtures (left), reading light (center), household lamps (center right and bottom), and low-power accent light (right) applications.

## Technology overview



Dropped ceiling with LED lamps

General purpose lighting needs white light. LEDs emit light in a very small band of wavelengths, emitting strongly colored light. The color is characteristic of the energy bandgap of the semiconductor material used to make the LED. To emit white light from LEDs requires either mixing light from red, green, and blue LEDs, or using a phosphor to convert some of the light to other colors.

The first method (RGB-LEDs) uses multiple LED chips each emitting a different wavelength in close proximity, to form the broad white light spectrum. The advantage of this method is that the intensity of each LED can be adjusted to "tune" the character of the light emitted. The major disadvantage is high production cost.

The second method, phosphor converted LEDs (pcLEDs) uses one short wavelength LED (usually blue or ultraviolet) in combination with a phosphor, which absorbs a portion of the blue light and emits a broader spectrum of white light. (The mechanism is similar to the way a fluorescent lamp emits white light from a UV-illuminated phosphor.) The major advantage here is the low production cost, and high CRI (color rendering index), while the disadvantage is the inability to dynamically change the character of the light and the fact that phosphor conversion reduces the efficiency of the device. The low cost and adequate performance makes it the most widely used technology for general lighting today.

A single LED is a low-voltage solid state device and cannot be directly operated on standard AC current without some circuitry to control the voltage applied and the current flow through the lamp. A series diode and resistor could be used to control the voltage polarity and to limit the current, but this is inefficient since most of the applied voltage would be dropped as wasted heat in the resistor. A single series string of LEDs would minimize dropped-voltage losses, but one LED failure could extinguish the whole string. Paralleled strings increase reliability by providing redundancy. In practice, three strings or more are usually used. To be useful for illumination for home or work spaces, a number of LEDs must be placed close together in a lamp to combine their illuminating effects. This is because individual LEDs emit only a fraction of the light of traditional light sources. When using the color-mixing method, a uniform color distribution can be difficult to achieve, while the arrangement of white LEDs is not critical for color balance. Further, degradation of different LEDs at various times in a color-mixed lamp can lead to an uneven color output. LED lamps usually consist of clusters of LEDs in a housing with both driver electronics, a heat sink and optics.

## **Application**

LED lamps are used for both general and special-purpose lighting. Where colored light is needed, LEDs come in multiple colors, which are emitted with no need for filters. This improves the energy efficiency over a white light source that generates all colors of light then discards some of the visible energy in a filter.

Compared to fluorescent bulbs, advantages claimed for LED light bulbs are that they contain no mercury (unlike a Compact fluorescent lamp or CFL), that they turn on instantly, and that lifetime is unaffected by cycling on and off, so that they are well suited for light fixtures where bulbs are often turned on and off. LED light bulbs are also less apt to break.

White-light light-emitting diode lamps have the traits of long life expectancy and relatively low energy use. The LED sources are compact, which gives flexibility in

designing lighting fixtures and good control over the distribution of light with small reflectors or lenses. Because of the small size of LEDs, control of the spatial distribution of illumination is extremely flexible, and the light output and spatial distribution of a LED array can be controlled with no efficiency loss.

LED lamps have no glass tubes to break, and their internal parts are rigidly supported, making them resistant to vibration and impact. With proper driver electronics design, an LED lamp can be made dimmable over a wide range; there is no minimum current needed to sustain lamp operation.

LEDs using the color-mixing principle can emit a wide range of colors by changing the proportions of light generated in each primary color. This allows full color mixing in lamps with LEDs of different colors. In contrast to other lighting technologies, LED emission tends to be directional (or at least lambertian). This can be either an advantage or a disadvantage, depending on the requirements of the application. For applications where non-directional light is required, either a diffuser is used, or multiple individual LED emitters are used to cover different directions.



## Household LED lamps



LED Lamp with E27 Edison screw, interchangeable with incandescent lamps

### Lamp sizes and bases

LED lamps intended to be interchangeable with incandescent lamps are made in standard light bulb shapes, such as an Edison screw base, an MR16 shape with a bi-pin base, or a GU5.3 (Bipin cap) or GU10 (bayonet socket). LED lamps are made in low voltage (typically 12 V halogen-like) varieties, and as replacements for regular AC (e.g. 120 or 240 V AC) lighting. These lamps typically include circuitry to rectify the AC power and to convert the voltage to a level usable by the internal LED elements.

## **LED light bulbs**

Many LED lamps have become available as replacements for screw-in incandescent or compact fluorescent light bulbs, ranging from low-power 5–40 watt incandescent bulbs, through conventional replacement bulbs for 60 watt incandescent bulbs (typically requiring about 7 watts of power), and as of 2010 a few lamps were available to replace higher wattage bulbs, e.g., a 13-watt LED bulb which is about as bright as a 100W incandescent. (A standard general purpose incandescent bulb emits light at an efficiency of about 14 to 17 lumens/W depending on its size and voltage. According to the European Union standard, an energy-efficient bulb that claims to be the equivalent of a 60W tungsten bulb must have a minimum light output of 806 lumens.)

Most LED bulbs are not designed to be dimmed (although some models are designed to work with dimmers), and are usually directional. The lamps have declined in cost to between US\$30 to \$50 each as of 2010. These bulbs are more power-efficient than compact fluorescent bulbs and offer lifespans of 30,000 or more hours, reduced operated at a higher temperature than specified. Incandescent bulbs have a typical life of 1,000 hours, compact fluorescents about 8,000 hours. A LED light bulb can be expected to last 25–30 years under normal use. The bulbs maintain output light intensity very well over their life-times. Energy Star specifications require the bulbs to typically drop less than 10% after 6000 or more hours of operation, and in the worst case not more than 15%. They are also mercury free, unlike fluorescent lamps. LED lamps are available with a variety of color properties. The higher purchase cost than other types may be more than offset by savings in energy and maintenance.

Several companies offer LED lamps for general lighting purposes. The C. Crane Company introduced a 7-watt replacement for a 60-watt bulb, the "Geobulb", with an efficiency of 59 lumens/W. The company also offers wedge-base lamps for replacement in low voltage fixtures. In the Netherlands, a company called Lemnis Lighting offers a dimmable LED lamp called Pharox. The company Eternleds Inc. offers a bulb called HydraLux-4 which uses liquid cooling of the LED chips. Philips makes a number of LED lamps which are commercially available in the United States and come with a six year warranty, and a number of smaller producers can be found that sell LED lights that are screw-in replacements for conventional bulbs, for example, the General LED Bulb from Arani



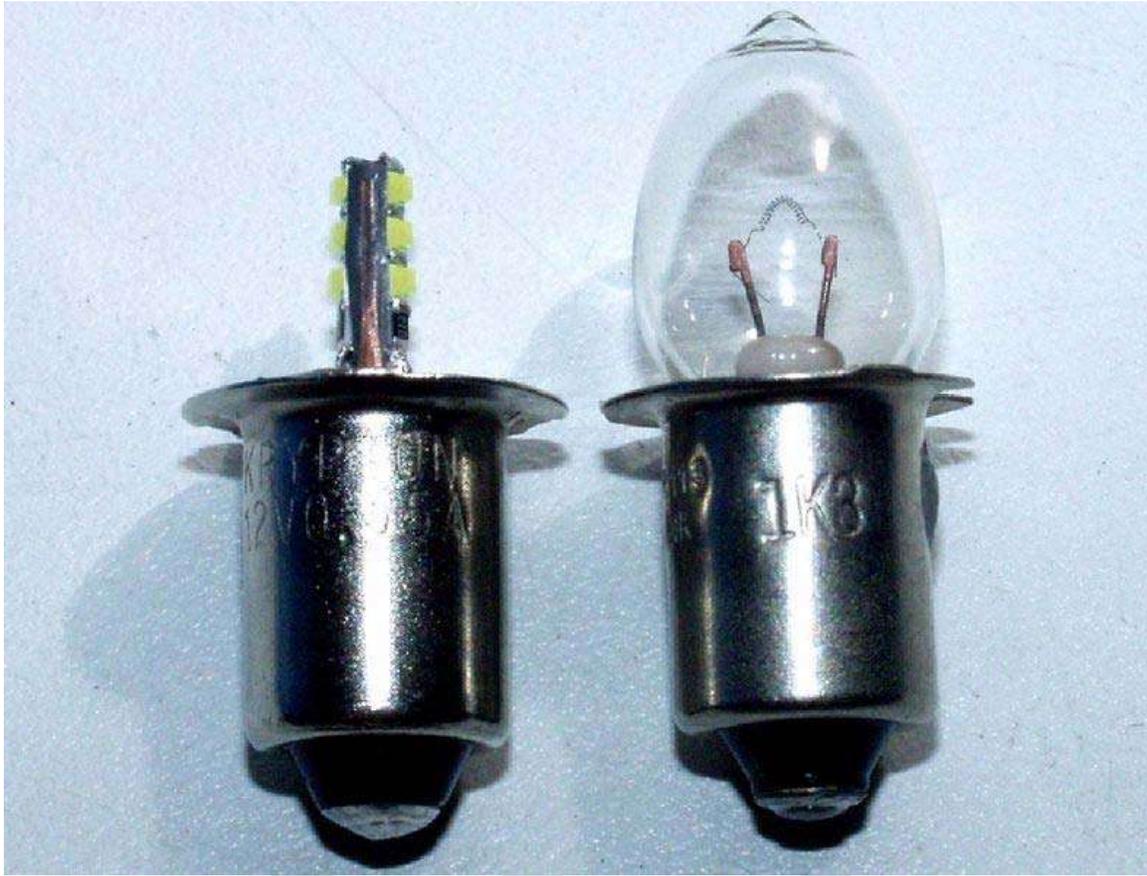
LED tubes in various length

The technology is improving rapidly, and new energy-efficient consumer LED lamps have been announced from three of the lighting industry's largest producers, Osram Sylvania, Philips, and General Electric, so these listings should be taken as not necessarily representative of what is currently available.



High power LED lamp with GU5.3 fitting and aluminum heat sink, intended to replace halogen reflector lamps.

## Specialty uses



LED Flashlight replacement bulb (left), with tungsten equivalent (right)

White LED lamps have achieved market dominance in applications where high efficiency is important at low power levels. Some of these applications include flashlights, solar-powered garden or walkway lights, and bicycle lights. Monochromatic (colored) LED lamps are now commercially used for traffic signal lamps, where the ability to emit bright monochromatic light is a desired feature, and in strings of holiday lights.

LED lights have also become very popular in gardening and agriculture by 2010. First used by NASA to grow plants in space, LEDs came into use for home and commercial applications for indoor horticulture (aka grow lights). The wavelengths of light emitted from LED lamps have been specifically tailored to supply light in the spectral range needed for chlorophyll absorption in plants, promoting growth while reducing wastage of energy by emitting minimal light at wavelengths that plants do not require. The red and blue wavelengths of the visible light spectrum are used for photosynthesis, so these are the colors almost always used in LED grow light panels. These lights are attractive to indoor growers since they use less power than other types for the same light intensity, need no ballasts, and emit much less heat than HID lamps. The reduction in heat allows

time between watering cycles to be extended because the plants transpire less under LED grow lights. Due to this change in growth conditions, users of LEDs are advised not to over-water the plants.

### **Pioneering mass use**

In 2008 Sentry Equipment Corporation in Oconomowoc, Wisconsin, USA, was able to light its new factory interior and exterior almost solely with LEDs. Initial cost was three times more than a traditional mix of incandescent and fluorescent lamps, but the extra cost will be repaid within two years via electricity savings, and the lamps should not need replacing for 20 years. In 2009, the Manapakkam, Chennai office of the Indian IT company iGate spent 3,700,000 Indian rupees (US\$80,000) to light 57,000 sq ft (5,300 m<sup>2</sup>) of office space with LEDs. The firm expects the new lighting to pay for itself fully within 5 years.



LEDs on a big Christmas tree

In 2009 the exceptionally big Christmas tree standing in front of the Turku Cathedral in Finland was hung with 710 LED bulbs, each using 2 watts. It has been calculated that these LED lamps will pay for themselves in three and a half years, even though the lights run for only 48 days per year.

By 2010 mass installations of LED lighting for commercial and public uses were becoming common.

In 2010, on the reconstructed section of Bulevar Kralja Aleksandra (King Aleksandar Boulevard) in Belgrade, Serbia, LED lamps were introduced for new street lighting.

LED lamps have also been used for a number of demonstration projects for outdoor lighting and street lights. The United States Department of Energy has available several reports on the results of many pilot projects for municipal outdoor lighting. Many additional streetlight and municipal outdoor lighting projects have been announced.

## **Comparison to other lighting technologies**

- Incandescent lamps (light bulbs) generate light by passing electric current through a resistive filament, thereby heating the filament to a very high temperature so that it glows and emits visible light. A broad range of visible frequencies are naturally produced, yielding a "warm" yellow or white color quality. Incandescent light is highly inefficient, as about 98% of the energy input is emitted as heat. A 100 W light bulb emits about 1,700 lumens, about 17 lumens/W. Incandescent lamps are relatively inexpensive to make. The typical lifespan of an AC incandescent lamp is around 1,000 hours. They work well with dimmers. Most older light fixtures are designed for the size and shape of these traditional bulbs.
- Fluorescent lamps (light bulbs) work by passing electricity through mercury vapor, which in turn emits ultraviolet light. The ultraviolet light is then absorbed by a phosphor coating inside the lamp, causing it to glow, or fluoresce. While the heat generated by a fluorescent lamp is much less than its incandescent counterpart, energy is still lost in generating the ultraviolet light and converting this light into visible light. If the lamp breaks, exposure to mercury can occur. Linear fluorescent lamps are typically five to six times the cost of equivalent incandescent lamps but have life spans around 10,000 and 20,000 hours. Lifetime varies from 1,200 hours to 20,000 hours for compact fluorescent lamps. Most fluorescent lamps are not compatible with dimmers. Those with "iron" ballasts flicker at 100 or 120 Hz, and are less efficient. The latest T8-sized triphosphate fluorescent lamps made by Osram, Philips, Crompton and others have a life expectancy greater than 50,000 hours, if coupled with a warm-start electronic ballast. The life expectancy depends on the number of on/off cycles, and is lower if the light is cycled often. The efficiency of these new lamps approaches 100 lumens/W. The efficiency of fluorescent tubes with modern electronic ballasts and compact fluorescents commonly ranges from 50 to 67 lumens/W. Most

compact fluorescents rated at 13 W or more with integral electronic ballasts achieve about 60 lumens/W, comparable to the LED bulb.

## Research and development

### US Department of Energy

In May 2008, the U. S. Department of Energy (DOE) announced details of the Bright Tomorrow Lighting Prize competition. The L Prize is the first government-sponsored technology competition designed to spur lighting producers to develop high quality, high efficiency solid-state lighting products to replace the common light bulb. The competition will award cash prizes, and may also lead to opportunities for federal purchasing agreements, utility programs, and other incentives for winning products.

The Energy Independence and Security Act (EISA) of 2007 authorizes DOE to establish the Bright Tomorrow Lighting Prize competition. The legislation challenges industry to develop replacement technologies for the most commonly used and inefficient products, 60 W incandescent lamps and PAR 38 halogen lamps. The L Prize specifies technical requirements for these two competition categories. Lighting products meeting the competition requirements would use just 17% of the energy used by most incandescent lamps in use today. A future L Prize program announcement will call for developing a new "21st Century Lamp," as authorized in the legislation.

The EISA legislation establishes basic requirements and prize amounts for each category. The legislation authorizes up to \$20 million in cash prizes. On September 24, 2009 the DOE announced that Philips was the first to submit lamps in the category to replace the standard 60 W A-19 "Swan/Edison" light bulb.

### National Institute of Standards and Technology

In June 2008, scientists at the National Institute of Standards and Technology (NIST) announced the first two standards for solid-state lighting in the United States. These standards detail the color specifications of LED lamps and LED light fixtures, and the test methods that producers should use when testing these solid-state lighting products for total light output, energy use, and chromaticity or color quality.

The Illuminating Engineering Society of North America (IESNA) published a documentary **standard LM-79**, which describes the methods for testing solid-state lighting products for their light output (lumens), energy efficiency (lumens per watt) and chromaticity.

The solid-state lights being studied are intended for general illumination, but white lights used today vary greatly in chromaticity, or specific shade of white. The American National Standards Institute (ANSI) published the **standard C78.377-2008**, which specifies the recommended color ranges for solid-state lighting products using cool to warm white LEDs with various correlated color temperatures.

DOE launched the Energy Star program for solid-state lighting products in 2008. NIST scientists assisted DOE by providing research, technical details and comments for the Energy Star specifications. Energy Star certification assures consumers that products save energy and are high quality and also serves as an incentive for producers to provide energy-saving products for consumers.

## **Other venues**

Philips Lighting has ceased research on compact fluorescents, and is devoting the bulk of its research and development budget, 5 percent of the company's global lighting revenue, to solid-state lighting.

In January 2009, it was reported that researchers at Cambridge University had developed an LED bulb that costs £2 (about \$3 U.S.), is 12 times as energy efficient as a tungsten bulb, and lasts for 100,000 hours.

## **Remaining problems**

The production process of white LEDs is complex and many aspects have room for improvement. This means that the production price of volume products is still relatively high compared to traditional light sources. The process used to deposit the active semiconductor layers of the LED is constantly improved to increase yields and production throughput. The phosphors, which are needed for their ability to emit a broader wavelength spectrum of light, problems tuning the absorption and emission, and inflexibility of form have been issues.

More apparent to the end user, however, is the color rendering index (CRI) of low quality LEDs. CRI measures a light source's ability to render colors, with 100 being the maximum. LEDs with CRI below 75 are not recommended use in indoor lighting. Better CRI LEDs are more expensive, and more research and development is needed to reduce costs.

Variations of CCT (color correlated temperature) at different viewing angles present another obstacle against widespread use of white LED. It has been shown that CCT variations can exceed 500 K. This is clearly noticeable by human observers, who normally can distinguish CCT differences of 50 to 100 K in the range from 2000 K to 6000 K, which is the range of CCT variations of daylight.

LEDs also have limited temperature tolerance and falling efficiency as component temperature rises. This limits the total LED power that can practically be fitted into lamps that physically replace existing filament and compact fluorescent types. Much research and development is invested in improving thermal traits. Thermal management of high-power LEDs is a significant factor in design of solid state lighting equipment.

The long life of solid-state lighting products, expected to be about 50 times the most common incandescent bulbs, poses a problem for bulb makers, whose current customers buy frequent replacements.

Some critics suggest that producers may over-represent the efficiency and traits of their products to sell into a rapidly growing marketplace, suggesting that consumers still need to be wary of claims made about products in this market.

WWT