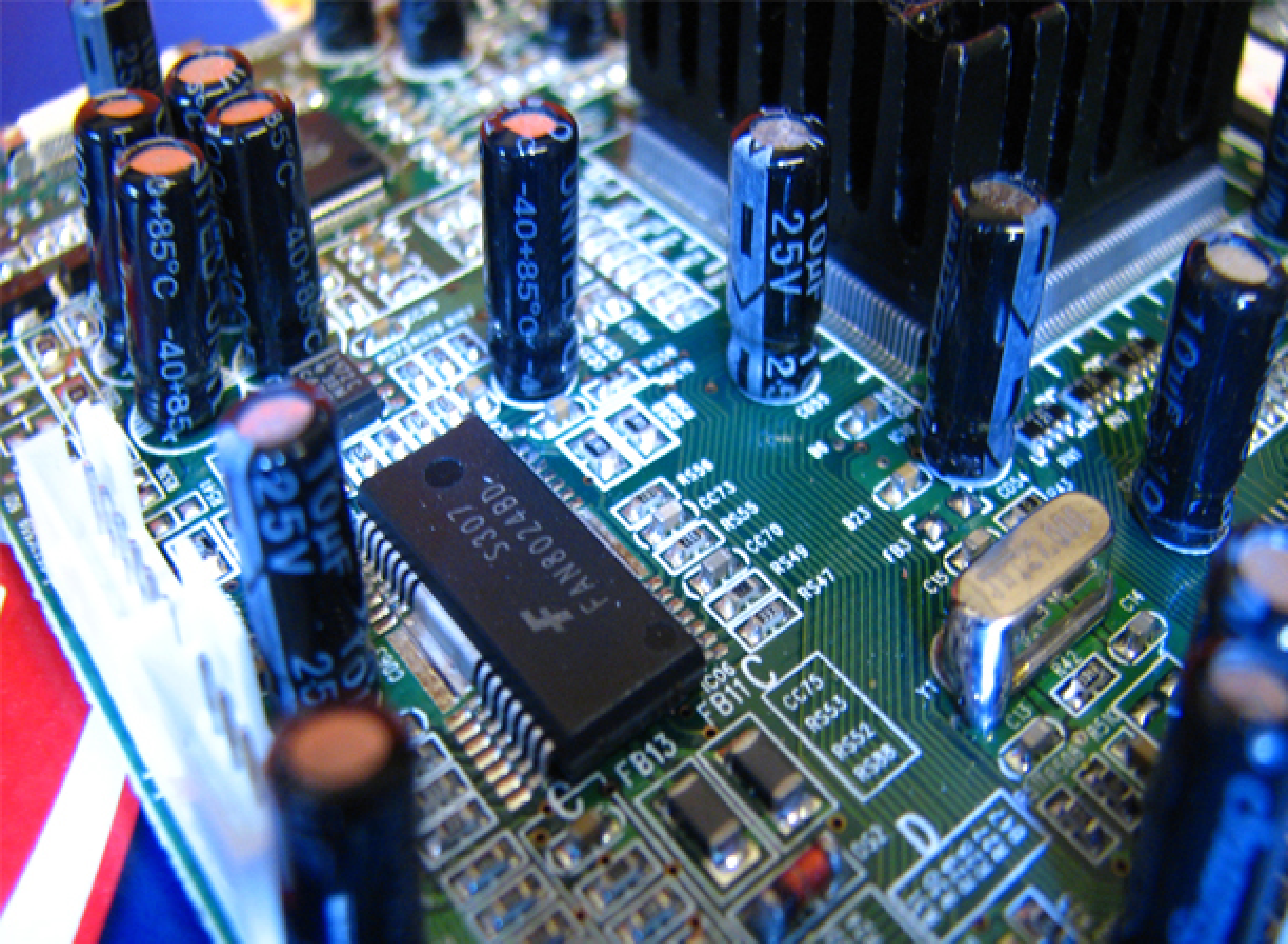

Macroelectronics Technology

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Introduction

For over half of century, the technology of microelectronics has been advancing by miniaturization, leading to significant increases in computing power and continuous decreases in manufacturing cost. In parallel, remarkable progress on enlarging system scale in recent years gives rise to a nascent field known as macroelectronics, in which microelectronic devices are distributed yet integrated over large area substrates with sizes much bigger than semiconductor wafers.

Currently, the macroelectronics industry is dramatically growing in the similar way as the microelectronics was in early ’90s. The most visible example of macroelectronics at present is flat-panel displays, which have been rapidly replacing cathode-ray tubes as the monitors of choice for computers and televisions since 2000. The flat-panel displays have enabled applications unimaginable for cathode-ray tubes. For example, the Dolphins Stadium in Miami will soon have the world’s largest high definition video display, about 15 m high and 42 m wide, comprising more than 4.6 million light-emitting diodes, showing image of more than 1.5 million pixels.

While the commercial success of flat-panel display opens an era of large area electronics, other emerging applications, such as rollable display, printable thin film solar cell and electronic skin, demonstrate further desirable attributes for macroelectronic systems, including flexibility, portability and low-cost. To realize these attributes, a growing trend is to fabricate macroelectronic products directly on flexible substrates, such as polymers. The flat-panel displays currently available in market are fabricated on glass substrates and are fragile. A case in recent news is the cracking of the screens of the iPod nano, a music player that Apple Computer expects to be its best-selling portable device. By contrast, displays made on thin polymer substrates are rugged. Flexible displays of large areas will be lightweight and can be rolled up – they will be portable. For example, in Sept. 2005, Philips Polymer Vision has revealed the world's first prototype of a rollable electronic reader, which can unfold to a 5-inch display and roll back into a pocket-size (100×60×20 mm) device. Furthermore, such thin-film devices on flexible polymer substrates can lend themselves to low-cost fabrication process (i.e., roll-to-roll printing), resulting in lightweight, rugged and flexible macroelectronic products.

Chapter-1

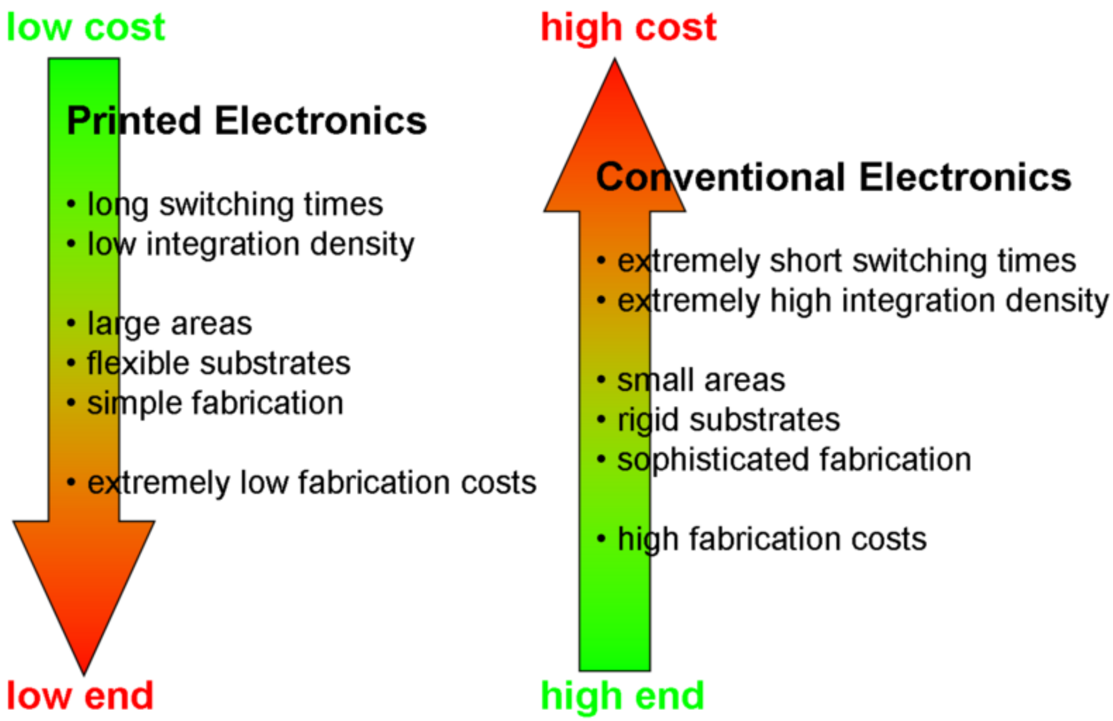
Printed Electronics

Printed electronics is a set of printing methods used to create electrical devices. Paper's rough surface and high water absorption rate has focused attention on materials such as plastic, ceramics and silicon. Printing typically uses common printing equipment, such as screen printing, flexography, gravure, offset lithography and inkjet. Electrically functional electronic or optical inks are deposited on the substrate, creating active or passive devices, such as thin film transistors or resistors. Printed electronics is expected to facilitate widespread, very low-cost, low-performance electronics for applications such as flexible displays, smart labels, decorative and animated posters, and active clothing that do not require high performance.

The term *printed electronics* is related to organic electronics or plastic electronics, in which one or more inks are composed of carbon-based compounds. These other terms refer to the ink material, which can be deposited by solution-based, vacuum-based or some other method. Printed electronics, in contrast, specifies the process, and can utilize any solution-based material, including organic semiconductors, inorganic semiconductors, metallic conductors, nanoparticles, nanotubes, etc.

For the preparation of printed electronics nearly all industrial printing methods are employed. Similar to conventional printing, printed electronics applies ink layers one atop another. so that the coherent development of printing methods and ink materials are the field's essential tasks.

The most important benefit of printing is low-cost volume fabrication. The lower cost enables use in more applications. An example is RFID-systems, which enable contactless identification in trade and transport. In some domains, such as light-emitting diodes printing does not impact performance. Printing on flexible substrates allows electronics to be placed on curved surfaces, for example, putting solar cells on vehicle roofs. More typically, conventional semiconductors justify their much higher costs by providing much higher performance.



Printed and conventional electronics as complementary technologies.

Resolution, registration, thickness, holes, materials

The maximum required resolution of structures in conventional printing is determined by the human eye. Feature sizes smaller than approximately 20 µm cannot be distinguished by the human eye and consequently exceed the capabilities of conventional printing processes. In contrast, higher resolution and smaller structures are necessary in electronics printing, because they directly affect circuit density and functionality (especially transistors). A similar requirement holds for the precision with which layers are printed on top of each other (layer to layer registration).

Control of thickness, holes, and material compatibility (wetting, adhesion, solvation) are essential, but matter in conventional printing only if the eye can detect them. Conversely, the visual impression is irrelevant.

Printing Technologies

The attraction of printing technology for the fabrication of electronics mainly results from the possibility to prepare stacks of micro-structured layers (and thereby thin-film devices) in a much more simple and cost-effective way compared to conventional electronics. Beside this, also the possibility to implement new or improved functionalities (e.g. mechanical flexibility) plays a role. The selection of used printing methods is determined by requirements concerning printed layers, by properties of printed materials as well as economic and technical considerations in terms of printed products.

Printing technologies divide between sheet-based and roll-to-roll-based approaches. Sheet-based techniques, such as inkjet and screen printing are best for low-volume, high-precision work. Gravure, offset and flexographic printing are more common for high-volume production, such as solar cells, reaching 10.000 square meters per hour (m^2/h). While offset and flexographic printing are mainly used for inorganic and organic conductors (the latter also for dielectrics), gravure printing is especially suitable for quality-sensitive layers like organic semiconductors and semiconductor/dielectric-interfaces in transistors, due to high layer quality. In connection with high resolution, is also suitable for inorganic and organic conductors. Organic field-effect transistors and integrated circuits can be prepared completely by means of mass-printing methods.

Inkjets are flexible and versatile, and can be set up with relatively low effort. Inkjets are probably the most commonly used method. However, inkjets offer lower througput of around 100 m^2/h and lower resolution (ca. 50 µm). It is well suited for low-viscosity, soluble materials like organic semiconductors. With high-viscosity materials, like organic dielectrics, and dispersed particles, like inorganic metal inks, difficulties due to nozzle clogging occur. Because ink is deposited via droplets, thickness and dispersion homogeneity is reduced. Simultaneously using many nozzles and pre-structuring the substrate allows improvements in productivity and resolution, respectively. However, in the latter case non-printing methods must be employed for the actual patterning step. Inkjet printing is preferable for organic semiconductors in organic field-effect transistors (OFETs) and organic light-emitting diodes (OLEDs), but also OFETs completely prepared by this method have been demonstrated. Frontplanes and backplanes of OLED-displays, integrated circuits, organic photovoltaic cells (OPVCs) and other devices can be prepared with inkjets.

Screen printing is appropriate for fabricating electrics and electronics on industrial scales due to its ability to produce thick layers from paste-like materials. This method can produce conducting lines from inorganic materials (e.g. for circuit boards and antennas), but also insulating and passivating layers, whereby layer thickness is more important than high resolution. Its 50 m^2/h throughput and 100 µm resolution are similar to inkjets. This versatile and comparatively simple method is used mainly for conductive and dielectric layers, but also organic semiconductors, e.g. for OPVCs, and even complete OFETs can be printed.

Other methods with similarities to printing, among them micro-contact printing and nano-imprint lithography are of interest. Here, µm- and nm-sized layers, respectively, are prepared by methods similar to stamping with soft and hard forms, respectively. Often the actual structures are prepared subtractively, e.g. by deposition of etch masks or by lift-off processes. For example electrodes for OFETs can be prepared Sporadically pad printing is used in a similar manner. Occasionally so-called transfer methods, where solid layers are transferred from a carrier to the substrate, are considered printed electronics. Electrophotography is currently not used in printed electronics.

Materials

Both organic and inorganic materials are used for printed electronics. Ink materials must be available in liquid form, for solution, dispersion or suspension. They must function as conductors, semiconductors, dielectrics, or insulators. Material costs must be fit the application.

Electronic functionality and printability can interfere with each other, mandating careful optimization. For example, a higher molecular weight in polymers enhances conductivity, but diminishes solubility. For printing, viscosity, surface tension and solid content must be tightly controlled. Cross-layer interactions such as wetting, adhesion, and solubility as well as post-deposition drying procedures affect the outcome. Additives often used in conventional printing inks are unavailable, because they often defeat electronic functionality.

Material properties largely determine the differences between printed and conventional electronics. Printable materials provide decisive advantages beside printability, such as mechanical flexibility and functional adjustment by chemical modification (e.g. light color in OLEDs).

Printed conductors offer lower conductivity and charge carrier mobility.

With a few exceptions, inorganic ink materials are dispersions of metallic micro- and nano-particles.

PMOS but not CMOS is possible in printed electronics.

Organic materials

Organic printed electronics integrates knowledge and developments from printing, electronics, chemistry, and materials science, especially from organic and polymer chemistry. Organic materials in part differ from conventional electronics in terms of structure, operation and functionality, which influences device and circuit design and optimization as well as fabrication method.

The discovery of conjugated polymers and their development into soluble materials provided the first organic ink materials. Materials from this class of polymers variously possess conducting, semiconducting, electroluminescent, photovoltaic and other properties. Other polymers are used mostly as insulators and dielectrics.

In most organic materials, hole transport is favored over electron transport. Recent studies indicate that this is a specific feature of organic semiconductor/dielectric-interfaces, which play a major role in OFETs. Therefore p-type devices should dominate over n-type devices. Durability (resistance to dispersion) and lifetime is less than conventional materials.

Organic semiconductors include the conductive polymers poly(3,4-ethylene dioxitiophene), doped with poly(styrene sulfonate), (PEDOT:PSS) and poly(aniline) (PANI). Both polymers are commercially available in different formulations and have been printed using inkjet, screen and offset printing or screen, flexo and gravure printing, respectively.

Polymer semiconductors are processed using inkjet printing, such as poly(thiopene)s like poly(3-hexylthiophene) (P3HT) and poly(9,9-dioctylfluorene co-bithiophen) (F8T2). The latter material has also been gravure printed. Different electroluminescent polymers are used with inkjet printing, as well as active materials for photovoltaics (e.g. blends of P3HT with fullerene derivatives), which in part also can be deposited using screen printing (e.g. blends of poly(phenylene vinylene) with fullerene derivatives).

Printable organic and inorganic insulators and dielectrics exist, which can be processed with different printing methods.

Inorganic materials

Inorganic electronics provides highly ordered layers and interfaces that organic and polymer materials cannot provide.

Silver nanoparticles are used with flexo, offset and inkjet. Gold particles are used with inkjet.

A.C. electroluminescent (EL) multi-color displays can cover many tens of square meters, or be incorporated in watch faces and instrument displays. They involve six to eight printed inorganic layers, including a copper doped phosphor, on a plastic film substrate.

CIGS cells can be printed directly onto molybdenum coated glass sheets.

A printed gallium arsenide germanium solar cell demonstrated 40.7% conversion efficiency, eight times that of the best organic cells, approaching the best performance of heavy silicon.

Substrates

Printed electronics allows the use of flexible substrates, which lowers production costs and allows fabrication of mechanically flexible circuits. While inkjet and screen printing typically imprint rigid substrates like glass and silicon, mass-printing methods nearly exclusively use flexible foil and paper. Poly(ethylene terephthalate)-foil (PET) is a common choice, due to its low cost and higher temperature stability. Poly(ethylene naphthalate)- (PEN) and poly(imide)-foil (PI) are alternatives. Paper's low costs and manifold applications make it an attractive substrate, however, its high roughness and large absorbency make it problematic for electronics.

Other important substrate criteria are low roughness and suitable wettability, which can be tuned pre-treatment (coating, corona). In contrast to conventional printing, high absorbency is usually disadvantageous.

Applications

Printed electronics are in use or under consideration for:

- Radio frequency identification (RFID) tags
- Monitoring
- Data storage
- Display and visual effects
- Toys
- Thin film solar cell

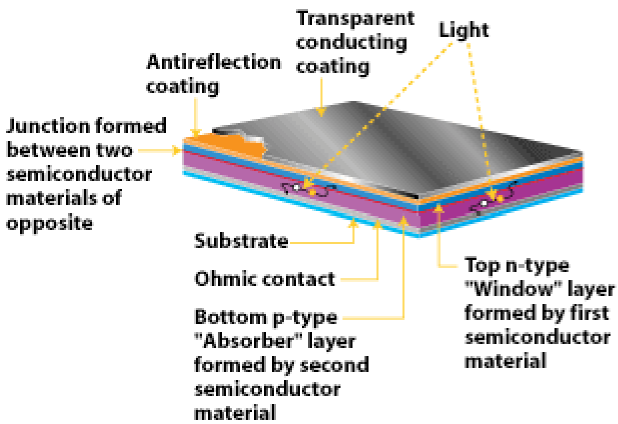
Standards development and activities

Technical standards and roadmapping initiatives are intended to facilitate value chain development (for sharing of product specifications, characterization standards, etc.) This strategy of standards development mirrors the approach used by silicon-based electronics over the past 50 years. Initiatives include:

- The IEEE Standards Association has published IEEE 1620-2004 and IEEE 1620.1-2006.
- Similar to the well-established International Technology Roadmap for Semiconductors (ITRS), the International Electronics Manufacturing Initiative (iNEMI) has published a roadmap for printed and other organic electronics.

Chapter-2

Thin Film Solar Cell



Cross-section of thin film polycrystalline solar cell.

A **thin-film solar cell** (TFSC), also called a **thin-film photovoltaic cell** (TFPV), is a solar cell that is made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers.

Many different photovoltaic materials are deposited with various deposition methods on a variety of substrates. Thin-film solar cells are usually categorized according to the photovoltaic material used:

- Amorphous silicon (a-Si) and other thin-film silicon (TF-Si)
- Cadmium Telluride (CdTe)
- Copper indium gallium selenide (CIS or CIGS)
- Dye-sensitized solar cell (DSC) and other organic solar cells

$$\begin{pmatrix} \mathrm{Cu} \\ \mathrm{Ag} \\ \mathrm{Au} \end{pmatrix} \begin{pmatrix} \mathrm{Al} \\ \mathrm{Ga} \\ \mathrm{In} \end{pmatrix} \begin{pmatrix} \mathrm{S} \\ \mathrm{Se} \\ \mathrm{Te} \end{pmatrix}_2$$

Possible combinations of Group-(I, III, VI) elements in the periodic table that yield a compound showing photovoltaic effect (*Cu, Ag, Au* | *Al, Ga, In* | *S, Se, Te*).

History

Initially appearing as small strips powering hand-held calculators, thin-film PV is now available in very large modules used in sophisticated building-integrated installations and vehicle charging systems. GBI Research projects thin film production to grow 24% from 2009 levels and to reach 22,214 MW in 2020. "Expectations are that in the long-term, thin-film solar PV technology would surpass dominating conventional solar PV technology, thus enabling the long sought-after grid parity objective."

Thin-film silicon

A silicon thin-film cell uses amorphous (a-Si or a-Si:H), protocrystalline, nanocrystalline (nc-Si or nc-Si:H) or black silicon. Thin-film silicon is opposed to *wafer* (or *bulk*) silicon (monocrystalline or polycrystalline).

Design and fabrication

The silicon is mainly deposited by chemical vapor deposition, typically plasma-enhanced (PE-CVD), from silane gas and hydrogen gas. Other deposition techniques being investigated include sputtering and hot wire techniques.

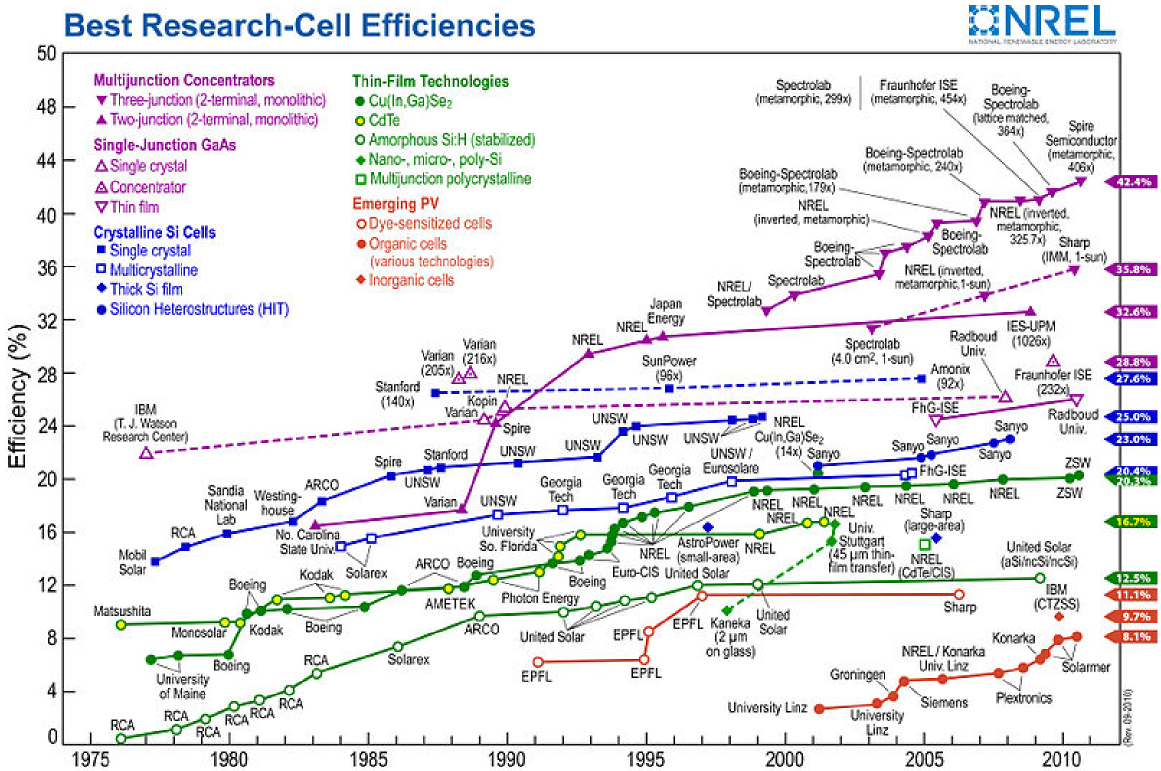
The silicon is deposited on glass, plastic or metal which has been coated with a layer of transparent conducting oxide (TCO).

A p-i-n structure is usually used, as opposed to an n-i-p structure. This is because the mobility of electrons in a-Si:H is roughly 1 or 2 orders of magnitude larger than that of holes, and thus the collection rate of electrons moving from the p- to n-type contact is better than holes moving from p- to n-type contact. Therefore, the p-type layer should be placed at the top where the light intensity is stronger, so that the majority of the charge carriers crossing the junction would be electrons.

Micromorphous silicon

Micromorphous silicon module technology combines two different types of silicon, amorphous and microcrystalline, in a top and a bottom photovoltaic cell. Use of protocrystalline silicon for the intrinsic layer has shown to optimize the open circuit voltage of an a-Si photovoltaic cell.

Efficiency



Solar Cell Efficiencies

These types of silicon present dangling and twisted bonds, which results in deep defects (energy levels in the bandgap) as well as deformation of the valence and conduction bands (band tails). The solar cells made from these materials tend to have lower energy conversion efficiency than bulk silicon (also called crystalline or wafer silicon), but are also less expensive to produce. The quantum efficiency of thin-film solar cells is also lower due to reduced number of collected charge carriers per incident photon.

Amorphous silicon has a higher bandgap (1.7 eV) than crystalline silicon (c-Si) (1.1 eV), which means it absorbs the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. As nc-Si has about the same bandgap as c-Si, the nc-Si and a-Si can advantageously be combined in thin layers, creating a layered cell called a *tandem cell*. The top cell in a-Si absorbs the visible light and leaves the infrared part of the spectrum for the bottom cell in nc-Si.

Recently, solutions to overcome the limitations of thin-film silicon have been developed. Light trapping schemes where the incoming light is obliquely coupled into the silicon and the light traverses the film several times enhance the absorption of sunlight in the films. Thermal processing techniques enhance the crystallinity of the silicon and pacify electronic defects.

Building integrated photovoltaics

Thin film photovoltaic panels being installed onto a roof

Thin film solar panels are commercially available for installation onto the roofs of buildings, either applied onto the finished roof, or integrated into the roof covering. The advantage over tradition PV panels is that they are very low in weight, are not subject to wind lifting, and can be walked on (with care). The comparable disadvantages are increased cost and reduced efficiency.

A silicon thin film technology is being developed for building integrated photovoltaics (BIPV) in the form of semitransparent solar cells which can be applied as window glazing. These cells function as window tinting while generating electricity.

Organic solar cells

The Organic solar cell is another alternative to the more conventional materials used to make photovoltaics. Although a very novel technology it is promising since it offers a very low cost solution.

Efficiencies, volumes and prices

Since the invention of the first modern silicon solar cell in 1954, incremental improvements have resulted in modules capable of converting 12 to 18 percent of solar radiation into electricity. The performance and potential of thin-film materials are high, reaching cell efficiencies of 12%-20%; prototype module efficiencies of 7%-13%; and production modules in the range of 9%. Future module efficiencies are expected to climb close to the state-of-the-art of today's best cells, or to about 10-16%.

Annual manufacturing volume in the United States has grown from about 12 megawatts (MW) per year in 2003 to more than 20 MW/yr in 2004; 40-50 MW/yr production levels are expected in 2005 with continued rapid growth in the years after that.

Costs are expected to drop to below $\$100/m^2$ in volume production, and could reach even lower levels—well under $\$50/m^2$, the DOE/NREL goal for thin films—when fully optimized. At these levels, thin-film modules will cost less than fifty cents per watt to manufacture, opening new markets such as cost-effective distributed power and utility production to thin-film electricity generation.

As crystalline silicon price rose, the production cost of silicon-based solar cell module in 2008 was at some point 4-5 times higher than that of thin film modules. Thin-film producers still enjoy in 2009 price advantage as its production cost is 20% less than that of silicon modules.It is expected that the production cost of thin-film will continue dropping (40% less than silicon), as Chinese producers are now putting more resources into R&D and partnering with manufacturing equipment suppliers

Production, cost and market

In recent years, the manufacturers of thin-film solar modules are bringing costs down and gaining in competitive strength through advanced thin film technology. However, the traditional crystalline silicon technologies will not give up their market positions for a few years because they still hold considerable development potential in terms of the cost. Efficiency of thin film solar is considerably lower and thin film solar manufacturing equipment suppliers intend to score costs of below USD 1/W, and Anwell Technologies Limited claimed that they intend to bring it down further to USD 0.5/W. Those equipment suppliers have been doing R&D for micro-morphous silicon modules since 2008. This technology represents a development based on the thin-film panels made of ordinary amorphous silicon marketed at present that brings higher cell efficiency by depositing an additional absorber layer made of micro crystalline silicon on the amorphous layer. Some equipment suppliers even claim that there will be machinery in market to manufacture these new modules at $0.70. With such potential of further development of thin film solar technology, the European Photovoltaic Industry Association (EPIA) expects that manufacturing capacities for these technologies will double to over 4GW by 2010 representing a market share of around 20%.

Installations

First Solar, the CdTe thin-film manufacturer stated that "at the end of 2007, over 300 MW of First Solar PV modules had been installed worldwide." Below is a list of several recent installations:

- Since 16 October 2008, Germany's largest thin-film pitched roof system, constructed by Riedel Recycling, has been in operation and producing solar power in Moers near Duisburg. Over eleven thousand cadmium telluride modules, from First Solar, deliver a total of 837 kW .
- First Solar recently completed a 2.4 MW rooftop installation as part of Southern California Edison program to install 250 MW of rooftop solar panels throughout Southern California over by 2013.
- First Solar announced a 7.5 MW system to be installed in Blythe, CA, where the California Public Utilities Commission has accepted a 12 ¢/kWh power purchase agreement with First Solar (after the application of all incentives).
- Construction of a 10 MW plant in the Nevada desert began in July 2008. First Solar is partnering with Sempra Generation, which will own and operate the PV power-plant, being built next to their natural gas plant.
- Stadtwerke Trier (SWT) in Trier, Germany is expected to produce over 9 GWh annually
- A 40 MW system is being installed by Juwi in Waldpolenz Solar Park, Germany. At the time of its announcement, it was both the largest planned and lowest cost PV system in the world. The price of 3.25 euros translated then (when the euro was equal to US$1.3) to $4.2 per installed watt.
- 4.8KW of thin film flexible solar panels manufactured by Uni-Solar Ovonic installed on a South Beach hurricane-prone residence in 2008..

Denver-based Conergy Americas and officials at California's South San Joaquin Irrigation District (SSJID) have installed what is believed to be the world's first single-axis solar tracking system featuring thin-film photovoltaic cells.

Chapter-3

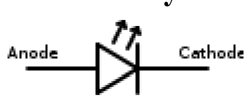
Light-emitting Diode

Light-emitting diode

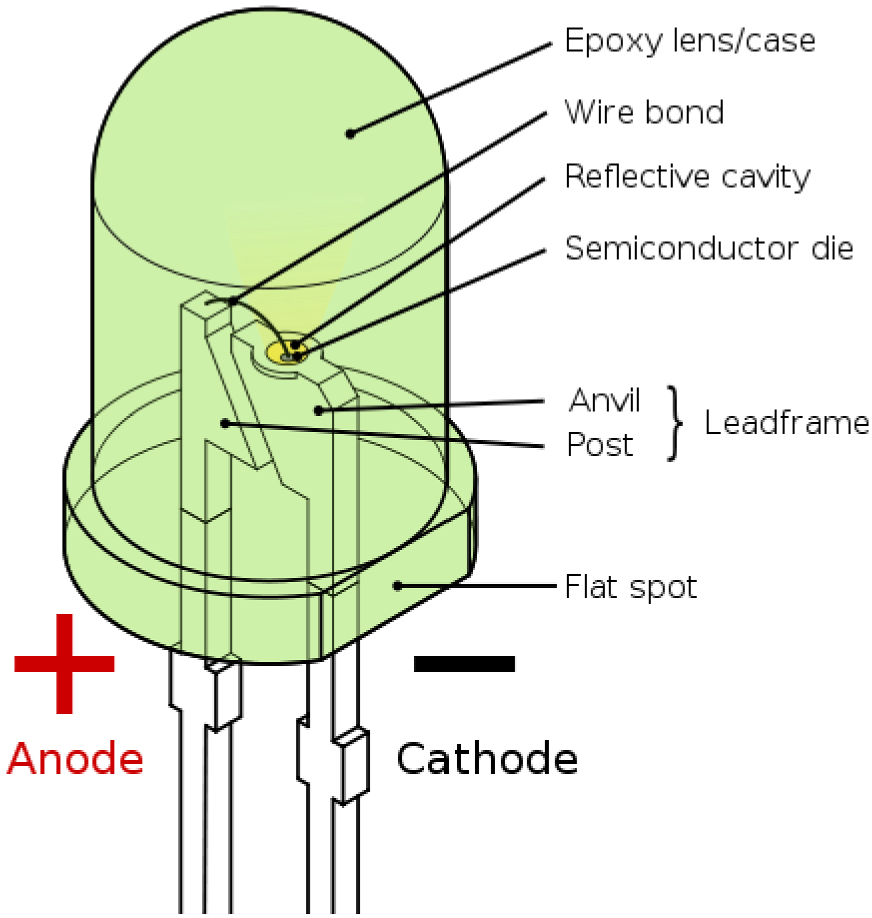
Red, green and blue LEDs of the 5mm diffused type

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

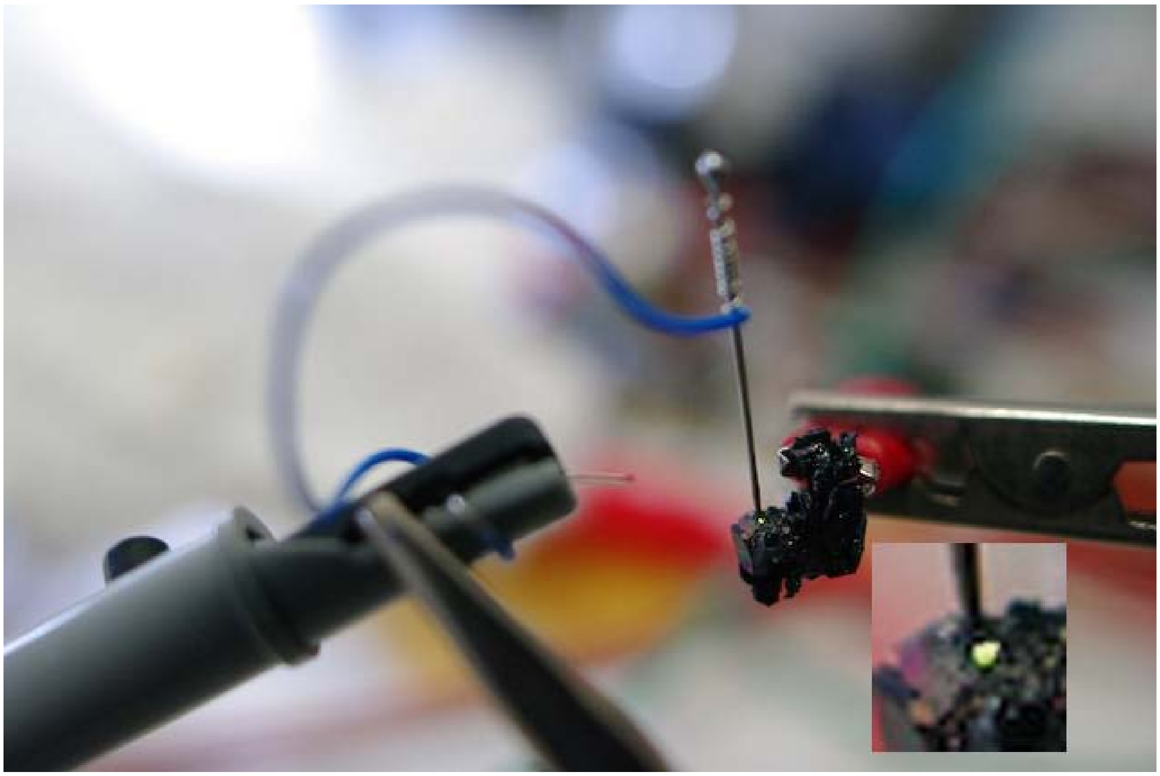
A **light-emitting diode** is a semiconductor light source. LEDs are used as indicator lamps in many devices and are increasingly used for other lighting. Introduced as a practical electronic component in 1962, early LEDs emitted low-intensity red light, but modern versions are available across the visible, 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 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 as a phenomenon 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 reported on the creation of a first 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, which is fast replacing incandescent and fluorescent lighting. Most LEDs were made in the very common 5 mm T1¾ 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.

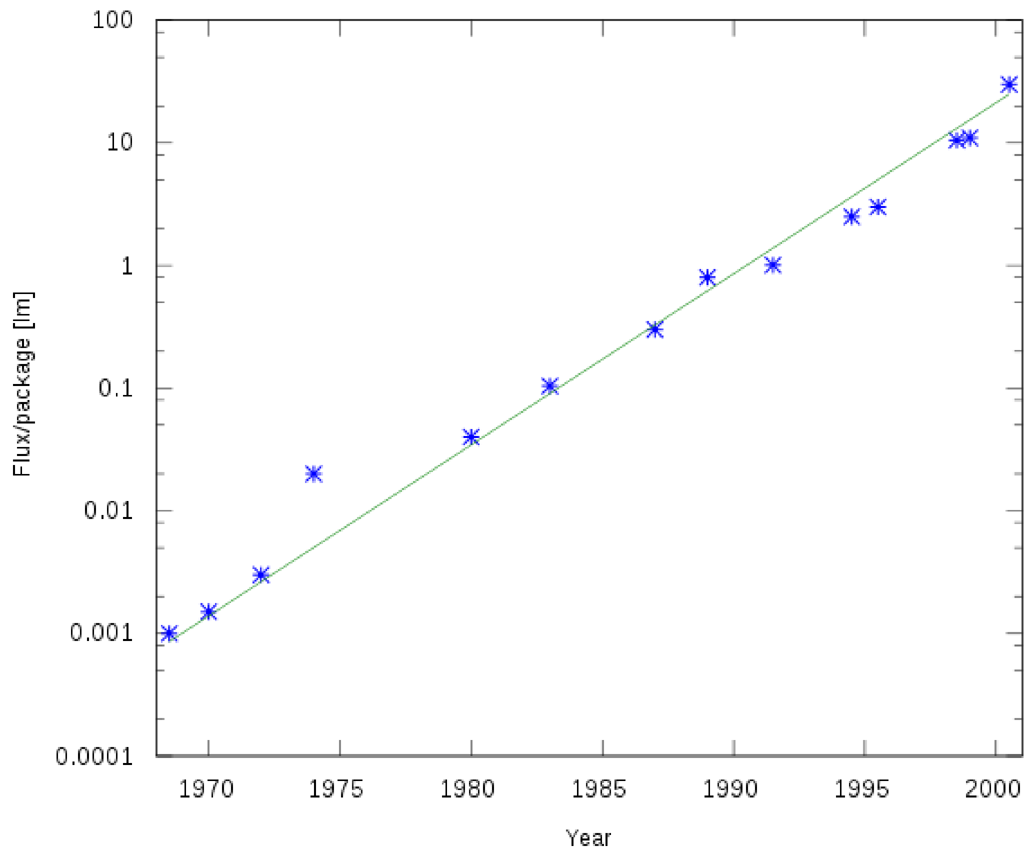


Illustration of Haitz's Law. Light output per LED as a function of production year, note the logarithmic scale on the vertical axis.

Continuing development

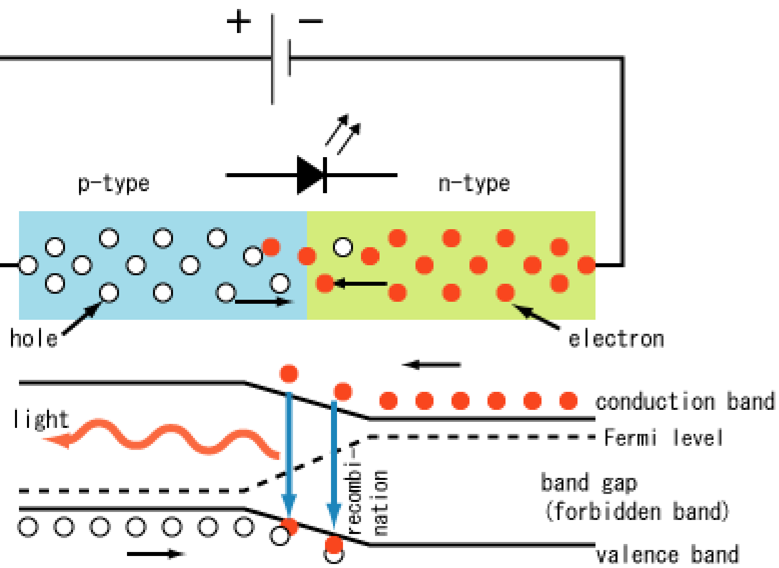
The first high-brightness blue LED was demonstrated by Shuji Nakamura of Nichia Corporation and was based on InGaN borrowing on critical developments in GaN nucleation on sapphire substrates and the demonstration of p-type doping of GaN which were developed by Isamu Akasaki and H. Amano in Nagoya. In 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.

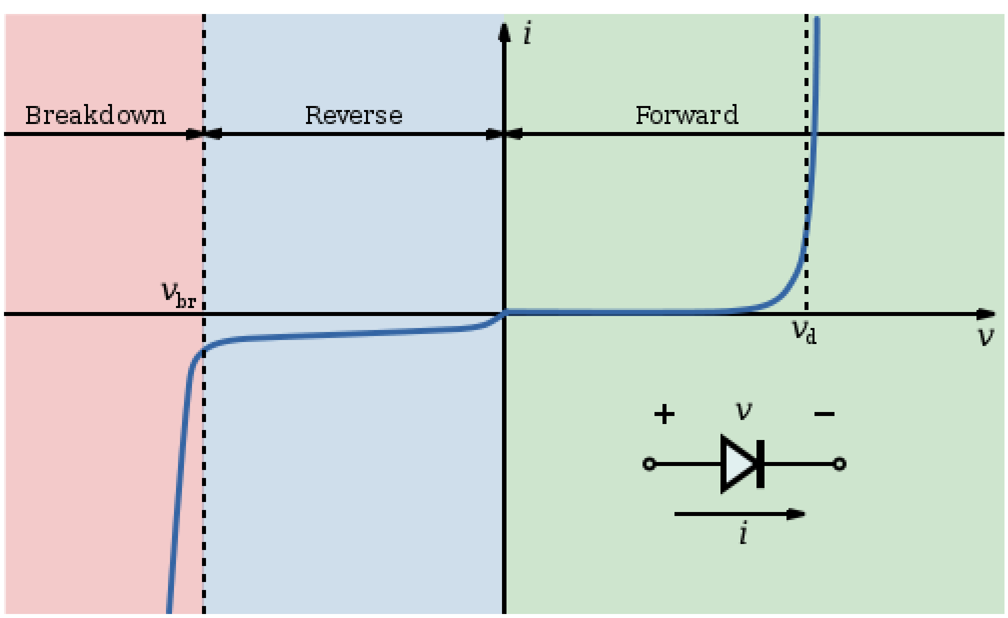
In February 2008, 300 lumens of visible light per watt luminous efficacy (not per electrical watt) and warm-light emission was achieved by using nanocrystals.

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

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.

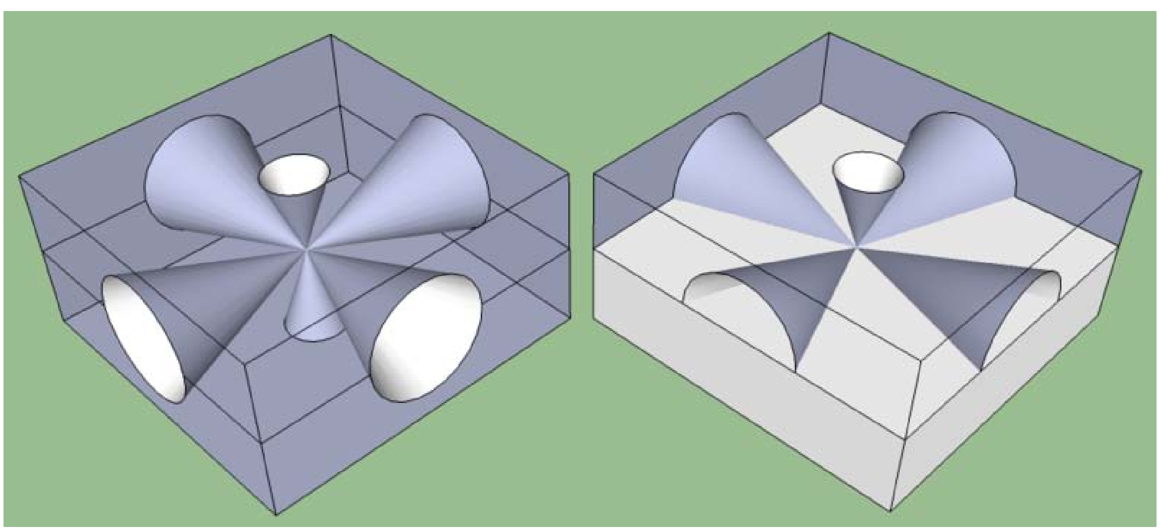
The wavelength of the light emitted, and thus its color depends on the band gap energy of the materials forming the *p-n junction*. In silicon or germanium diodes, the electrons and holes recombine by a *non-radiative transition* which produces no optical emission, because these are indirect band gap 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.

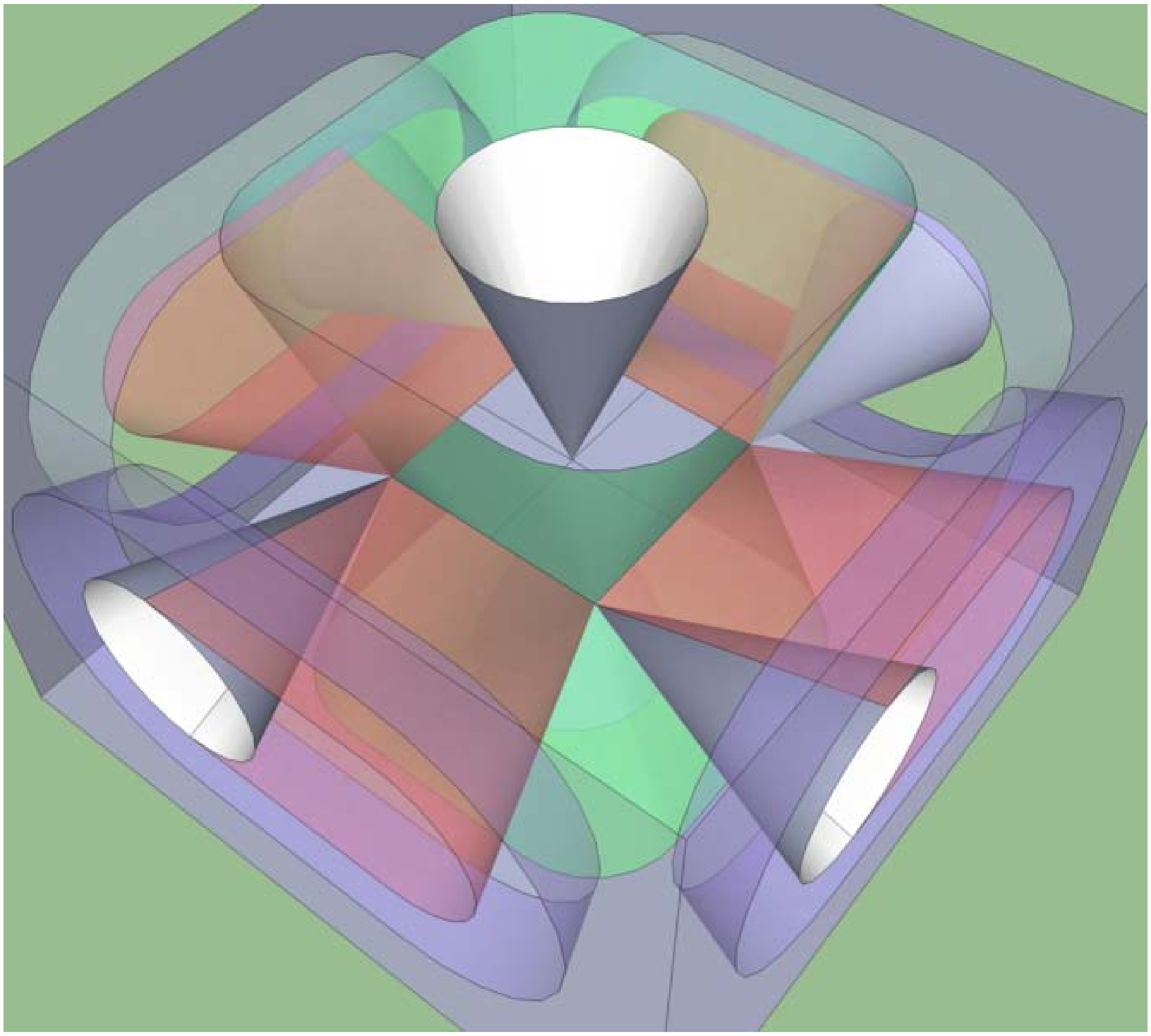
LEDs are usually built on an n-type substrate, with an electrode attached to the p-type layer deposited on its surface. P-type substrates, while less common, occur as well. Many commercial LEDs, especially GaN/InGaN, also use sapphire substrate.

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	$570 < \lambda < 590$	$2.10 < \Delta V <$	Gallium arsenide phosphide (GaAsP)

		2.18	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)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm) 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 AlGaN and AlGaInN, even shorter wavelengths are achievable. Ultraviolet LEDs in a range of wavelengths are becoming available on the market. Near-UV emitters at wavelengths around 375–395 nm are already cheap and often encountered, for example, as black light lamp replacements for inspection of anti-counterfeiting UV watermarks in some documents and paper currencies. Shorter wavelength diodes, while substantially more expensive, are commercially available for wavelengths down to 247 nm. 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.

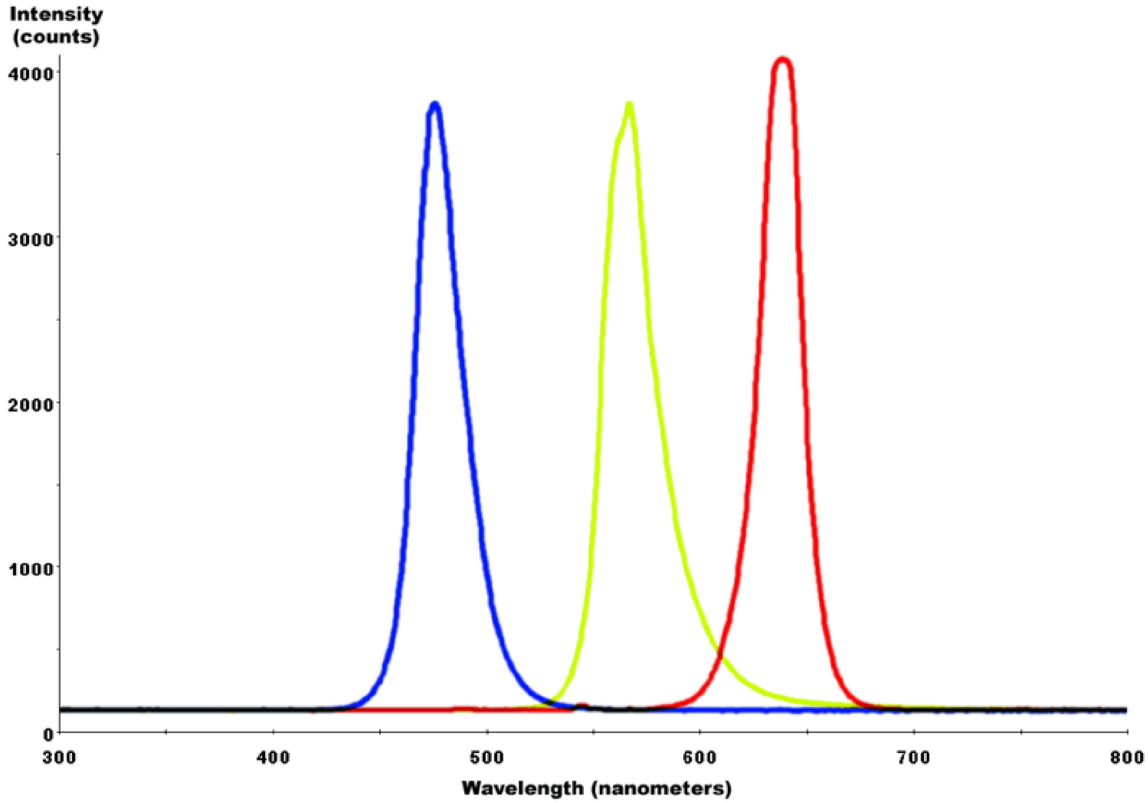
Deep-UV wavelengths were obtained in laboratories using aluminium nitride (210 nm), boron nitride (215 nm) and diamond (235 nm).

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



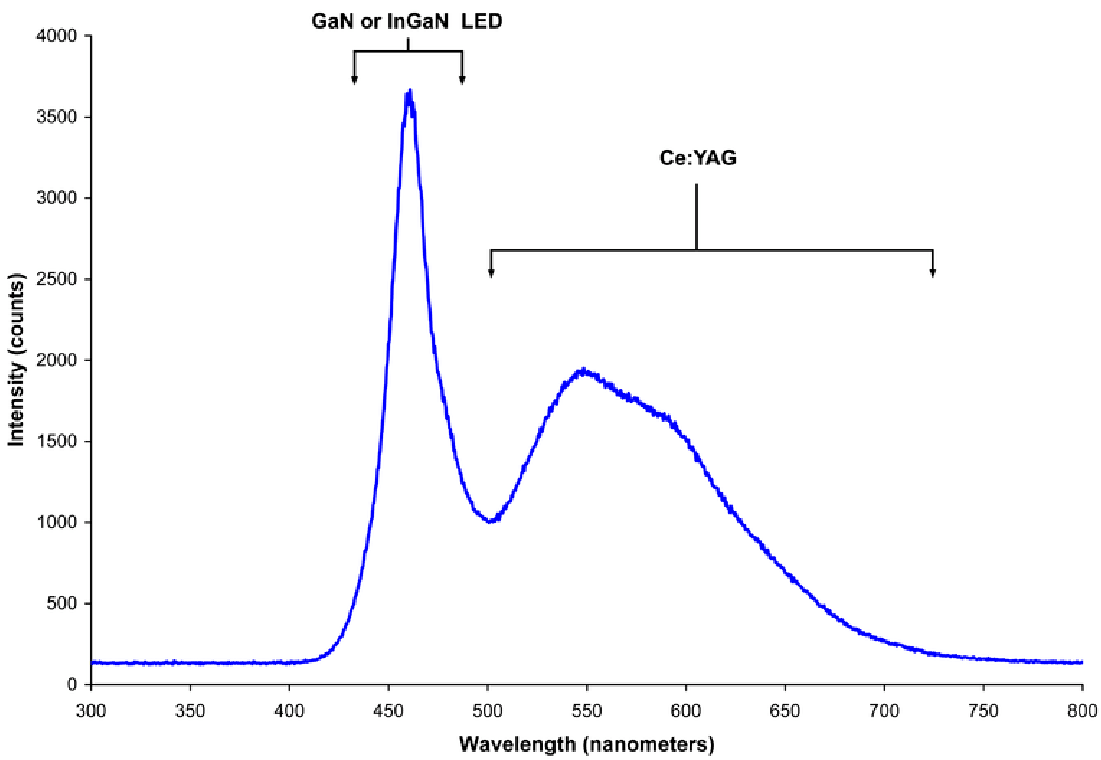
Combined spectral curves for blue, yellow-green, and high brightness red solid-state semiconductor LEDs. FWHM spectral bandwidth is approximately 24–27 nm for all three colors.

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 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.

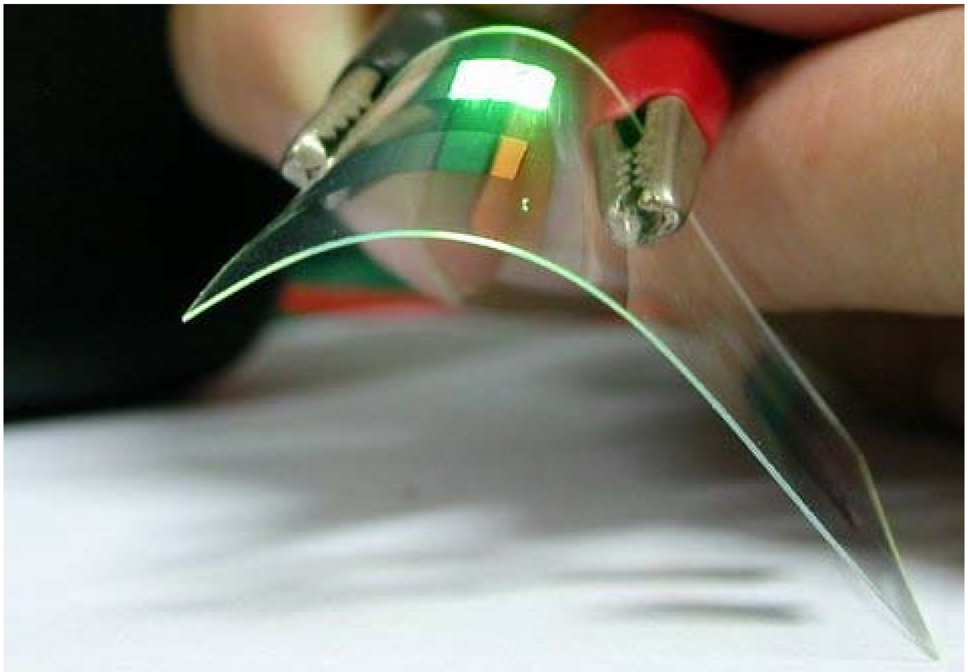
The phosphor based white LEDs encapsulate InGaN blue LEDs inside phosphor coated epoxy. A common yellow phosphor material is cerium-doped yttrium aluminium garnet (Ce^{3+}:YAG).

White LEDs can also be made by coating near ultraviolet (NUV) emitting LEDs with a mixture of high efficiency europium-based red and blue emitting phosphors plus green emitting copper and aluminium doped zinc sulfide (ZnS:Cu, Al). This is a method analogous to the way fluorescent lamps work. This method is less efficient than the blue LED with YAG:Ce phosphor, as the Stokes shift is larger, 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 (ZnSe) on a 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.

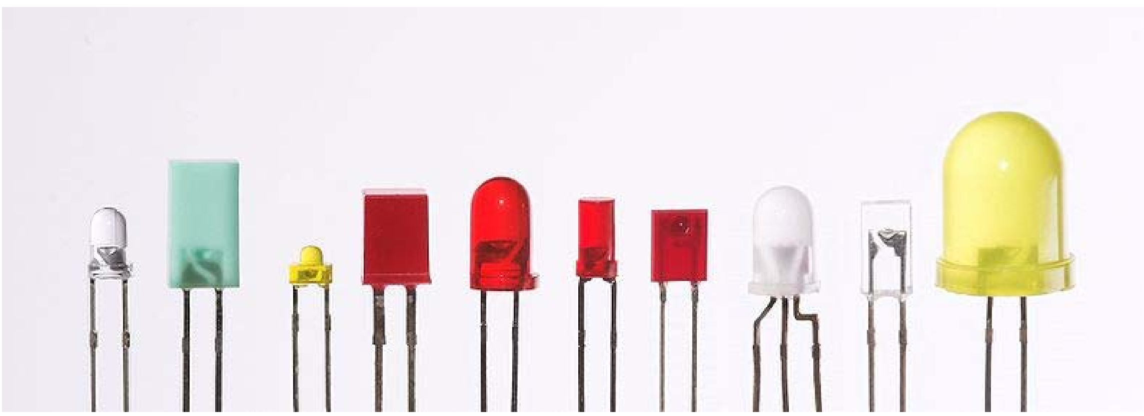
Quantum dots (QD) are semiconductor nanocrystals that possess unique optical properties. Their emission color can be tuned from the visible throughout the infrared spectrum. This allows quantum dot LEDs to create almost any color on the CIE diagram.

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.

The major difficulty in using quantum dots based LEDs is the insufficient stability of QDs under prolonged irradiation. In February 2011 scientists at PlasmaChem GmbH could synthesize quantum dots for LED applications and build a light converter on their basis, which could efficiently convert light from blue to any other color for many hundred hours. Such QDs can be used to emit visible or near infrared light of any wavelength being excited by light with a shorter wavelength.

Types



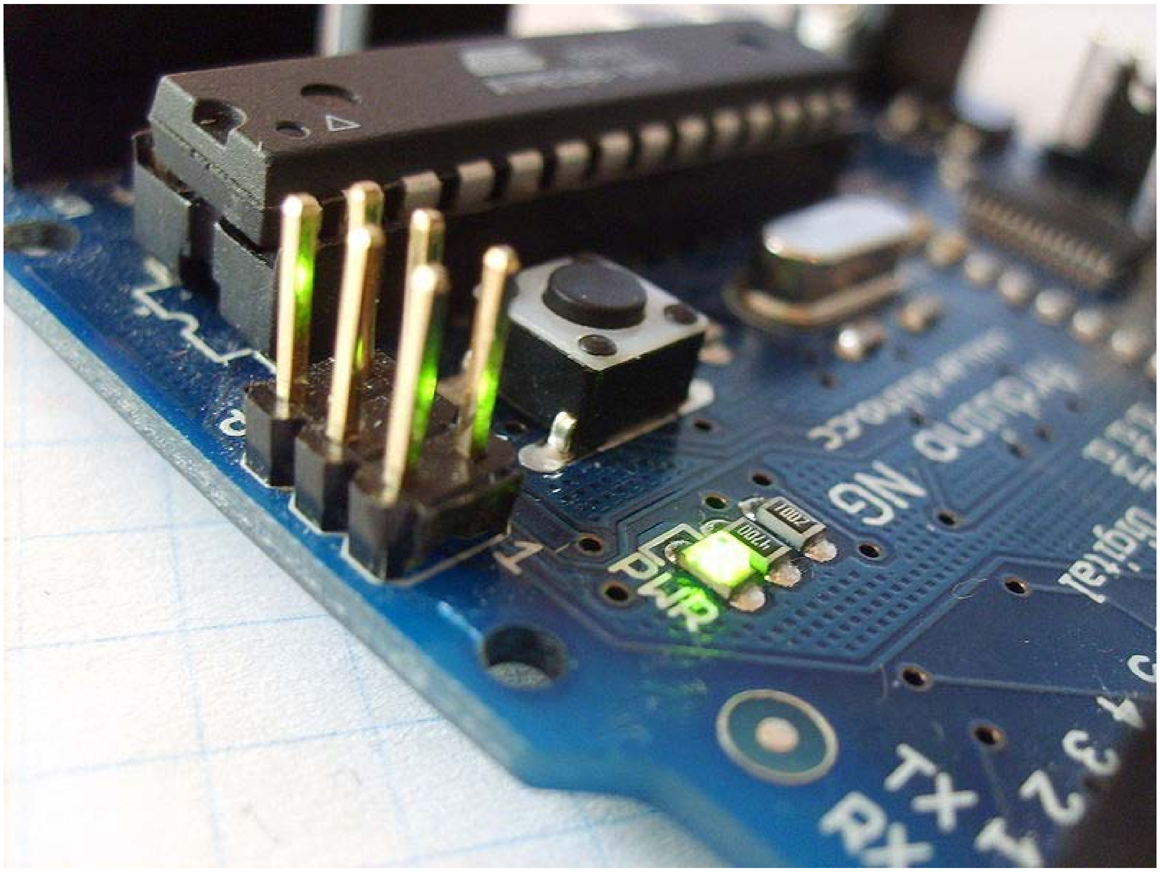
LEDs are produced in a variety of shapes and sizes. The 5 mm cylindrical package (red, fifth from the left) is the most common, estimated at 80% of world production. The color of the plastic lens is often the same as the actual color of light emitted, but not always. For instance, purple plastic is often 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.

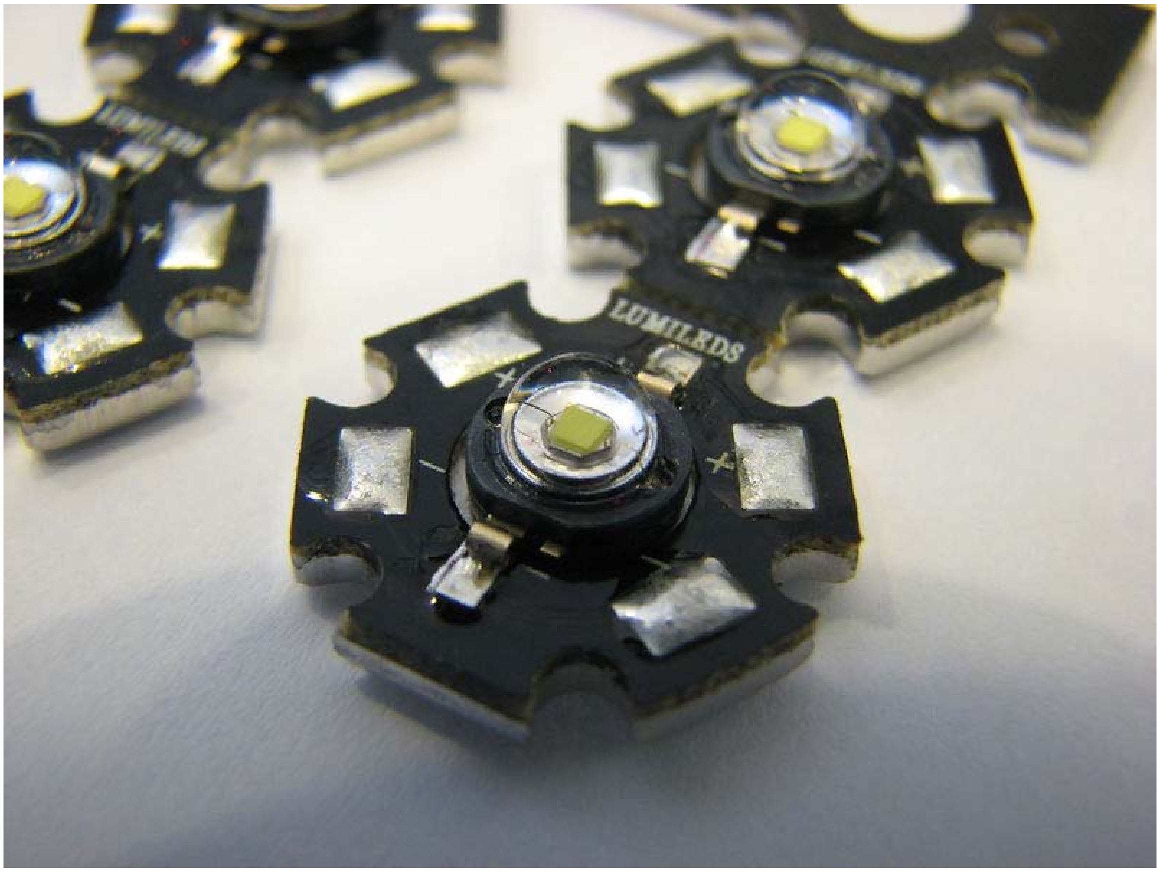


A green surface-mount LED mounted on a circuit board.

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 emiting diodes (Luxeon, Lumileds)

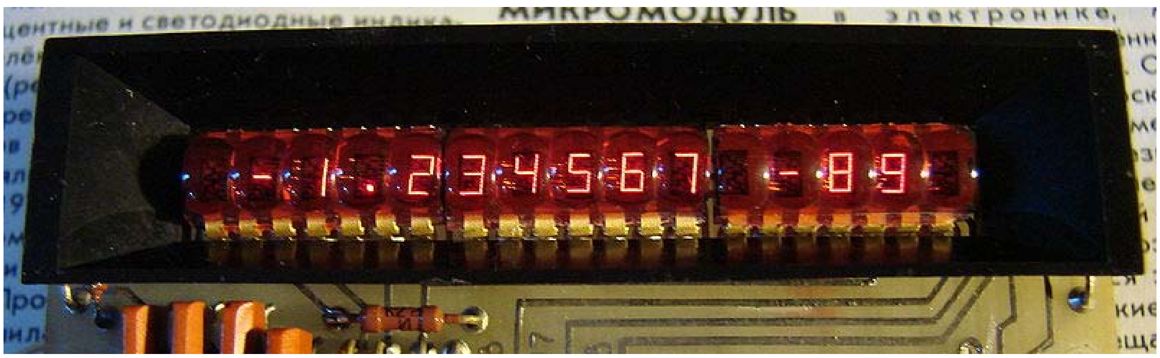
High power LEDs (HPLED) can be driven at currents from hundreds of mA to more than an ampere, compared with the tens of mA for other LEDs. Some can emit over a thousand lumens. Since overheating is destructive, the HPLEDs must be mounted on a heat sink to allow for heat dissipation. If the heat from 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 and health

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

While LEDs have the advantage over fluorescent lamps that they do not contain mercury, they may contain other hazardous metals such as lead and arsenic. A study published in 2011 states: "According to federal standards, LEDs are not hazardous except for low-intensity red LEDs, which leached Pb [lead] at levels exceeding regulatory limits (186 mg/L; regulatory limit: 5). However, according to California regulations, excessive levels of copper (up to 3892 mg/kg; limit: 2500), Pb (up to 8103 mg/kg; limit: 1000), nickel (up to 4797 mg/kg; limit: 2000), or silver (up to 721 mg/kg; limit: 500) render all except low-intensity yellow LEDs hazardous.".

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^2) 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.

Disadvantages

- **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.

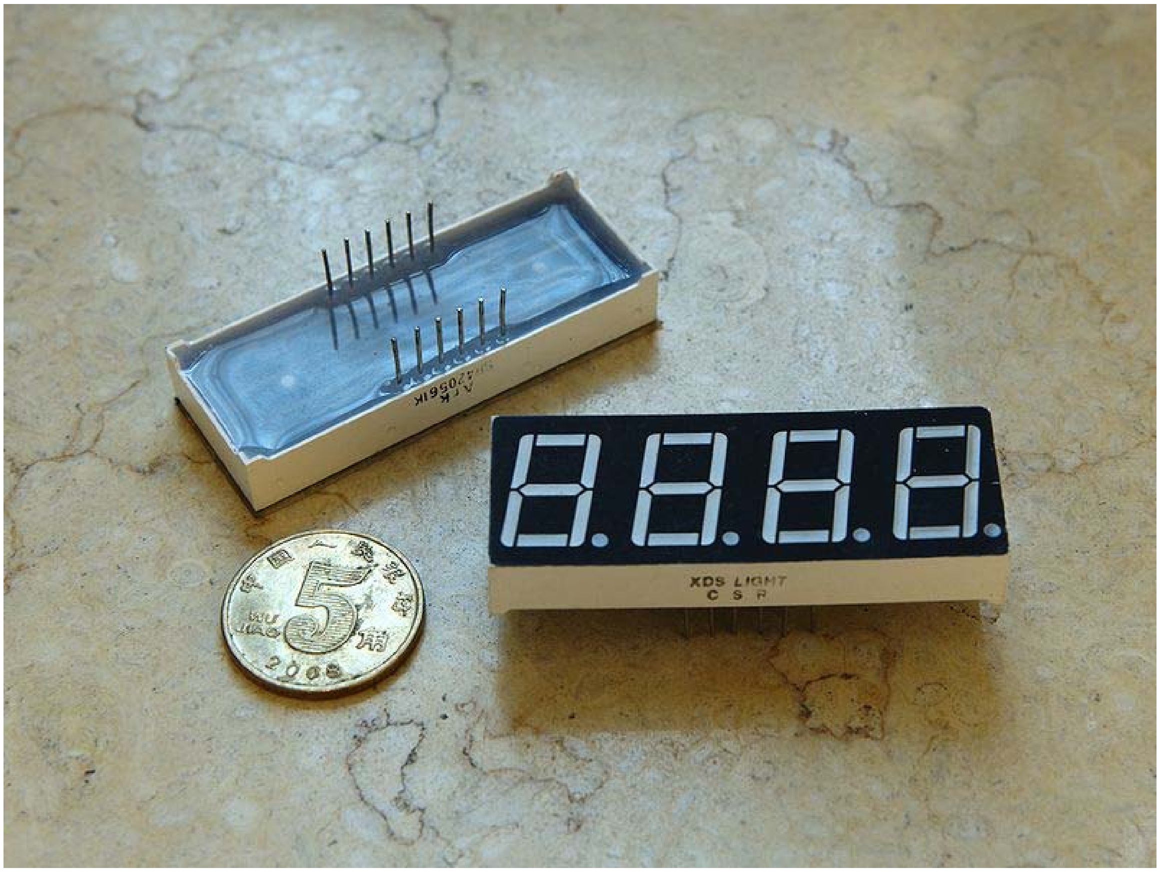
- **Blue pollution:** Because cool-white LEDs (i.e., LEDs with high color temperature) emit proportionally more blue light than conventional outdoor light sources such as high-pressure sodium vapor lamps, the strong wavelength dependence of Rayleigh scattering means that cool-white LEDs can cause more 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.

Applications

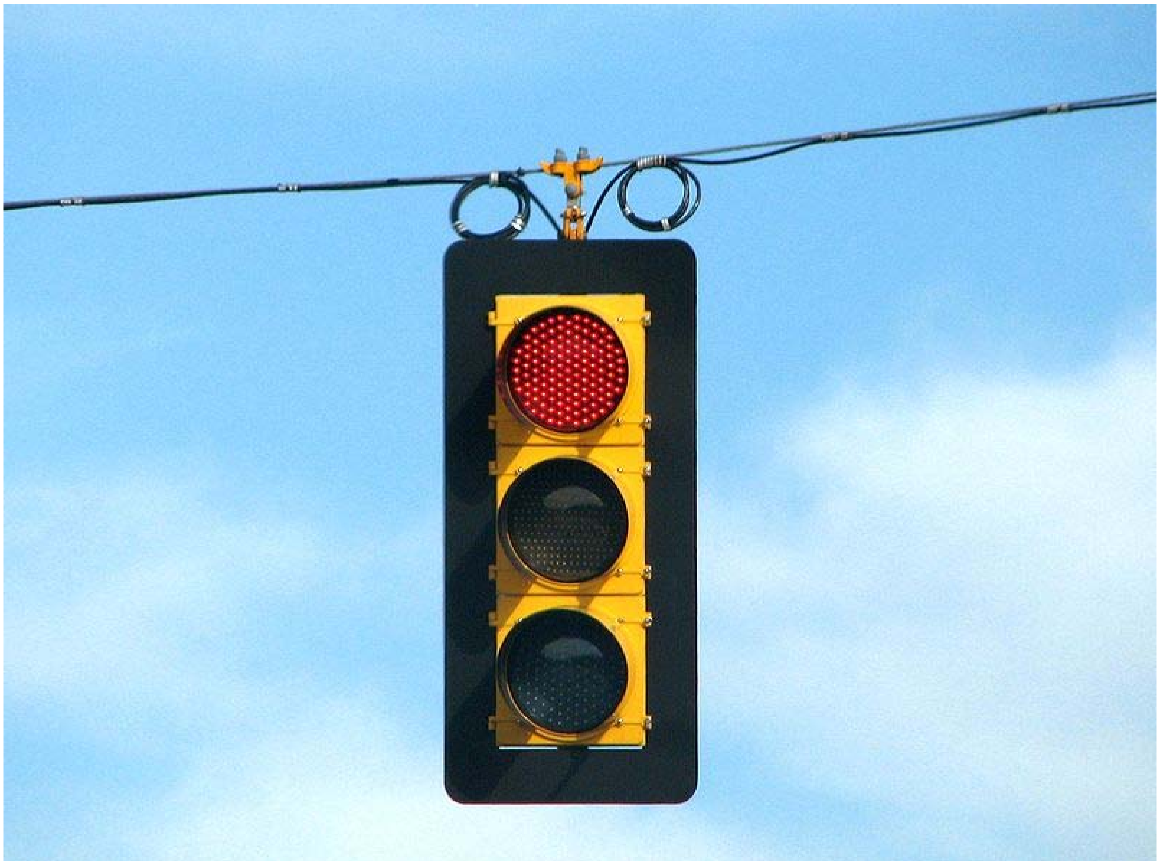
LED lighting in the aircraft cabin of an Airbus A320 Enhanced.

A large LED display behind a disc jockey.

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



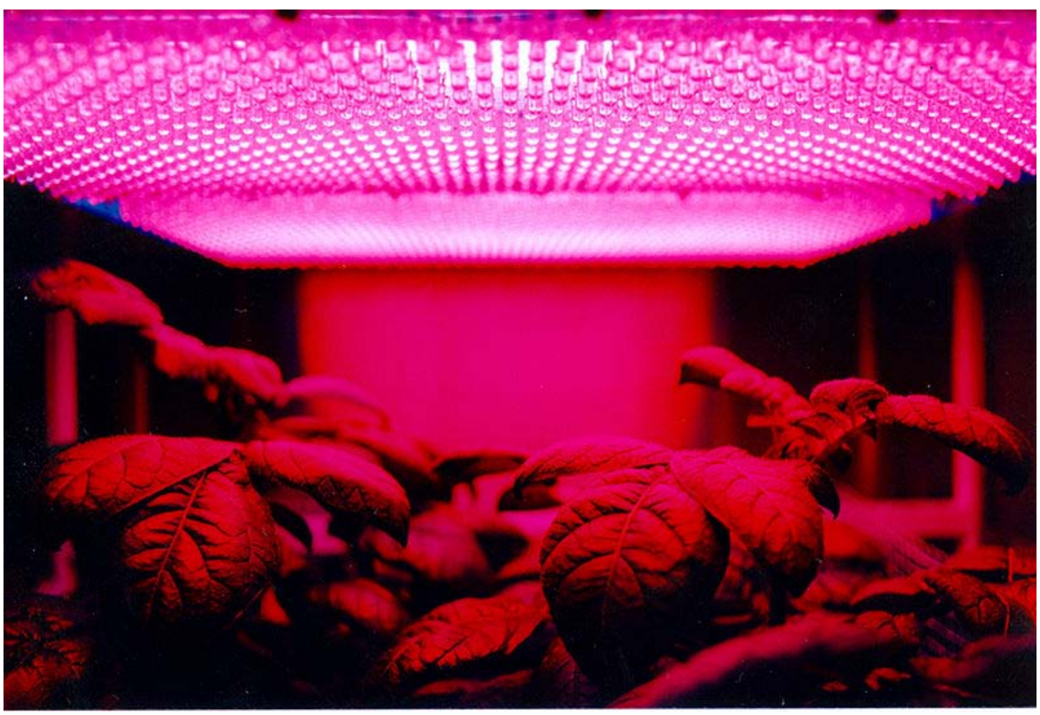
LED digital display that can display 4 digits along with points.



Traffic light using LED

Western Australia Police car using LED

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.

LED Illumination.

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.

For more than 70 years, until the LED, practically all lighting was incandescent and fluorescent with the first fluorescent light only being commercially available after the 1939 World's Fair.

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.

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.

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.

Energy consumption

One kilowatt-hour of electricity will cause 1.34 pounds (610 g) of CO_2 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_2 emission per year. The 13-watt LED equivalent will only cause 63 pounds (29 kg) of CO_2 over the same time span. A building's carbon footprint from lighting can be reduced by 68% by exchanging all incandescent bulbs for new LEDs in warm climates. In cold climates, the energy saving may be lower, since more heating is needed to compensate for the lower temperature.

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

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).

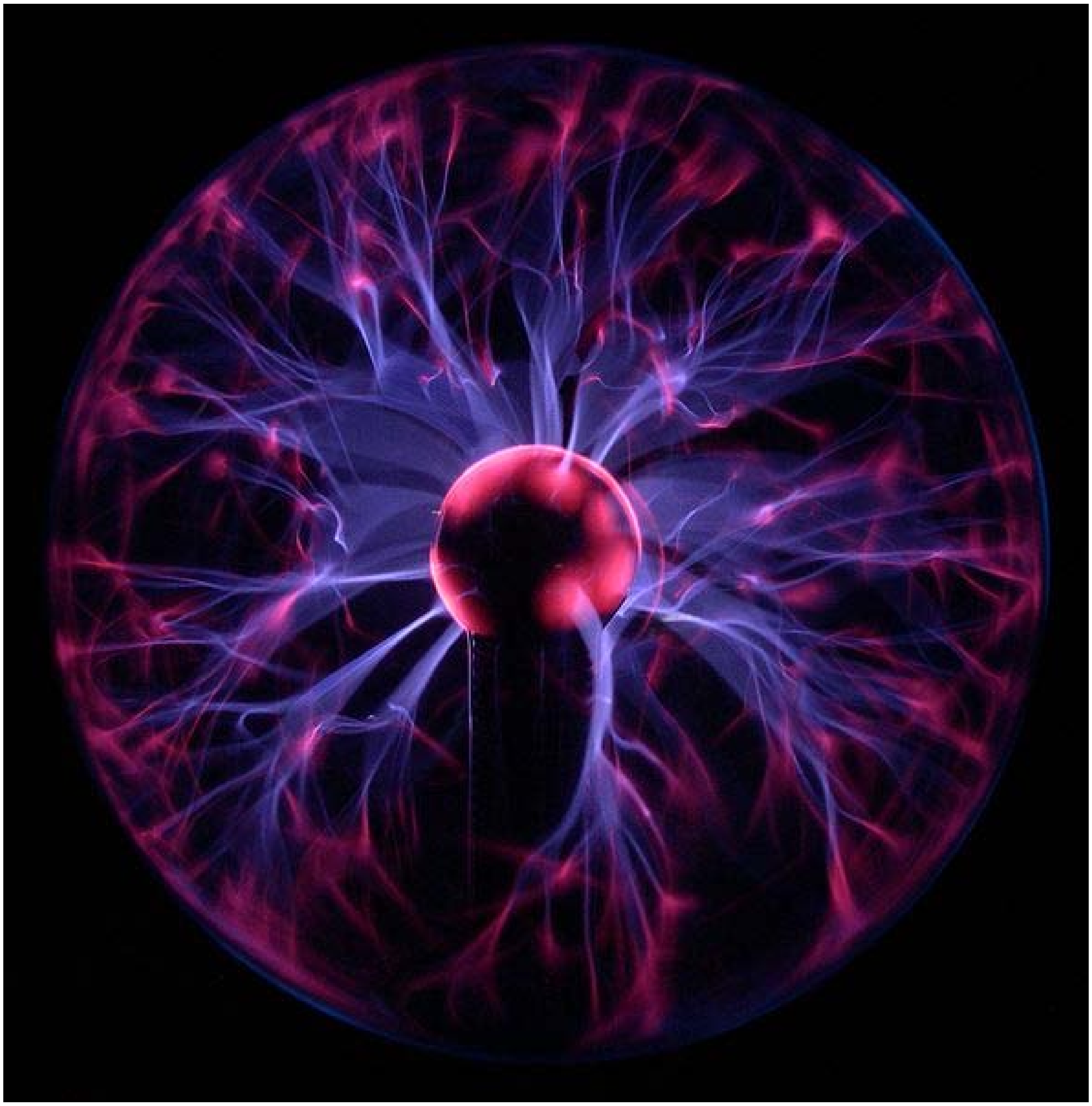
LEDs can be easily strobed (in the microsecond range and below) and synchronized with imaging. High-power LEDs are available allowing well lit images even with very short light pulses. This is often used to obtain crisp and sharp “still” images of quickly moving parts.

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-4

Plasma Display

A typical modern plasma screen television



Ionized gases such as the ones shown here are confined to millions of tiny individual cells across the face of a plasma display, to collectively form a visual image.

A **plasma display** panel (PDP) is a type of flat panel display common to large TV displays (80 cm/30 in or larger). They are called "plasma" displays because the technology utilizes small cells containing electrically charged ionized gases, or what are in essence chambers more commonly known as fluorescent lamps.

General characteristics

A 103" plasma display panel by Panasonic

Plasma displays are bright (1,000 lux or higher for the module), have a wide color gamut, and can be produced in fairly large sizes—up to 150 inches (3.8 m) diagonally. They have a very low-luminance "dark-room" black level compared to the lighter grey of the unilluminated parts of an LCD screen (i.e. the blacks are blacker on plasmas and greyer on LCDs). LED-backlit LCD televisions have been developed to reduce this distinction. The display panel itself is about 6 cm (2.5 inches) thick, generally allowing the device's total thickness (including electronics) to be less than 10 cm (4 inches). Plasma displays use as much power per square meter as a CRT or an AMLCD television. Power consumption varies greatly with picture content, with bright scenes drawing significantly more power than darker ones - this is also true of CRTs. Typical power consumption is 400 watts for a 50-inch (127 cm) screen. 200 to 310 watts for a 50-inch (127 cm) display when set to cinema mode. Most screens are set to 'shop' mode by default, which draws at least twice the power (around 500-700 watts) of a 'home' setting of less extreme brightness. Panasonic has greatly reduced power consumption ("1/3 of 2007 models") Panasonic claims that PDPs will consume only half the power of their previous series of plasma sets to achieve the same overall brightness for a given display size. The lifetime of the latest generation of plasma displays is estimated at 100,000 hours of actual display time, or 27 years at 10 hours per day. This is the estimated time over which maximum picture brightness degrades to half the original value.

Plasma display screens are made from glass, which reflects more light than the material used to make an LCD screen. This causes glare from reflected objects in the viewing area. Companies such as Panasonic coat their newer plasma screens with an anti-glare filter material. Currently, plasma panels cannot be economically manufactured in screen sizes smaller than 32 inches. Although a few companies have been able to make plasma EDTVs this small, even fewer have made 32in plasma HDTVs. With the trend toward larger and larger displays, the 32in screen size is rapidly disappearing. Though considered bulky and thick compared to their LCD counterparts, some sets such as Panasonic's Z1 and Samsung's B860 series are as slim as one inch thick making them comparable to LCDs in this respect.

Competing display technologies include CRT, OLED, LCD, DLP, SED, LED, FED, and QLED.

Plasma display advantages and disadvantages

Advantages

- Picture quality
    - Produces deep blacks allowing for superior contrast ratio
    - Much wider viewing angles than those of LCD; images do not suffer from degradation at high angles unlike LCDs
    - No visible motion blur, thanks in large part to very high refresh rates and a faster response time, contributing to superior performance when displaying content with significant amounts of rapid motion

- Physical
    - Slim profile
    - Can be wall mounted
    - Less bulky than rear-projection televisions

Disadvantages

- Picture quality
    - Earlier generation displays were more susceptible to screen burn-in and image retention, although most recent models have a pixel orbiter that moves the entire picture faster than is noticeable to the human eye, which reduces the effect of burn-in but does not prevent it. However, turning off individual pixels does counteract screen burn-in on modern plasma displays.
    - Earlier generation displays (2006 and prior) had phosphors that lost luminosity over time, resulting in gradual decline of absolute image brightness (newer models are less susceptible to this, having lifespans exceeding 100,000 hours, far longer than older CRT technology)
    - Earlier generation (circa 2001 and earlier) models were susceptible to "large area flicker"

    - Heavier screen-door effect when compared to LCD or OLED based TVs

- Physical
    - Generally do not come in smaller sizes than 37 inches
    - Heavier than LCD due to the requirement of a glass screen to hold the gases

- Other
    - Use more electricity, on average, than an LCD TV
    - Do not work as well at high altitudes due to pressure differential between the gases inside the screen and the air pressure at altitude. It may cause a buzzing noise. Manufacturers rate their screens to indicate the altitude parameters.
    - For those who wish to listen to AM radio, or are Amateur Radio operators (Hams) or Shortwave Listeners (SWL), the Radio Frequency Interference (RFI) from these devices can be irritating or disabling.
    - Due to the strong infrared emissions inherent with the technology, standard IR repeater systems can not be used in the viewing room. A more expensive "plasma compatible" sensor must be used.

Native plasma television resolutions

Fixed-pixel displays such as plasma TVs scale the video image of each incoming signal to the native resolution of the display panel. The most common native resolutions for plasma display panels are 853×480 (EDTV), 1,366×768 or 1,920×1,080 (HDTV). As a result picture quality varies depending on the performance of the video scaling processor and the upscaling and downscaling algorithms used by each display manufacturer.

Enhanced-definition plasma television

Early plasma televisions were enhanced-definition (ED) with a native resolution of 840×480 (discontinued) or 853×480, and down-scaled their incoming high definition signals to match their native display resolution.

ED Resolutions

- 840×480
- 853×480

High-definition plasma television

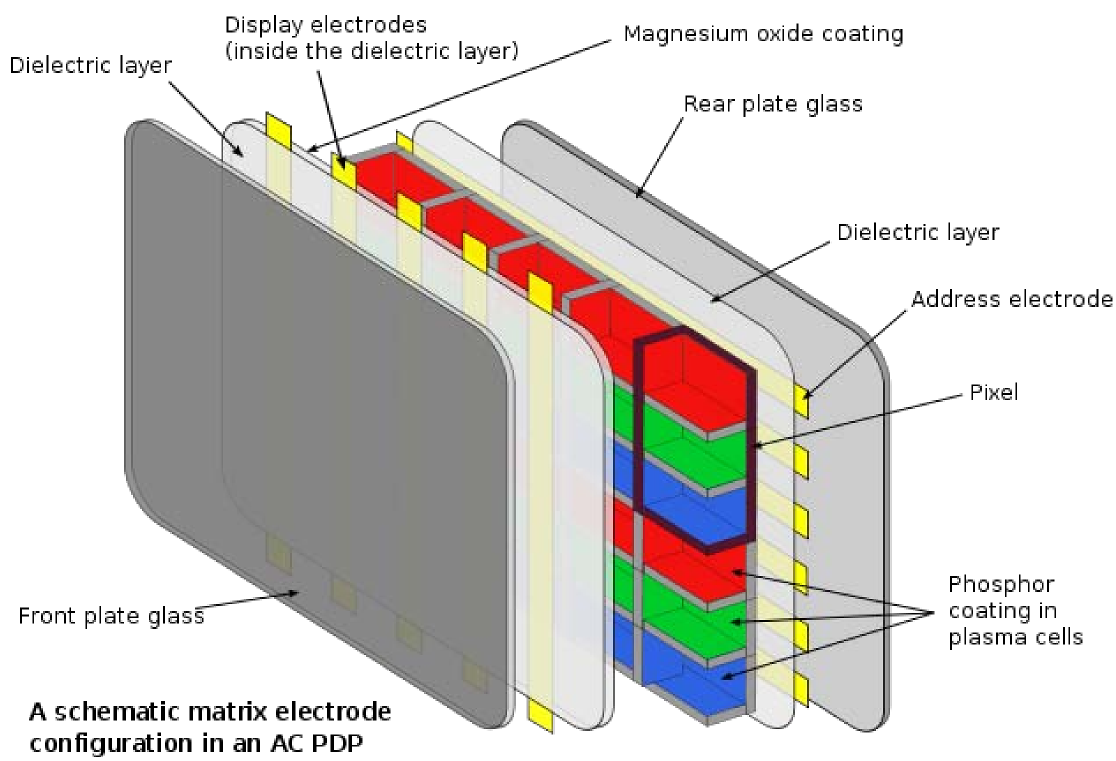
Early high-definition (HD) plasma displays had a resolution of 1024x1024 and were alternate lighting of surfaces (ALiS) panels made by Fujitsu/Hitachi. These were interlaced displays, with non-square pixels.

Modern HDTV plasma televisions usually have a resolution of 1,024×768 found on many 42 inch plasma screens, 1,280×768, 1,366×768 found on 50 in, 60 in, and 65 in plasma screens, or 1,920×1,080 found in plasma screen sizes from 42 inch to 103 inch. These displays are usually progressive displays, with square pixels, and will up-scale their incoming standard-definition signals to match their native display resolution.

HD Resolutions

- 1024×1024
- 1024×768
- 1280×768
- 1366×768
- 1280×1080
- 1920×1080

How plasma displays work



Composition of plasma display panel

A panel typically has millions of tiny cells in compartmentalized space between two panels of glass. These compartments, or "bulbs" or "cells", hold a mixture of noble gases and a minuscule amount of mercury. Just as in the fluorescent lamps over an office desk, when the mercury is vaporized and a voltage is applied across the cell, the gas in the cells form a plasma. With flow of electricity (electrons), some of the electrons strike mercury particles as the electrons move through the plasma, momentarily increasing the energy level of the molecule until the excess energy is shed. Mercury sheds the energy as ultraviolet (UV) photons. The UV photons then strike phosphor that is painted on the inside of the cell. When the UV photon strikes a phosphor molecule, it momentarily raises the energy level of an outer orbit electron in the phosphor molecule, moving the electron from a stable to an unstable state; the electron then sheds the excess energy as a photon at a lower energy level than UV light; the lower energy photons are mostly in the infrared range but about 40% are in the visible light range. Thus the input energy is shed as mostly heat (infrared) but also as visible light. Depending on the phosphors used, different colors of visible light can be achieved. Each pixel in a plasma display is made up of three cells comprising the primary colors of visible light. Varying the voltage of the signals to the cells thus allows different perceived colors.

A plasma display panel is an array of hundreds of thousands of small, luminous cells positioned between two plates of glass. Each cell is essentially a tiny neon lamp filled with rarefied neon, xenon, and other inert gases; the cells are luminous when they are electrified through "electrodes".

The long electrodes are stripes of electrically conducting material that also lie between the glass plates, in front of and behind the cells. The "address electrodes" sit behind the cells, along the rear glass plate, and can be opaque. The transparent display electrodes are mounted in front of the cell, along the front glass plate. As can be seen in the illustration, the electrodes are covered by an insulating protective layer. Control circuitry charges the electrodes that cross paths at a cell, creating a voltage difference between front and back. Some of the atoms in the gas of a cell then lose electrons and become ionized, which creates an electrically conducting plasma of atoms, free electrons, and ions. The collisions of the flowing electrons in the plasma with the inert gas atoms leads to light emission; such light-emitting plasmas are known as glow discharges.

In a monochrome plasma panel, the gas is usually mostly neon, and the color is the characteristic orange of a neon-filled lamp (or sign). Once a glow discharge has been initiated in a cell, it can be maintained by applying a low-level voltage between all the horizontal and vertical electrodes–even after the ionizing voltage is removed. To erase a cell all voltage is removed from a pair of electrodes. This type of panel has inherent memory. A small amount of nitrogen is added to the neon to increase hysteresis.

In color panels, the back of each cell is coated with a phosphor. The ultraviolet photons emitted by the plasma excite these phosphors, which give off visible light with colors determined by the phosphor materials. This aspect is comparable to fluorescent lamps and to the neon signs that use colored phosphors.

Every pixel is made up of three separate subpixel cells, each with different colored phosphors. One subpixel has a red light phosphor, one subpixel has a green light phosphor and one subpixel has a blue light phosphor. These colors blend together to create the overall color of the pixel, the same as a triad of a shadow mask CRT or color

LCD. Plasma panels use pulse-width modulation (PWM) to control brightness: by varying the pulses of current flowing through the different cells thousands of times per second, the control system can increase or decrease the intensity of each subpixel color to create billions of different combinations of red, green and blue. In this way, the control system can produce most of the visible colors. Plasma displays use the same phosphors as CRTs, which accounts for the extremely accurate color reproduction when viewing television or computer video images (which use an RGB color system designed for CRT display technology).

Plasma displays should not be confused with liquid crystal displays (LCDs), another lightweight flat-screen display using very different technology. LCDs may use one or two large fluorescent lamps as a backlight source, but the different colors are controlled by LCD units, which in effect behave as gates that allow or block the passage of light from the backlight to red, green, or blue paint on the front of the LCD panel.

Contrast ratio

Contrast ratio is the difference between the brightest and darkest parts of an image, measured in discrete steps, at any given moment. Generally, the higher the contrast ratio, the more realistic the image is (though the "realism" of an image depends on many factors including color accuracy, luminance linearity, and spatial linearity.) Contrast ratios for plasma displays are often advertised as high as 5,000,000:1. On the surface, this is a significant advantage of plasma over most other current display technologies, a notable exception being organic light-emitting diode. Although there are no industry-wide guidelines for reporting contrast ratio, most manufacturers follow either the ANSI standard or perform a full-on-full-off test. The ANSI standard uses a checkered test pattern whereby the darkest blacks and the lightest whites are simultaneously measured, yielding the most accurate "real-world" ratings. In contrast, a full-on-full-off test measures the ratio using a pure black screen and a pure white screen, which gives higher values but does not represent a typical viewing scenario. Some displays, using many different technologies, have some "leakage" of light, through either optical or electronic means, from lit pixels to adjacent pixels so that dark pixels that are near bright ones appear less dark than they do during a full-off display. Manufacturers can further artificially improve the reported contrast ratio by increasing the contrast and brightness settings to achieve the highest test values. However, a contrast ratio generated by this method is misleading, as content would be essentially unwatchable at such settings.

Plasma is often cited as having better (i.e. darker) black levels (and higher contrast ratios), although both plasma and LCD each have their own technological challenges.

Each cell on a plasma display has to be precharged before it is due to be illuminated (otherwise the cell would not respond quickly enough) and this precharging means the cells cannot achieve a true black, whereas an LED backlit LCD panel can actually turn off parts of the screen. Some manufacturers have worked hard to reduce the precharge and the associated background glow, to the point where black levels on modern plasmas are starting to rival CRT. With LCD technology, black pixels are generated by a light polarization method; many panels are unable to completely block the underlying backlight. However, more recent LCD panels (particularly those using white LED illumination) can compensate by automatically reducing the backlighting on darker scenes, though this method — analogous to the strategy of noise reduction on analog audio tape — obviously cannot be used in high-contrast scenes, leaving some light showing from black parts of an image with bright parts, such as (at the extreme) a solid black screen with one fine intense bright line. This is called a "halo" effect which has been almost completely minimized on newer LED backlit LCD's with local dimming. Edgelit models cannot compete with this as the light is reflected via a light funnell to distribute the light behind the panel.

Screen burn-in

An example of a plasma display that has suffered severe burn-in from stationary text

Image burn-in occurs on CRTs and plasma panels when the same picture is displayed for long periods of time. This causes the phosphors to overheat, losing some of their luminosity and producing a "shadow" image that is visible with the power off. Burn-in cannot be repaired (except on monochrome CRTs), and is especially a problem on plasma panels because they run hotter than CRTs. Early plasma televisions were plagued by burn-in, making it impossible to use video games or anything else that displayed static images.

Plasma displays also exhibit another image retention issue which is sometimes confused with screen burn-in damage. In this mode, when a group of pixels are run at high brightness (when displaying white, for example) for an extended period of time, a charge build-up in the pixel structure occurs and a ghost image can be seen. However, unlike burn-in, this charge build-up is transient and self corrects after the image condition that caused the effect has been removed and a long enough period of time has passed (with the display either off or on).

Plasma manufacturers have tried various ways of reducing burn-in such as using gray pillarboxes, pixel orbiters and image washing routines, but none to date have eliminated the problem and all plasma manufacturers continue to exclude burn-in from their warranties.

Environmental impact

Nitrogen trifluoride, cited as a very potent greenhouse gas, is used during production of plasma screens, which are therefore alleged to contribute to climate change. Plasma screens have also been lagging behind CRT and LCD screens in terms of energy consumption. To reduce the energy consumption, new technologies are also being found. Although it can be expected that plasma screens will continue to become more energy efficient in the future, a growing problem is that people tend to keep their old TVs running and an increasing trend to escalating screen sizes.

History

Plasma displays were first used in PLATO computer terminals. This PLATO V model illustrates the display's monochromatic orange glow as seen in 1988.

In 1936 Kálmán Tihanyi described the principle of "plasma television" and conceived the first flat-panel television system.

The monochrome plasma video display was co-invented in 1964 at the University of Illinois at Urbana-Champaign by Donald Bitzer, H. Gene Slottow, and graduate student Robert Willson for the PLATO Computer System. The original neon orange monochrome Digivue display panels built by glass producer Owens-Illinois were very popular in the early 1970s because they were rugged and needed neither memory nor circuitry to refresh the images. A long period of sales decline occurred in the late 1970s because semiconductor memory made CRT displays cheaper than the US$2500 512 x 512 PLATO plasma displays. Nonetheless, the plasma displays' relatively large screen size and 1 inch thickness made them suitable for high-profile placement in lobbies and stock exchanges.

Electrical engineering student Larry F. Weber became interested in plasma displays while studying at the University of Illinois at Urbana-Champaign in the 1960s, and pursued postgraduate work in the field under Bitzer and Slottow. His research eventually earned him 15 patents relating to plasma displays. One of his early contributions was development of the power-saving "energy recovery sustain circuit", now included in every color plasma display.

Burroughs Corporation, a maker of adding machines and computers, developed the Panaplex display in the early 1970s. The Panaplex display, generically referred to as a gas-discharge or gas-plasma display, uses the same technology as later plasma video displays, but began life as seven-segment display for use in adding machines. They became popular for their bright orange luminous look and found nearly ubiquitous use in cash registers, calculators, pinball machines, aircraft avionics such as radios, navigational instruments, and stormscopes; test equipment such as frequency counters and multimeters; and generally anything that previously used nixie tube or numitron displays with a high digit-count throughout the late 1970s and into the 1990s. These displays remained popular until LEDs gained popularity because of their low-current draw and module-flexibility, but are still found in some applications where their high-brightness is desired, such as pinball machines and avionics. Pinball displays started with six- and seven-digit seven-segment displays and later evolved into 16-segment alphanumeric displays, and later into 128x32 dot-matrix displays in 1990, which are still used today.

1983

In 1983, IBM introduced a 19-inch (48 cm) orange-on-black monochrome display (model 3290 'information panel') which was able to show up to four simultaneous IBM 3270 terminal sessions. Due to heavy competition from monochrome LCD's, in 1987 IBM planned to shut down its factory in upstate New York, the largest plasma plant in the world, in favor of manufacturing mainframe computers. Consequently, Larry Weber co-founded a startup company Plasmaco with Stephen Globus, as well as James Kehoe, who was the IBM plant manager, and bought the plant from IBM. Weber stayed in Urbana as CTO until 1990, then moved to upstate New York to work at Plasmaco.

1992

In 1992, Fujitsu introduced the world's first 21-inch (53 cm) full-color display. It was a hybrid, the plasma display created at the University of Illinois at Urbana-Champaign and NHK Science & Technology Research Laboratories.

1994

In 1994, Weber demonstrated color plasma technology at an industry convention in San Jose. Panasonic Corporation began a joint development project with Plasmaco, which led in 1996 to the purchase of Plasmaaco, its color AC technology, and its American factory.

1997

In 1997, Fujitsu introduced the first 42-inch (107 cm) plasma display; it had 852x480 resolution and was progressively scanned. Also in 1997, Philips introduced a 42-inch (107 cm) display, with 852x480 resolution. It was the only plasma to be displayed to the retail public in 4 Sears locations in the US. The price was US$14,999 and included in-home installation. Later in 1997, Pioneer started selling their first plasma television to the public, and others followed.

2006 - Present

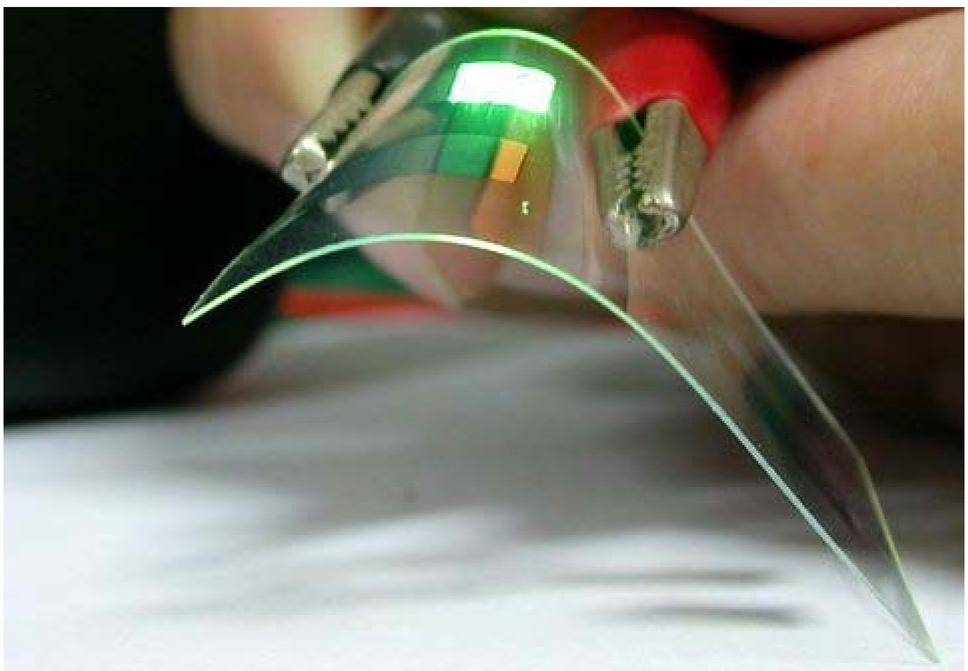
In late 2006, analysts noted that LCDs overtook plasmas, particularly in the 40-inch (1.0 m) and above segment where plasma had previously gained market share. Another industry trend is the consolidation of manufacturers of plasma displays, with around fifty brands available but only five manufacturers. In the first quarter of 2008 a comparison of worldwide TV sales breaks down to 22.1 million for direct-view CRT, 21.1 million for LCD, 2.8 million for Plasma, and 0.1 million for rear-projection.

Until the early 2000s, plasma displays were the most popular choice for HDTV flat panel display as they had many benefits over LCDs. Beyond plasma's deeper blacks, increased contrast, faster response time, greater color spectrum, and wider viewing angle; they were also much bigger than LCDs, and it was believed that LCD technology was suited only to smaller sized televisions. However, improvements in VLSI fabrication technology have since narrowed the technological gap. The increased size, lower weight, falling prices, and often lower electrical power consumption of LCDs now make them competitive with plasma television sets.

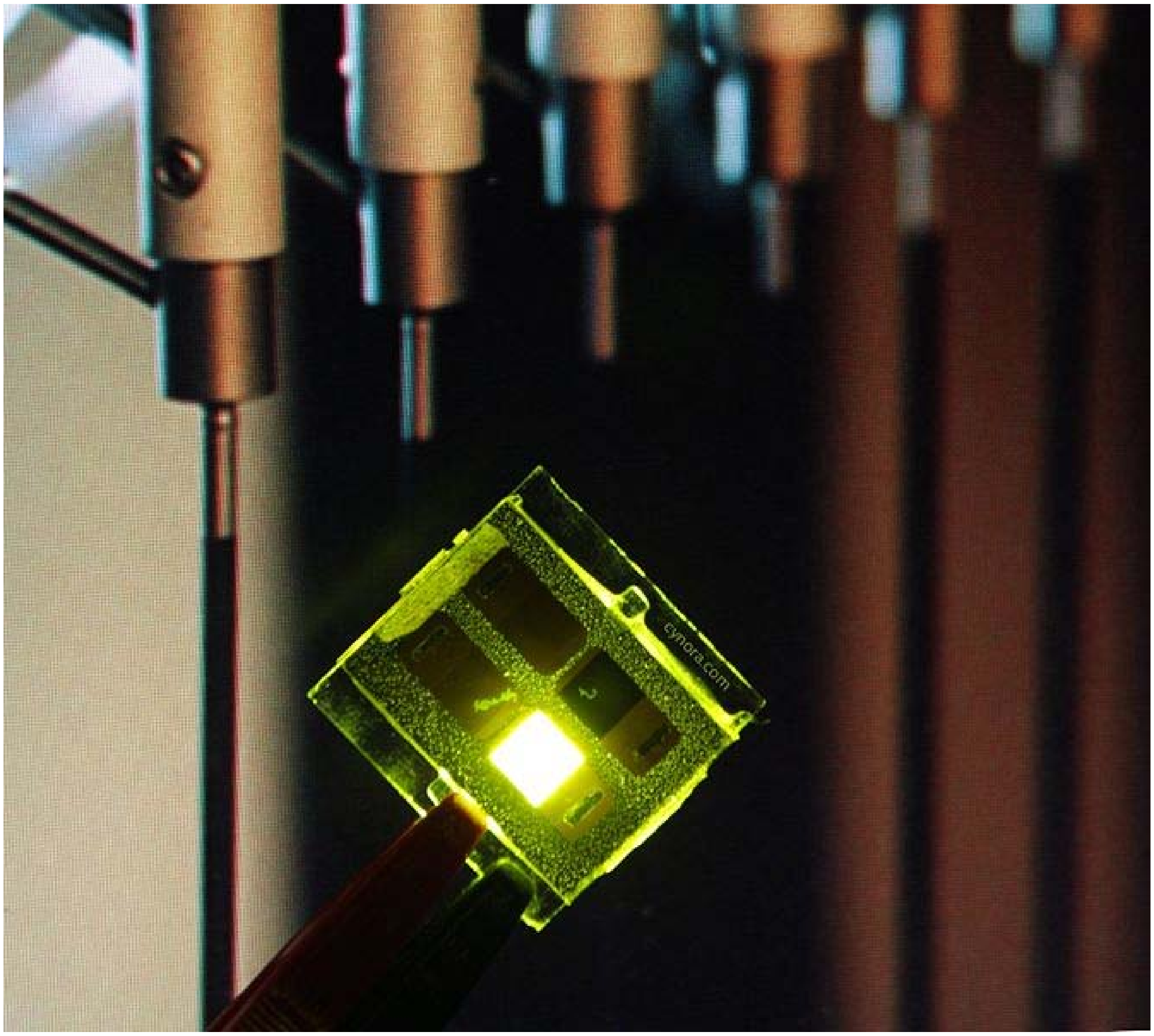
Screen sizes have increased since the introduction of plasma displays. The largest plasma video display in the world at the 2008 Consumer Electronics Show in Las Vegas, Nevada, was a 150-inch (381 cm) unit manufactured by Matsushita Electric Industrial (Panasonic) standing 6 ft (180 cm) tall by 11 ft (330 cm) wide. At the 2010 Consumer Electronics Show in Las Vegas, Panasonic introduced their 152" 2160p 3D plasma. In 2010 Panasonic shipped 19.1 million plasma TV panels.

Chapter-5

Organic Light-emitting Diode



Demonstration of a flexible OLED device



A green emitting OLED device

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 space illumination and in large-area light-emitting elements. Due to their 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 be thinner and lighter than liquid crystal displays. 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.

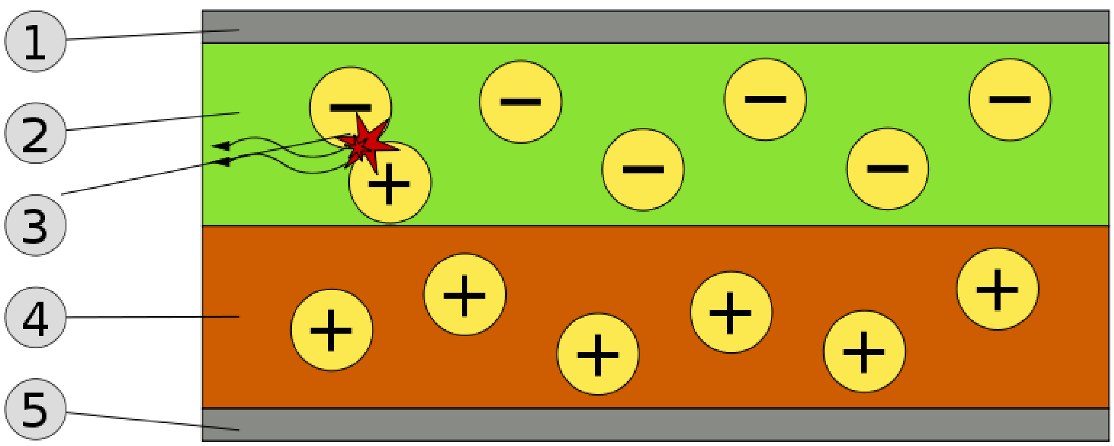
Device performance was limited by the poor electrical conductivity of contemporary organic materials. This was overcome by the discovery and development of highly conductive polymers.

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.

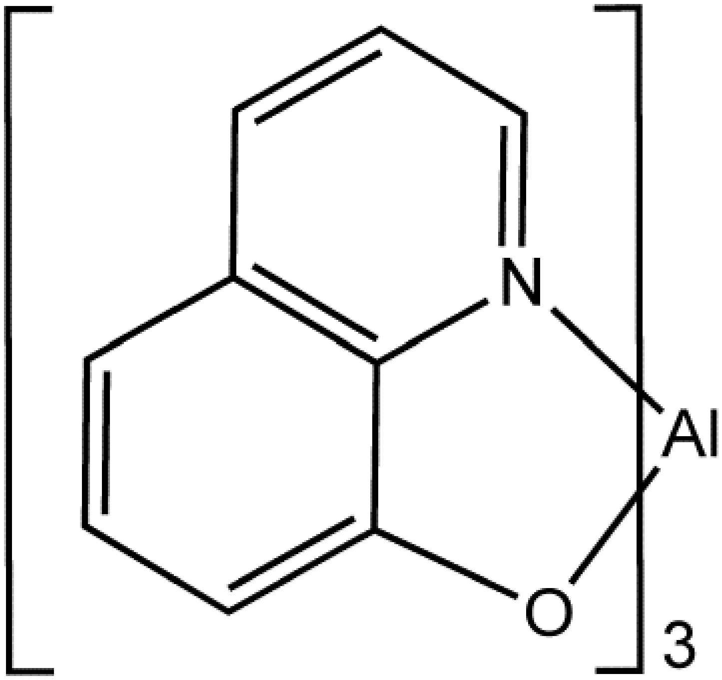
As electrons and holes are fermions with half integer spin, an exciton may either be in a singlet state or a triplet state depending on how the spins of the electron and hole have been combined. Statistically three triplet excitons will be formed for each singlet exciton. Decay from triplet states (phosphorescence) 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$_3$, commonly used in small molecule OLEDs.

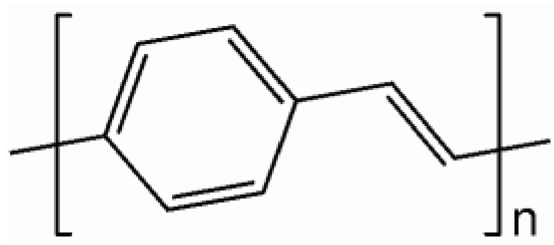
Efficient OLEDs using small molecules were first developed by Dr. Ching W. Tang *et al.* at Eastman Kodak. The term OLED traditionally refers specifically to this type of device, though the term SM-OLED is also in use.

Molecules commonly used in OLEDs include organometallic chelates (for example Alq$_3$, 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$_3$ 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.

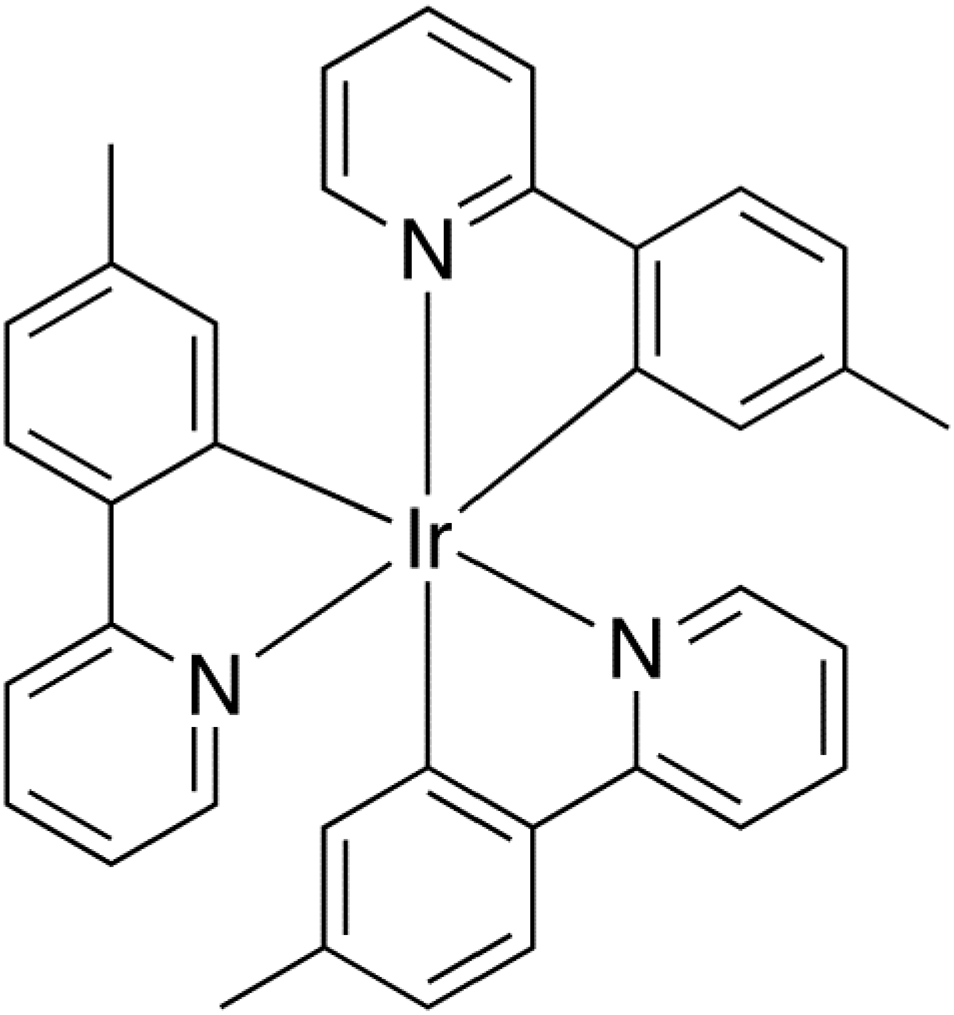
Polymer light-emitting diodes (PLED), also light-emitting polymers (LEP), involve an electroluminescent conductive polymer that emits light when connected to an external voltage. They are used as a thin film for full-spectrum colour displays. Polymer OLEDs are quite efficient and require a relatively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



Ir(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 Ir(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^2.

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. Roll-roll vapour-deposition methods for organic devices do allow mass production of thousands of devices per minute for minimal cost, although this technique also induces problems in that multi-layer devices can be challenging to make.

- **Light weight & flexible plastic substrates:** OLED displays can be fabricated on flexible plastic substrates leading to the possibility of flexible organic light-emitting diodes 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.

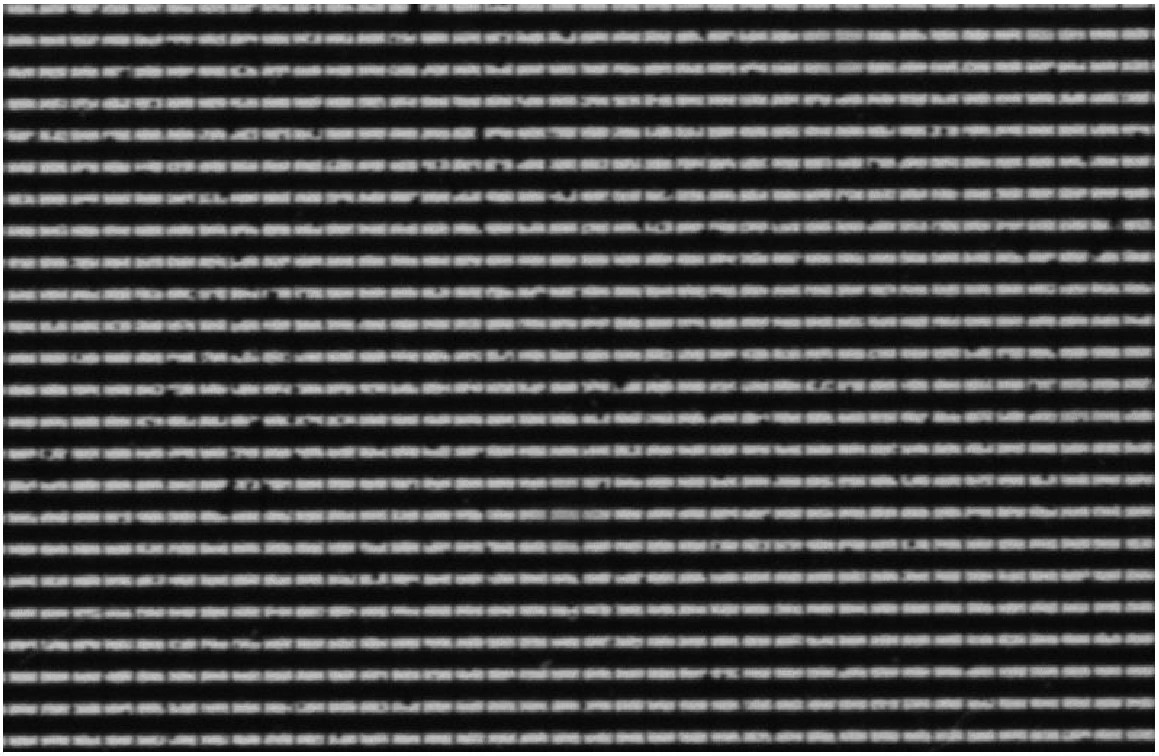
- **Wider viewing angles & improved brightness:** OLEDs can enable a greater artificial contrast ratio (both dynamic range and static, measured in purely dark conditions) and viewing angle compared to LCDs because OLED pixels directly emit light. OLED pixel colours appear correct and unshifted, even 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

- **Current costs:** OLED manufacture currently requires process steps that make it extremely expensive. Specifically, it requires the use of Low-Temperature Polysilicon backplanes; LTPS backplanes in turn require laser annealing from an amorphous silicon start, so this part of the manufacturing process for AMOLEDs starts with the process costs of standard LCD, and then adds an expensive, time-consuming process that cannot currently be used on large-area glass substrates.

- **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 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.

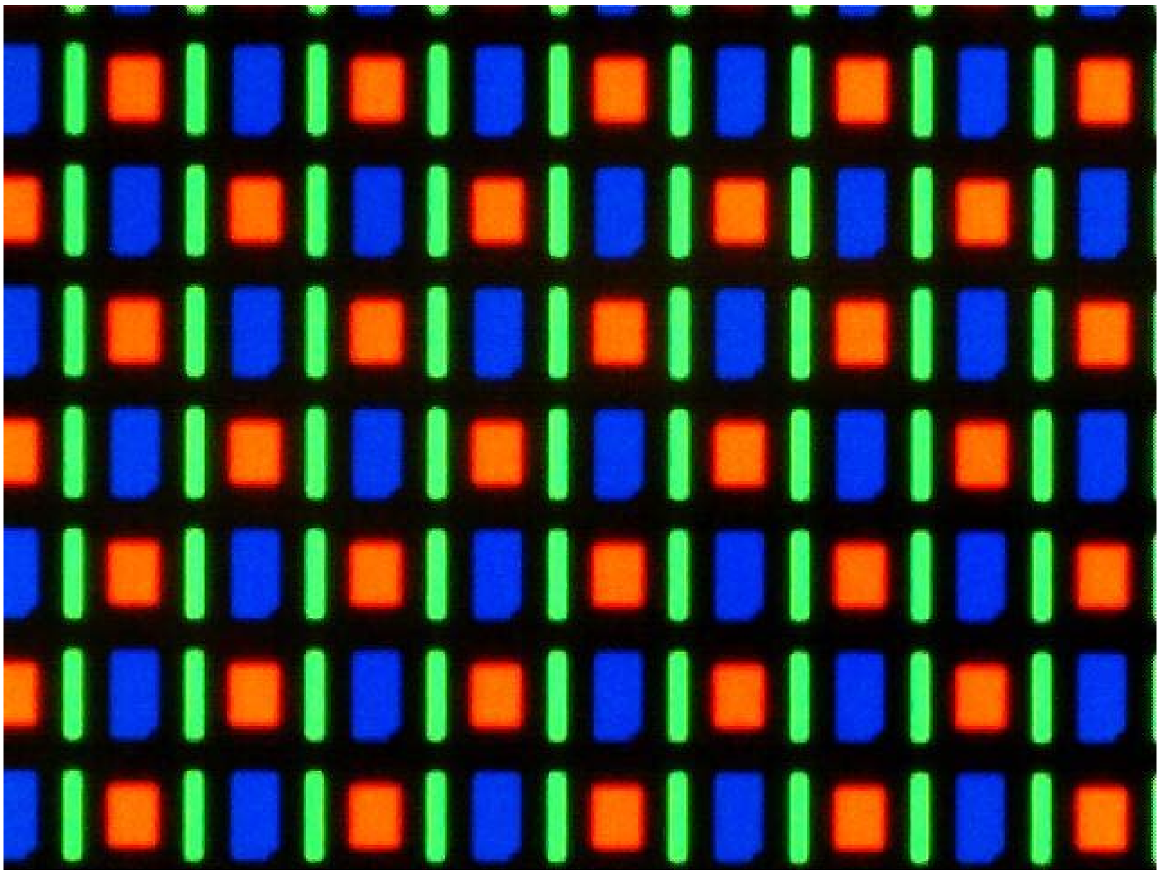
- **Outdoor performance:** As an emissive display technology, OLEDs rely completely upon converting electricity to light, unlike most LCDs which are to some extent reflective; e-ink leads the way in efficiency with ~ 33% ambient light reflectivity, enabling the display to be used without any internal 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 reduced real-world battery life in mobile devices.

- **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 Bluray pointer) and can damage the display almost instantly with more than 20 mW 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.

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/m². 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/m² (peak luminance of 600 cd/m²).

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. In January 2011 Samsung announced their Super AMOLED Plus displays - which offer several advances over the older Super AMOLED displays - real stripe matrix (50% more sub pixels), thinner form factor, brighter image and a 18% reduction in energy consumption.

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 Next Generation Portable handheld game console (the successor to the PSP) will feature a 5-inch OLED screen.

On February 17, 2011, Sony announced its 25" OLED Professional Reference Monitor aimed at the Cinema and high end Drama Post Production market.

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-6

Surface-conduction Electron-emitter Display

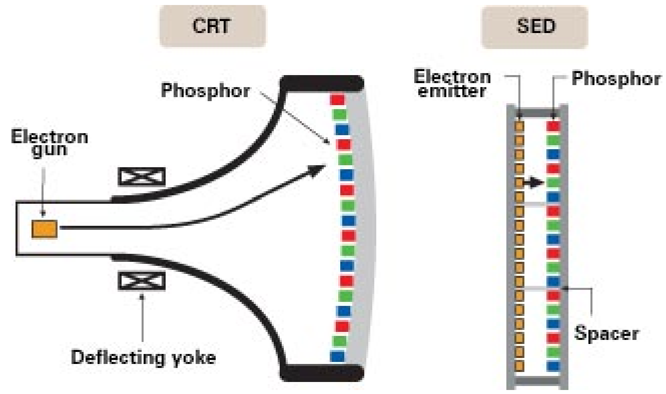
Canon's 36" prototype SED, shown at the 2006 CES.

Another view of the same display.

A **surface-conduction electron-emitter display** (**SED**) is a flat panel color television technology currently being developed by a number of companies. SEDs use nanoscopic-scale electron emitters to energize colored phosphors and produce an image. In a general sense, a SED consists of a matrix of tiny cathode ray tubes, each "tube" forming a single sub-pixel on the screen, grouped in threes to form red-green-blue (RGB) pixels. SEDs combine the advantages of CRTs, namely their high contrast ratios, wide viewing angles and very fast response times, with the packaging advantages of LCD and other flat panel displays. They also use much less power than an LCD television of the same size.

After considerable time and effort in the early and mid-2000s, SED efforts started winding down in 2009 as LCD became the dominant technology. In August 2010, Canon announced they were shutting down their joint effort to develop SEDs commercially, signalling the end of development efforts. SEDs are closely related to another developing display technology, the field emission display, or FED, differing primarily in the details of the electron emitters. Sony, the main backer of FED, has similarly backed off from their development efforts.

Description



A conventional cathode ray tube (CRT) is powered by an electron gun, essentially an open-ended vacuum tube. At one end of the gun electrons are produced by "boiling" them off a metal filament, which requires relatively high currents and consumes a large proportion of the CRT's power. The electrons are then accelerated and focused into a fast-moving beam, flowing forward towards the screen. Electromagnets surrounding the gun end of the tube are used to steer the beam as it travels forward, allowing the beam to be scanned across the screen to produce a 2D display. When the fast-moving electrons strike phosphor on the back of the screen, light is produced. Color images are produced by painting the screen with spots or stripes of three colored phosphors, one each for red, green and blue (RGB). When viewed from a distance, the spots, known as "sub-pixels", blend together in the eye to produce a single colored spot known as a pixel.

The SED replaces the single gun of a conventional CRT with a grid of nanoscopic emitters, one for each sub-pixel of the display. The surface conduction electron emitter apparatus consists of a thin slit across which electrons jump when powered with high-voltage gradients. Due to the nanoscopic size of the slits, the required field can correspond to a potential on the order of tens of volts. A few of the electrons, on the order of 3%, impact with slit material on the far side and are scattered out of the emitter surface. A second field, applied externally, accelerates these scattered electrons towards the screen. Production of this field requires kilovolt potentials, but is a constant field requiring no switching, so the electronics that produce it are quite simple.

Each emitter is aligned behind a colored phosphor dot, and the accelerated electrons strike the dot and cause it to give off light in a fashion identical to a conventional CRT. Since each dot on the screen is lit by a single emitter, there is no need to steer or direct the beam as there is in an CRT. The quantum tunneling effect that emits electrons across the slits is highly non-linear, and the process tends to be fully on or off for any given voltage. This allows the selection of particular emitters by powering a single horizontal row on the screen and then powering all of the needed vertical columns at the same time, thereby powering the selected emitters. Any power leaked from one column to surrounding emitters will cause too small a field to produce a visible output; if that emitter was not turned on the leaked power will be too low to switch it, if it was already on the additional power will have no visible effect. This allows SED displays to work without an active matrix of thin-film transistors that LCDs and similar displays require, and further reduces the complexity of the emitter array. However, this also means that changes in voltage cannot be used to control the brightness of the resulting pixels. Instead, the emitters are rapidly turned on and off using pulse width modulation, so that the total brightness of a spot in any given time can be controlled.

SED screens consist of two glass sheets separated by a few millimeters, the rear layer supporting the emitters and the front the phosphors. The front is easily prepared using methods similar to existing CRT systems; the phosphors are painted onto the screen using a variety of silkscreen or similar technologies, and then covered with a thin layer of aluminum to make the screen visibly opaque and provide an electrical return path for the electrons once they strike the screen. In the SED, this layer also serves as the front electrode that accelerates the electrons toward the screen, held at a constant high voltage relative to the switching grid. As is the case with modern CRT's, a dark mask is applied to the glass before the phosphor is painted on, to give the screen a dark charcoal grey color and improve contrast ratio.

Creating the rear layer with the emitters is a multi-step process. First, a matrix of silver wires is printed on the screen to form the rows or columns, an insulator is added, and then the columns or rows are deposited on top of that. Electrodes are added into this array, typically using platinum, leaving a gap of about 60 micrometres between the columns. Next, square pads of palladium oxide (PdO) only 20 nm thick are deposited into the gaps between the electrodes, connecting to them to supply power. A small slit is cut into the pad in the middle by repeatedly pulsing high currents though them, the resulting erosion causing a gap to form. The gap in the pad forms the emitter. The width of the gap has to be tightly controlled in order to work properly, and this proved difficult to control in practice.

Modern SEDs add another step that greatly eases production. The pads are deposited with a much larger gap between them, as much as 50 nm, which allows them to be added directly using technology adapted from inkjet printers. The entire screen is then placed in an organic gas and pulses of electricity are sent through the pads. Carbon in the gas is pulled onto the edges of the slit in the PdO squares, forming thin films that extend vertically off the tops of the gaps and grow toward each other at a slight angle. This process is self-limiting; if the gap gets too small the pulses erode the carbon, so the gap width can be controlled to produce a fairly constant 5 nm slit between them.

Since the screen needs to be held in a vacuum in order to work, there is a large inward force on the glass surfaces due to the surrounding atmospheric pressure. Because the emitters are laid out in vertical columns, there is a space between each column where there is no phosphor, normally above the column power lines. SEDs use this space by placing thin sheets or rods on top of the conductors that keep the two glass surfaces apart. A series of these is used to reinforce the screen over its entire surface, which greatly reduces the needed strength of the glass itself. A CRT has no place for similar reinforcements, so the glass at the front screen has to be thick enough to support all the pressure. SEDs are thus much thinner and lighter than CRTs.

Comparison

The primary large-screen television technology being deployed in the 2000s is the liquid crystal display televisions. SEDs are aimed at the same market segment.

LCDs do not directly produce light, and have to be back-lit using cold cathode fluorescent lamps (CCFLs) or high-power LEDs. The light is first passed through a polarizer, which cuts out half of the light. It then passes through the LCD layer, which selectively reduces the output for each sub-pixel. In front of the LCD shutters are small colored filters, one for each RGB sub-pixel. Since the colored filters cut out all but a narrow band of the white light, the amount of light that reaches the viewer is always less than 1/3 of what left the polarizer. Since the color gamut is produced by selectively reducing the output for certain colors, in practice much less light makes it through to the view, about 8 to 10% on average. In spite of using highly efficient light sources, an LCD display uses about the same power as a CRT of the same size.

LCD shutters consist of an encapsulated liquid that changes its polarization in response to an applied electrical field. This response is fairly linear, so even a small amount of leaked power that reaches surrounding shutters causes the image to become blurry. To counteract this effect, and improve switching speed, LCD displays use an Active matrix addressing of transparent thin-film transistors to directly switch each shutter. This adds complexity to the LCD screen and makes them more difficult to manufacture. The shutters are not perfect and allow light to leak through, which means that the contrast ratio of an LCD is less than that of a CRT, and this causes the color gamut to be reduced as well. Additionally the use of a polarizer to create the shutter limits the viewing angles where this contrast can be maintained. Most importantly, the switching process takes some time, on the order of milliseconds, which leads to blurring on fast moving scenes. Massive investment in the LCD manufacturing process has addressed all of these concerns to some degree.

The SED produces light directly on its front surface. Scenes are lit only on those pixels that require it, and only to the amount of brightness they require. In spite of the light generating process being less efficient than CCFLs or LEDs, the overall power efficiency of an SED is about ten times better than a LCD of the same size. SEDs are also much less complex in overall terms – they lack the active matrix layer, backlighting section, color filters and the driver electronics that adjusts for various disadvantages in the LCD shuttering process. Despite of having two glass layers instead of one in a typical LCD, this reduction in overall complexity makes SEDs similar in weight and size as LCDs.

Canon's 55" prototype SED offered bright images of 450 cd/m^2, 50,000:1 contrast ratios, and a response time of less than 1 ms. Canon has stated that production versions would improve the response time to 0.2 ms and 100,000:1 contrast ratios. SEDs can be viewed from extremely wide angles without any effect on the quality of the image.

In comparison, a modern LCD televisions like the Sony KDL-52W4100 claims to offer 30,000:1 contrast ratios, but this uses the "dynamic contrast" measurement, and the "on-screen contrast ratio" is a more realistic 3,000:1. Contrast ratios of LCD televisions are widely inflated in this manner. The same set claims to offer viewing angles of 178 degrees, but the useful viewing angles are much narrower, and beyond that the color gamut changes. Sony does not quote their response times, but 4 ms is common for larger sets, although this is also a dynamic measurement that only works for certain transitions.

SEDs are very closely related to the field emission display (FED), differing only in the details of the emitter. FEDs use small spots containing hundreds of carbon nanotubes whose sharp tips give off electrons when placed in a strong electrical field. FEDs suffer from erosion of the emitters, and require extremely high vacuum in order to operate. For this reason, industry observers generally state that the SED is a more practical design. FEDs have one advantage the SED does not offer; since each sub-pixel has hundreds of emitters, "dead" emitters can be corrected by applying slightly more power to the working ones. In theory, this could increase yields because the chance of a pixel being completely dead is very low, and the chance that a screen has many dead pixels is greatly reduced. Sony has demonstrated a 26" FED drawing only 12 W showing a bright scene, SEDs should be even lower powered.

Throughout the flat-screen introduction, several other technologies had been vying with LCDs and PDPs for market acceptance. Among these were the SED, the FED, and the organic light-emitting diode system that uses printable LEDs. All of these shared the advantages of low power use, excellent contrast ratio and color gamut, fast response times and wide viewable angles. All of them also shared the problem of scaling up manufacturing to produce large screens. Example systems of limited size, generally 13", have been shown for several years and are available for limited sales, but wide-scale production has not started on any of these alternatives.

History

Canon began SED research in 1986. Their early research used PdO electrodes without the carbon films on top, but controlling the slit width proved difficult. At the time there were a number of flat-screen technologies in early development, and the only one close to commercialization was the plasma display panel (PDP), which had numerous disadvantages – manufacturing cost and energy use among them. LCDs were not suitable for larger screen sizes due to low yields and complex manufacturing.

In 2004 Canon signed an agreement with Toshiba to create a joint venture to continue development of SED technology, forming "SED Ltd." Toshiba introduced new technology to pattern the conductors underlying the emitters using technologies adapted from inkjet printers. At the time both companies claimed that production was slated to begin in 2005. Both Canon and Toshiba started displaying prototype units at trade shows during 2006, including 55" and 36" units from Canon, and a 42" unit from Toshiba. They were widely lauded in the press for their image quality, saying it was "something that must be seen to believe[d]."

However, by this point Canon's SED introduction date had already slipped several times. It was first claimed it would go into production in 1999. This was pushed back to 2005 after the joint agreement, and then again into 2007 after the first demonstrations at CES and other shows.

In October 2006, Toshiba's president announced the company plans to begin full production of 55-inch SED TVs in July 2007 at its recently built SED volume-production facility in Himeji.

In December 2006, Toshiba President and Chief Executive Atsutoshi Nishida said Toshiba was on track to mass-produce SED TV sets in cooperation with Canon by 2008. He said the company planned to start small-output production in the fall of 2007, but they do not expect SED displays to become a commodity and will not release the technology to the consumer market because of its expected high price, reserving it solely for professional broadcasting applications.

Also, in December 2006 it was revealed that one reason for the delay was a lawsuit brought against Canon by Applied Nanotech. On 25 May 2007, Canon announced that the prolonged litigation would postpone the launch of SED televisions, and a new launch date would be announced at some date in the future.

Applied Nanotech, a subsidiary of Nano-Proprietary, holds a number of patents related to FED and SED manufacturing. They had sold Canon a perpetual license for a coating technology used in their newer carbon-based emitter structure. Applied Nanotech claimed that Canon's agreement with Toshiba amounted to an illegal technology transfer, and a separate agreement would have to be reached. They first approached the problem in April 2005.

Canon responded to the lawsuit with several actions. On 12 January 2007 they announced that they would buy all of Toshiba's shares in SED Inc. in order to eliminate Toshiba's involvement in the venture. They also started re-working their existing RE40,062 patent filing in order to remove any of Applied Nanotech's technologies from their system. The modified patent was issued on 12 February 2008.

On 22 February 2007, the U.S. District Court for the Western District of Texas, a district widely known for agreeing with patent holders in intellectual property cases, ruled in a summary judgment that Canon had violated its agreement by forming a joint television venture with Toshiba. However, on 2 May 2007 a jury ruled that no additional damages beyond the $5.5m fee for the original licensing contract were due.

On 25 July 2008, the U.S. Court of Appeals for the 5th Circuit reversed the lower court's decision and provided that Canon's "irrevocable and perpetual" non-exclusive licence was still enforceable and covers Canon's restructured subsidiary SED. On 2 December 2008, Applied Nanotech dropped the lawsuit, stating that continuing the lawsuit "would probably be a futile effort".

In spite of their legal success, Canon announced at the same time that the financial crisis of 2008 was making introduction of the sets far from certain, going so far as to say they would not be launching the product at that time "because people would laugh at them".

Canon also had an ongoing OLED development process that started in the midst of the lawsuit. In 2007 they announced a joint deal to form "Hitachi Displays Ltd.", with Matsushita and Canon each taking a 24.9% share of Hitachi's existing subsidiary. Canon later announced that they were purchasing Tokki Corp, a maker of OLED fabrication equipment.

In April 2009 during NAB 2009, Peter Putman was quoted as saying "I was asked on more than one occasion about the chances of Canon's SED making a comeback, something I would not have bet money on after the Nano Technologies licensing debacle. However, a source within Canon told me at the show that the SED is still very much alive as a pro monitor technology. Indeed, a Canon SED engineer from Japan was quietly making the rounds in the Las Vegas Convention Center to scope out the competition."

Canon officially announced on 25 May 2010 the end of the development of SED TVs for the home consumer market, but indicated that they will continue development for commercial applications like medical equipment. On 18 August 2010, Canon decided to liquidate SED Inc., a consolidated subsidiary of Canon Inc. developing SED technology, citing difficulties to secure appropriate profitability and effectively ending hopes to one day see SED TVs in the living room.

Chapter-7

Field Emission Display and LED Display

Field emission display

A **field emission display** (**FED**) is a flat panel display technology that uses large-area field electron sources to provide electrons that strike colored phosphor to produce a color image. In a general sense, a FED consists of a matrix of cathode ray tubes, each tube producing a single sub-pixel, grouped in threes to form red-green-blue (RGB) pixels. FEDs combine the advantages of CRTs, namely their high contrast levels and very fast response times, with the packaging advantages of LCD and other flat panel technologies. They also offer the possibility of requiring less power, about half that of an LCD system.

After considerable time and effort in the early and mid-2000s, Sony's FED efforts started winding down in 2009 as LCD became the dominant technology. In January 2010, AU Optronics announced that it acquired essential FED assets from Sony and intends to continue development of the technology.

FEDs are closely related to another developing display technology, the surface-conduction electron-emitter display, or SED, differing primarily in details of the electron emission system. In August 2010, Canon announced they were shutting down their joint effort to develop SEDs commercially, signalling the end of development efforts.

Operation

FED display operates like a conventional cathode ray tube (CRT) with an electron gun that uses high voltage (10 kV) to accelerate electrons which in turn excite the phosphors, but instead of a single electron gun, a FED display contains a grid of individual nanoscopic electron guns.

A FED screen is constructed by laying down a series of metal stripes onto a glass plate to form a series of cathode lines. Photolithography is used to lay down a series of rows of switching gates at right angles to the cathode lines, forming an addressable grid. At the intersection of each row and column a small patch of emitters are deposited, typically using methods developed from inkjet printers. The metal grid is laid on top of the switching gates to complete the gun structure.

A high voltage-gradient field is created between the emitters and a metal mesh suspended above them, pulling electrons off the tips of the emitters. This is a highly non-linear process and small changes in voltage will quickly cause the number of emitted electrons to saturate. The grid can be individually addressed but only the emitters located at the crossing points of the powered cathode and gate lines will have enough power to produce a visible spot, and any power leaks to surrounding elements will not be visible. The non-linearity of the process allows avoidance of active matrix addressing schemes – once the pixel lights up, it will naturally glow for some time. Non-linearity also means that the brightness of the sub-pixel is pulse-width modulated to control the number of electrons being produced, like in plasma displays.

The grid voltage sends the electrons flowing into the open area between the emitters at the back and the screen at the front of the display, where a second accelerating voltage additionally accelerates them towards the screen, giving them enough energy to light the phosphors. Since the electrons from any single emitter are fired toward a single sub-pixel, the scanning electromagnets are not needed.

Disadvantages

Just like any other displays with individually addressable sub-pixels, FED displays can potentially suffer from manufacturing problems that will result in dead pixels. However, the emitters are so small that many "guns" can power a sub-pixel, the screen can be examined for dead emitters and brightness corrected by increasing the pulse width to make up for the loss through increased emissions from the other emitters feeding the same pixel

The efficiency of the field emitters is based on the extremely small radii of the tips, but this small size renders the cathodes susceptible to damage by ion impact. The ions are produced by the high voltages interacting with residual gas molecules inside the device.

FED display requires a vacuum to operate, so the display tube has to be sealed and mechanically robust. However, since the distance between the emitters and phosphors is quite small, generally a few millimeters, the screen can be mechanically reinforced by placing spacer strips or posts between the front and back face of the tube.

FEDs require high vacuum levels which are difficult to attain: the vacuum suitable for conventional CRTs and vacuum tubes is not sufficient for long term FED operation. Intense electron bombardment of the phosphor layer will also release gas during use.

Competing technologies

CRT

FEDs eliminate much of the electrical complexity of a CRT, including the heated filaments in the electron gun and the electromagnets used to steer the beam, and are thus much more power efficient than a CRT of similar size.

LCD

Flat-panel LCD displays use a bright light source and filter out half of the light with a polarizer, and then filter most of the light to produce red green and blue (RGB) sources for the sub-pixels. That means that only 1/6 (or less in practice) of the light being generated at the back of the tube reaches the screen, at best. In most cases the LCD itself then filters out additional light in order to change the brightness of the sub-pixels and produce a color gamut. So in spite of using extremely efficient light sources like cold cathode fluorescent lamps or high-power white LEDs, the overall efficiency of an LCD display is not very high. Although the lighting process used in the FED is less efficient, only lit sub-pixels require power, which means that FEDs are more efficient than LCDs. Sony's 36" FED prototypes have been shown drawing only 14 W when displaying brightly lit scenes, whereas a conventional LCD screen of similar size would normally draw well over 100 W.

Avoiding the need for a backlighting system and thin-film transistor active matrix also greatly reduces the complexity of the set as a whole, while also reducing its front-to-back thickness. While a FED has two sheets of glass instead of the one in an LCD, the overall weight is likely to be less than a similarly sized LCD. FEDs are also claimed to be cheaper to manufacture, as they have fewer total components and processes involved. However, they are not easy devices to manufacture as a reliable commercial device, and considerable production difficulties have been encountered. This had led to a race with two other front-running technologies aiming to replace LCDs in television use, the Active-Matrix OLED and surface-conduction electron-emitter display, or SED.

OLED

Organic light-emitting diodes (OLED) are similar to the LCDs but replace the backlights and polarizing cells with an OLED cell that directly emits light. They require no separate light source, and are highly efficient in terms of light output. They offer the same high contrast levels and fast response times that FED offers. OLEDs are a serious competitor to FEDs, but suffer from the same sorts of problems bringing them to mass production.

SED

SEDs are very similar to FEDs, the primary difference between the two technologies is that SED uses a single emitter for each column instead of the individual spots of the FED. Whereas a FED uses electrons emitted directly toward the front of the screen, the SED uses electrons that are emitted from the vicinity of a small "gap" in a surface-conducting track laid down parallel to the plane of the panel, and extracted sideways to their original direction of motion. SED uses an emitter array based on palladium oxide laid down by an inkjet or silk-screen process. SED has been considered to be the variant of FED that is feasible to mass-produce, however, as of late 2009 no commercial SED display products have been made available by the industry.

History

The first concentrated effort to develop FED systems started in 1991 by Silicon Video Corporation1, later Candescent Technologies. Their "ThinCRT" displays used metal emitters, originally built out of tiny molybdenum cones known as Spindt tips. They suffered from erosion due to the high accelerating voltages. Attempts to lower accelerating voltages and find suitable phosphors that would work at lower power levels, as well as address the erosion problem through better materials, were unsuccessful.

Candescent pushed ahead with development in spite of problems, breaking ground on a new production facility in Silicon Valley in 1998, partnering with Sony. However the technology was not ready, and the company suspended equipment purchases in early 1999, citing "contamination issues". The plant was never completed, and after spending $600 million on development they filed for Chapter 11 protection in June 2004, and sold all of their assets to Canon that August.

Another attempt to address the erosion issues was made by Advance Nanotech, a subsidiary of SI Diamond Technology of Austin, Texas. Advance Nanotech developed a doped diamond dust, whose sharp corners appeared to be an ideal emitter. However the development never panned out and was adandoned in 2003. Advance Nanotech then applied their efforts to the similar SED display, licensing their technology to Canon. When Canon brought in Toshiba to help developing the display, Advance Nanotech sued, but ultimately lost in their efforts to re-negotiate the contracts based on their claim that Canon transferred the technology to Toshiba.

Recent FED research focuses on carbon nanotubes (CNTs) as emitters. **Nano-emissive display** (NED) is Motorola's term for their carbon-nanotube-based FED technology. A prototype model was demonstrated in May 2005, but Motorola has now halted all FED-related development.

Futaba Corporation has been running a Spindt-type development program since 1990. They have produced prototypes of smaller FED systems for a number of years and demonstrated them at various trade shows, but like the Candescent efforts no large-screen production has been forthcoming. Development continues on a nanotube based version.

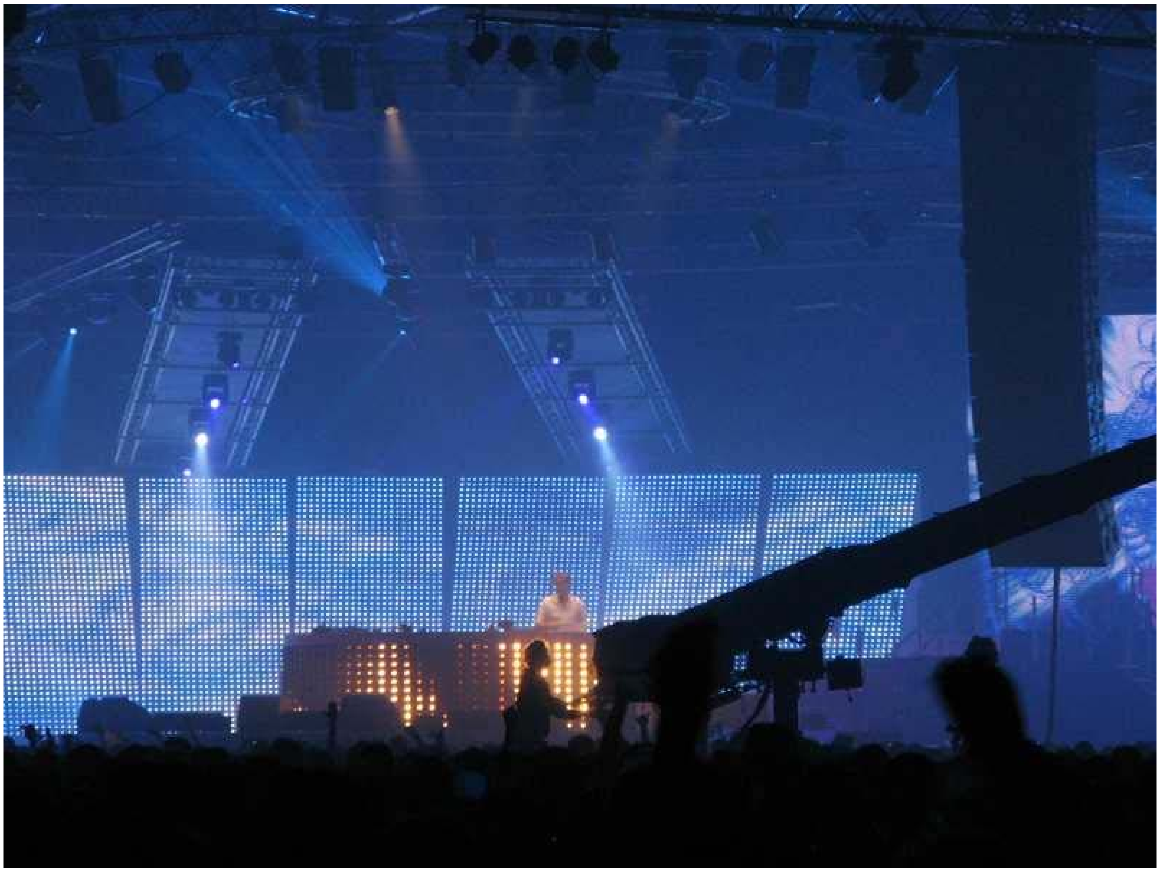
Sony, having abandoned their efforts with Candescent, licensed CNT technology from Carbon Nanotechnologies Inc. , of Houston, Texas, who were the public licensing agent for a number of technologies developed at Rice University's Carbon Nanotechnology Laboratory. In 2007 they demonstrated a FED display at a trade show in Japan and claimed they would be introducing production models in 2009. They later spun off their FED efforts to "Field Emission Technologies", which continued to aim for a 2009 release.

Their plans to start production at a former Pioneer factory in Kagoshima were delayed by financial issues in late 2008. On March 26, 2009 "Field Emission Technologies" (FET) announced that it was closing down due to the inability to raise capital.

In January 2010, Taiwanese AU Optronics Corporation (AUO) announced that it had acquired assets from Sony's FET and FET Japan, including "patents, know-how, inventions, and relevant equipment related to FED technology and materials". In November 2010, Nikkei reported that AUO plans to start mass production of FED panels in the fourth quarter of 2011, however AUO commented that the technology is still in the research stage and there are no plans to begin mass production at this moment.

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 trollybus 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 × 72 ft (49 × 22 m), 11,520 square feet (1,070 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 (cd/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 cd/m^2 is required for most situations, whereas higher-brightness types of up to 5,000 cd/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.