Post-Grant Review of U.S. Patent No. D799,100

Exhibit 1015

Section 1

Light-emitting diode

From Wikipedia, the free encyclopedia

A **light-emitting diode** (**LED**) is a semiconductor light source.[3] LEDs are used as indicator lamps in many devices and are increasingly used for other lighting. Introduced as a practical electronic component in 1962,[4] 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. LEDs are often small in area (less than 1 mm^2), and integrated optical components may be used to shape its radiation pattern.[5] LEDs present many advantages over incandescent light sources including lower energy consumption, longer lifetime, improved robustness, smaller size, and faster switching. 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 aviation lighting, automotive lighting, advertising, general lighting, and traffic signals. LEDs have allowed new text, 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.

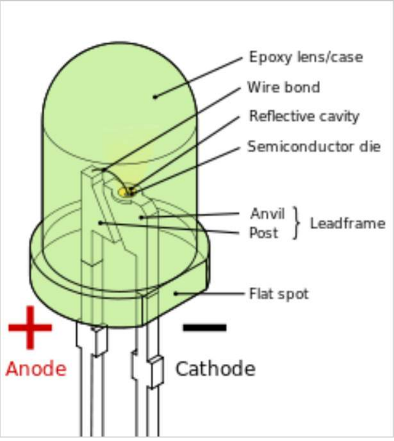
Light-emitting diode

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

Type	Passive, optoelectronic
Working principle	Electroluminescence
Invented	Nick Holonyak Jr. (1962)[1]
First production	1968[2]

Electronic symbol

Pin configuration	anode and cathode



Parts of an LED. Although not directly labeled, the flat bottom surfaces of the anvil and post embedded inside the epoxy act as anchors, to prevent the conductors from being forcefully pulled out from mechanical strain or vibration.

Contents

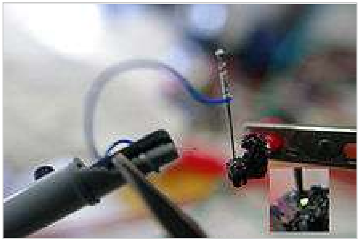
- 1 History
  - 1.1 Discoveries and early devices
  - 1.2 Practical use
  - 1.3 Continuing development
- 2 Technology
  - 2.1 Physics
  - 2.2 Refractive index
    - 2.2.1 Transition coatings
  - 2.3 Efficiency and operational parameters
  - 2.4 Lifetime and failure
- 3 Colors and materials
  - 3.1 Ultraviolet and blue LEDs
  - 3.2 White light
    - 3.2.1 RGB systems
    - 3.2.2 Phosphor-based LEDs
    - 3.2.3 Other white LEDs
  - 3.3 Organic light-emitting diodes (OLEDs)
  - 3.4 Quantum dot LEDs (experimental)
- 4 Types
  - 4.1 Miniature
  - 4.2 Mid-range
  - 4.3 High-power
  - 4.4 Application-specific variations
- 5 Considerations for use
  - 5.1 Power sources

- 5.4 Advantages
- 6 Applications
    - 6.1 Indicators and signs
    - 6.2 Lighting
    - 6.3 Smart lighting
    - 6.4 Sustainable lighting
        - 6.4.1 Energy consumption
        - 6.4.2 Economically sustainable
    - 6.5 Other applications
    - 6.6 Light sources for machine vision systems
- 7 See also
- 8 References
- 9 Further reading
- 10 External links

LED retrofit "bulb" with aluminium heatsink, a diffusing dome and E27 base, using a built-in power supply working on mains voltage

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.[6][7] Russian Oleg Vladimirovich Losev reported creation of the first LED in 1927.[8][9] His research was distributed in Russian, German and British scientific journals, but no practical use was made of the discovery for several decades.[10][11] Rubin Braunstein[12] of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys in 1955.[13] 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,[14] 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.[4] Holonyak is seen as the "father of the light-emitting diode".[15] M. George Craford,[16] 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.[17] 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.[18]

Until 1968, visible and infrared LEDs were extremely costly, on the order of US$200 per unit, and so had little practical use.[2] The Monsanto Company was the first organization to mass-produce visible LEDs, using gallium arsenide phosphide (GaAsP) in 1968 to produce red LEDs suitable for indicators.[2] 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 less than 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.[19] 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.[20]

Practical use

The first commercial LEDs were commonly used as replacements for incandescent and neon indicator lamps, and in seven-segment displays,[21] first in expensive equipment such as laboratory and electronics test equipment, then later in such appliances as TVs, radios, telephones, calculators, and even watches (see list of signal uses). 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

h
a d fluorescent lighting[22][23] (see list of illumination applications). Most LEDs were made in t mm T1¾ and 3 mm T1 packages, but with rising power output, it has grown increasingly necessary to shed excess heat to maintain reliability,[24] 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.

LED display of a TI-30 scientific calculator (ca. 1978), which uses plastic lenses to increase the visible digit size

Continuing development

The first high-brightness blue LED was demonstrated by Shuji Nakamura of Nichia Corporation and was based on InGaN,[25] 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.[*citation needed*] 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.[26]

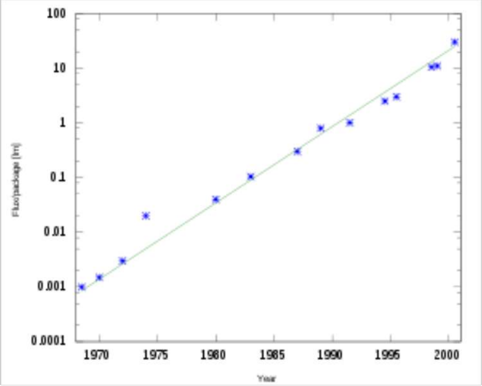


Illustration of Haitz's law. Light output per LED as a function of production year; note the logarithmic scale on the vertical axis

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 in general attributed to the parallel development of other semiconductor technologies and advances in optics and material science. This trend is called Haitz's law after Dr. Roland Haitz.[27]

In February 2008, a luminous efficacy of 300 lumens of visible light per watt of radiation (not per electrical watt) and warm-light emission was achieved by using nanocrystals.[28]

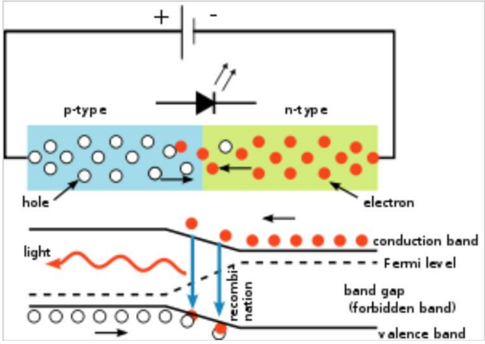
In 2001[29] and 2002,[30] processes for growing gallium nitride (GaN) LEDs on silicon were successfully demonstrated, yielding high power LEDs reported in January 2012.[31] Epitaxy costs could be reduced by up to 90% using six-inch silicon wafers instead of two-inch sapphire wafers.[32]

In 2011, Zhong Li Wang from the Georgia Institute of Technology discovered that the energy efficiency of Piezoelectric UV LED's can be increased by 400% (from 2% to 8%) by using zinc oxide nanowires.[33]

Technology

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.



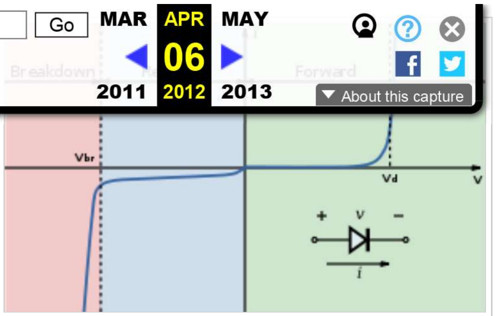
The inner workings of an LED

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.

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.

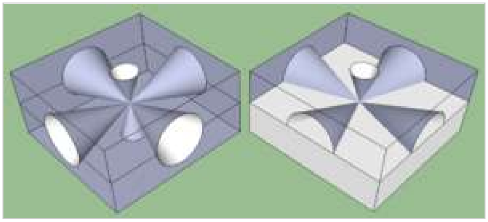


I-V diagram for a diode. An LED will begin to emit light when the on-voltage is exceeded. Typical on voltages are 2–3 volts.

Refractive index

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 1.0002926.[35]

In general, a flat-surface uncoated LED semiconductor chip will emit light only 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*,[36] or the *escape cone*.[37] 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.[37]

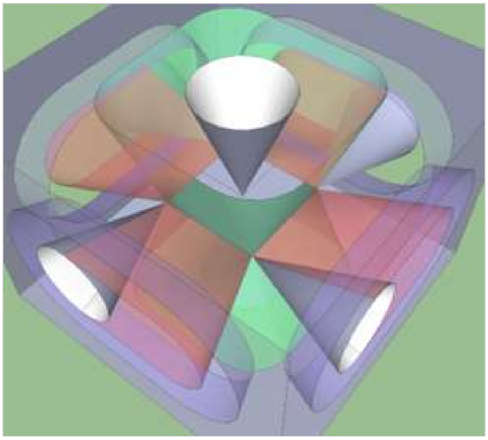


Idealized example of light emission cones in a semiconductor, for a single point-source emission zone. The left illustration is for a fully translucent wafer, while the right illustration shows the half-cones formed when the bottom layer is fully opaque. The light is actually emitted equally in all directions from the point-source, so the areas between the cones shows the large amount of trapped light energy that is wasted as heat.[34]

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.[37]

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.[38]

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.[39]



The light emission cones of a real LED wafer are far more complex than a single point-source light emission. The light emission zone is typically a two-dimensional plane between the wafers. Every atom across this plane has an individual set of emission cones.

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 two-dimensional emission plane.

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.[40]

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. 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.

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**