LIGHT EMITTING DIODES
An Analysis on construction, material, uses and socio-economic impact

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Introduction

A Light-Emitting Diode (LED) in essence is a P-N junction solid-state semi-conductor diode that emits light when a current is applied though the device.[1] By scientific definition, it is a solid-state device that controls current without the deficiency of having heated filaments. How does a LED work? White LEDs ordinarily need 3.6 Volts of Direct Current (DC) and use approximately 30 milliamps (mA) of current and has a power dissipation of approximately 100 milliwatts (mW). The positive power is connected to one side of the LED semiconductor through the anode and a whisker and the other side of the semiconductor is attached to the top of the anvil or the negative power lead (cathode). It is the chemical composition or makeup of the LED semiconductor that determines the color of the light that the LED produces as well as the intensity level. The epoxy resin enclosure allows most of the light to escape from the elements and protects the LED making it virtually indestructible. Furthermore, a light-emitting diode does not have any moving parts, which makes the device extremely resistant to damage due to vibration and shocks. These characteristics make it ideal for purposes that demand reliability and strength. LEDs therefore can be deemed invulnerable to catastrophic failure when operated within design parameters.

Figure 1 shows a typical traditional indicator LED. Traditional indicator LEDs utilize a small LED semiconductor chip that is mounted on a reflector cup also known as the anvil, on a lead-frame (whisker).This whole configuration is encased in epoxy which also serves the purpose of a lens. LEDs have very high thermal resistance with upwards of 200K per Watt.
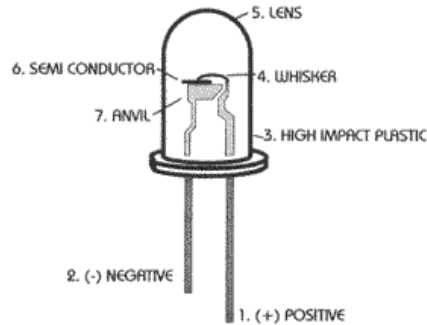
Figure 1[2]
Cross Section of traditional indicator LED

LEDs are highly monochromatic, only emitting a single pure color in a narrow frequency range. The color emitted from an LED is identified by peak wavelength (lpk) which is measured in nanometers (nm). The peak wavelength is a function of the material that is used in the manufacturing of the semiconductor.[3] Most LEDs are produced using gallium-based crystals that differ in one or more additional materials such as phosphorous to produce distinct colors. Different LED chip technologies enable manufacturers to produce LEDs that emit light in a specific region of the visible light spectrum and replicate different intensity levels. Thus, one would vary the material used in the production of LEDs in order to obtain the desired results. The graph below depicts the variation in response time for the specific wavelength of light.
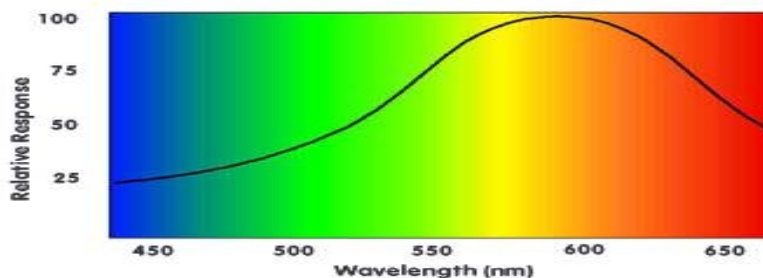

Figure 2 [4]
The relative response time versus different wavelengths of light
(The lower the response time the better. Currently, most LEDs are made with higher
wavelengths (i.e. longer response time) because they are cheaper to manufacture.)

Principle & Mechanism

The essential portion of the Light Emitting Diode is the semiconductor chip. Semiconductors can be either intrinsic or extrinsic. Intrinsic semiconductors are those in which the electrical behavior is based on the electronic structure inherent to the pure material.[5] When the electrical characteristics are dictated by impurity atoms, the semiconductor is said to be extrinsic.[6] See Appendix A for further information regarding the different materials and their characteristics. This chip is further divided into two parts or regions which are separated by a boundary called a junction. The p-region is dominated by positive electric charges (holes) and the n-region is dominated by negative electric charges (electrons). The junction serves as a barrier to the flow of the electrons between the p and the n-regions. This is somewhat similar to the role of the band-gap because it determines how much voltage is needed to be applied to the semiconductor chip before the current can flow and the electrons pass the junction into the p-region.
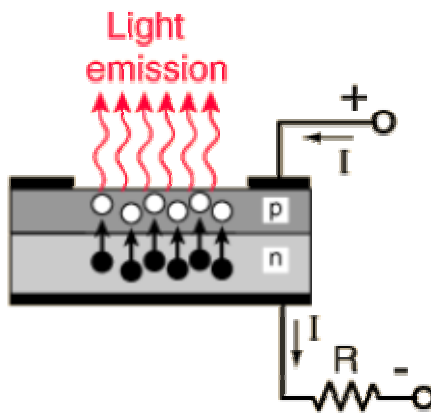

Figure 3 [7]

Cross section of a typical semiconductor LED showing the n and p-type semiconductor layers

In general, to achieve higher momentum states (with higher velocities), there must be an empty energy state into which the electron may be excited. (In other words, to achieve a net flow of electrons in one direction, some electrons must change their wave vectors thereby increasing their energy.) [8] Band-gaps determine how much energy is needed for the electron to jump from the valence band to the conduction band. As an electron in the conduction band recombines with a hole in the valence band, the electron makes a transition to a lower-lying energy state and releases energy in an amount equal to the band-gap energy. This energy is released in photons. Normally the energy heats the material. In an LED this energy goes into emitted infrared or visible light.

The bandgap energy, E_g is approximately equal to the emitted photon's energy.

$$E_g = h \nu \quad [9]$$

where h is the Planck's constant , $h = 6.626 \times 10^{-34}$ Js $= 4.135 \times 10^{-15}$ eVs

The number of photons may be obtained via the following expression

$$N = E / (h\nu) = (P\Delta t)/[h(c/\lambda)] = (\lambda P \Delta t)/(hc) \quad [10]$$

The diode current on the other hand, is related to the band-gap energy via the following formula

$$J = J_1 \exp[(e(V-V_g))/kT] \qquad \text{for} \qquad eV/kT \gg 1 \quad [11]$$

If a large enough electric potential difference (voltage) is absent, across the anode and cathode, the junction serves as an electric potential barrier to the flow of electrons. When sufficient voltage is applied across the chip of the LED, the electron has enough driving force to move in one direction over the junction that separates the p-region and the n-region. The p-region (holes) is where the positive charge forms the majority of charges. (Implicitly, there are also negative charges but they are the minority). Vice versa for the n-region. The electrons from the n-region basically flow across the junction into the p-region. In the p-region, the electrons are attracted to the positive charges due the mutual Coulombic forces of attraction between opposite charges of same magnitude. Thus "recombination" occurs.

After every successful recombination, electric potential energy is transformed into electromagnetic energy. This releases a quantum electromagnetic energy that is emitted in the form of a photon of light with frequencies characteristic of the semiconductor that was used in the process. These photons have specific wavelengths thus specific colors according to the different materials used. Therefore, different compositions of the chemical elements used in the manufacturing of the semiconductor results in different colors emitted as well as different energies needed to light them.

The electrical energy is in proportion to the voltage required to enable the electrons to flow across the p-n junction. Predominantly, LEDs emit light of a single color. The energy (E) of the light emitted is related to the electric charge (q) of an electron and the voltage (V) required to power the LED by the equation:

$$E = qV \text{ (Joules) [12]}$$

This equation or expression depicts that the voltage is proportional to the electric energy, and encompasses any circuit that has any electrical components. The constant q is the electric charge of a single electron which is given the value

$$q = -1.6 \text{ x} 10^{-19} \text{ Coulomb.}$$

As the voltage required to light the LED differs from manufacturer, therefore the energy required to light the LED also differs accordingly.

The frequency of light (f) is related to the wavelength of light by the following formula:

$$f = \frac{c}{\lambda} \quad [13]$$

where

c is the speed of light (3 x 10^8 m/s) and λ is the wavelength of light obtained from a spectrometer (in units of nanometers or 10^{-9} meters). This equation gives the frequency at which the LED emits most of its light.

Application

There are various materials that are used in the manufacturing of Light Emitting Diodes. Most of the materials are gallium-based crystals and are used in high-brightness applications. Gallium is a minor metal noted by its low melting point of 29.8 ºC, the name being derived from Gallia, the Latin for France, which was where it was discovered. [14] Among these include AlGaAs (Aluminum-Gallium-Arsenide), a semiconductor that typically generates the red spectrum, often used in signs, displays and electronic equipment. InGaAlP(Indium-Gallium-Aluminum-Phosphide) produces the yellow-green wavelength to red are often used in signs, auto interior as well as exterior, traffic signals and cell-phones.[15] InGaN (Indium-Gallium-Nitride) typically generates Blue, Green and white spectrums and are used most often in full color signs, cell-phones, auto interior, traffic signals.[16]. Furthermore, there is room for further improvement on the design of traffic lights. The visible light from the LEDs in a traffic light can further be modulated and encoded with information. Hence, it can be used for the broadcasting of audio messages or any traffic or road information. Essentially, all LED traffic lights can be used as communications devices. [17] InGaN LEDs too has been made the light source of choice for many diagnostic and photo-therapy applications from the Ultra-violet to the near Infra-red.[18] Light-emitting diodes (LED) emit light in proportion to the forward current through the diode.

Light Emitting Diodes are the cutting edge technology of lighting today. Generally, Light Emitting Diodes are categorized according to their performance. The performance of a LED is linked to a few primary characteristics of the LED itself which includes color, peak wavelength and intensity. As LEDs are highly monochromatic, LEDs are differentiated

according to their peak wavelength. Peak wavelength is a function of the LED chip material. Although manufacturing process variations produce a standard deviation of ±10nm, nevertheless, these variations are perceptible to the human eye because the 565nm to 600nm wavelength spectral region (yellow to amber) is where the sensitivity level of the human eye is at its peak. [19] See Appendix B for details on the different semiconductor types as well as characteristics of those semiconductors.

The light output of a specific LED varies with the type of chip, encapsulation and efficiency of individual wafer lots. There may be other random variables that may affect the performance of the LED too. This typically is categorized into the nuisance variable factor and is taken into account as the error margin. Many LED manufacturers use different terms such as "super-bright," and "ultra-bright" to describe LED intensity. However, such terminology is entirely subjective, as there really is no industry standard for LED brightness.

Luminous intensity is roughly proportional to the amount of current (I) supplied to the LED. The greater the current, the higher the intensity.[20] Nevertheless, luminous intensity (Iv) does not represent the total light output from an LED. Both the luminous intensity and the spatial radiation pattern (viewing angle) must be taken into account. If two LEDs have the same luminous intensity value, the lamp with the larger viewing angle will have the higher total light output.
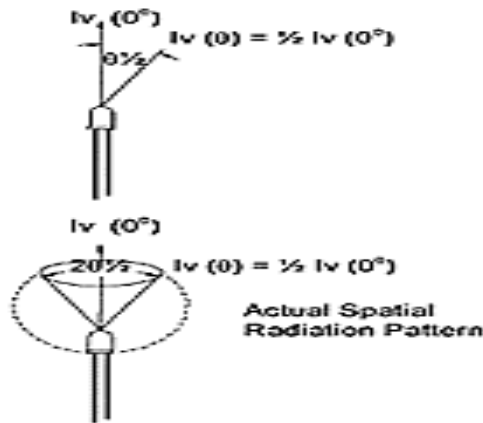
Figure 3 [21]
Spatial Radiation Pattern or Viewing Angle

Overall visibility can be enhanced by increasing the number of LED chips in the encapsulation, increasing the number of individual LEDs, as well as utilizing secondary optics to distribute light. To illustrate, consider similar red GaAlAs LED chip technology in four different configurations:

Single-Chip LED
(6,500 mcd, 6°)

6-Chip LED
(58 mcd, 160°)

7-LED Cluster
(7 LEDs × 80 mcd/30° each)

Lensed LED Cluster
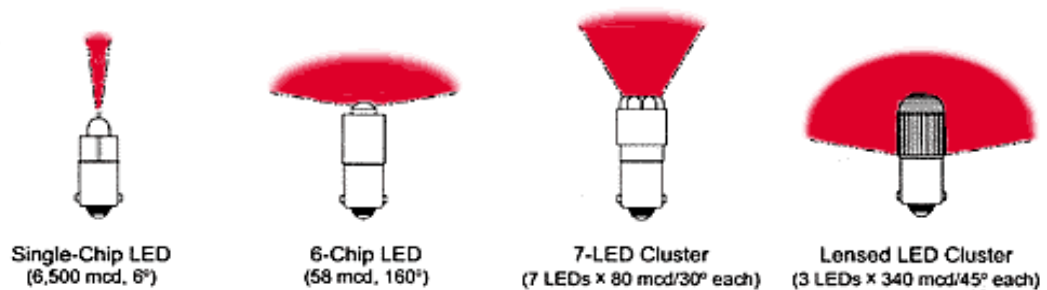(3 LEDs × 340 mcd/45° each)

Figure 4 [22]
Different Configurations of LEDs

In each individual case, the amount of visible light depends on the application of the LED as well as how the LED is being viewed. The single chip setup may be suitable for direct viewing in contrast with high ambient lighting. The 6-chip may be more suitable as a backlight to a switch or small legend, while the cluster or lensed LED design may best be used to illuminate a pilot light or larger lens.

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In this millennium, Light Emitting Diodes or LEDs are making major inroads into a lot of industries. In the past, filament bulbs like incandescent and halogen lamps dominated and were the main source of lighting. Today, in the automotive industry, we see cars with LEDs for taillights and instrument panels. Why the switch to the new technology? Among the reasons why include the longevity of the LED itself. It lasts on average 20,000 hours for a 15-Watt traffic light in comparison to 1000 hours for typical filament bulbs.[23] Generally, LEDs are designed to operate upwards of 100,000 hours. This greatly supercedes the standard incandescent bulb with an average lifespan of about 5000 hours.LEDs too are low voltage devices that respond almost instantaneously to changes in current (~10Mhz).[24] This would entail better safety for motorists on the road. Costs of maintenance of the vehicle would too decrease as replacements of the lighting fixtures need not be done as often. With such fast reponse times, LEDs used as an unbiased photodiode, exhibits a non-linear power dependent response that also can be used for sensitive detection and characterization of mode-locked femtosecond and picosecond laser pulses. [25]

In the electronic industry, we have LEDs for lighting of almost everything. The ergonomic flat-panel computer screens otherwise known as liquid crystal displays (LCDs) are also in essence miniature LED clusters. The introduction of LCDs marks another milestone in development in the hi-tech industry. Displays now can be made that use less power as well as emit much less radiation in comparison with the traditional cathode ray tube (CRT) display. According to Keith Robinson for Frost & Sullivan, "The light emitting diode (LED) market, especially the visible LED (VLED) market, is poised to experience explosive growth once economic conditions improve in North America. The most significant

technology improvement that has taken place in the last 10 years for LEDs is the introduction

of blue and blue-green LEDs. The nitride-based LEDs have opened new opportunities for

manufacturers of lighting products, such as traffic signal manufacturers and outdoor

signboard manufacturers. The increased use of the new colors in consumer products and

automotive applications is expected to have a positive impact on the market." [26]

Manufacturers have always been striving to replicate colors as accurately as possible.

This is has always been the "holy grail" for the display industry. LEDs have made this a

reality. Typical incandescent bulbs cannot replicate the vivid colors that can be reproduced

using LEDs. LEDs give pure saturated colors with up to 130% more gamut compared to

standard NTSC specifications.[27] Take the reproduction of white light. When light from all

parts of the visible spectrum overlap one another, the additive mixture of colors appears

white. However, the eye does not require a mixture of all the colors of the spectrum to

perceive white light. Primary colors from the upper, middle, and lower parts of the spectrum

(red, green, and blue), when combined, appear white. To achieve this combination with

LEDs requires a sophisticated electro-optical design to control the blend and diffusion of

colors. Variations in LED color and intensity further complicate this process.

Presently, it is possible to produce white light with a single LED using a phosphor

layer (Yttrium Aluminum Garnet) on the surface of a blue (Gallium Nitride) chip.[28]

Although this technology produces various hues, white LEDs may be appropriate to

illuminate opaque lenses or backlight legends. However, using colored LEDs to illuminate

similarly colored lenses produces better visibility and overall appearance in comparison with

CRTs. Moreover, LEDs are not deficient in the reliability department. LEDs are solid state devices with no moving parts as well as no fragile glass or filaments.

LEDs too use up to 90% less energy in comparison with conventional bulbs and lamps today.[29] Today a LED flashlight may last up to 200% longer with the same batteries used to operate conventional filament flashlights. [30] Furthermore, LEDs are environmental friendly because they contain no mercury and since they last longer (about 100,000 continuous hours of life); there will be less disposal waste in the environment. This in turn would result is less pollution and less wastage of our precious and limited resources.

LEDs also form the foundation for applications in optical-fiber communication and diode lasers. They produce a narrow spectrum of coherent red or infrared light that can be well collimated. This characteristic of the light produced by LEDs has enabled engineers to manipulate the setup to enable data transfer. This has made it possible for continents to be linked via the internet. Information can be sent across the globe in a matter of fractions of a second and vast chunks of data can be transmitted without a hitch. With the improvement of infrastructure, the benefits extend also to the general populace. Before we had modems that used coaxial copper cables, today we have T1 to T3 connections which utilize fiber optics. Most institutions, organizations and companies that require the use of large bandwidths of data have such connections. Take for example, San Jose State University, it utilizes several T3 connections to the internet and has T1 connections locally across campus to alleviate data congestion. In this way, data is made readily available to those hungry for knowledge.

Conclusion

Light Emitting Diodes has such a profound impact on society. It affects our daily lives as well as activities. It is used in so many applications and so many places. With Light Emitting Diodes, so many significant improvements to already existing technology could be made. Historically the LED market has experienced signal digit growth of about 8.5 percent. The laser diode market has experienced double-digit growth in the past of approximately 30.0 percent and once economic conditions improve it is anticipated that the market will experience strong growth rates once again. [31] As this technology expands, so does our horizon and our conquest for the betterment of today's technology. Light Emitting Diodes truly is a great invention of the age.

References

1. Alan J. Heeger, Alan G. MacDiarmid and Hideki Shirakawa The Royal Swedish Academy of Sciences, Sweden,http://www.nobel.se/chemistry/laureates/2000/public.html , Accessed November 8, 2002.

2. Lumen Maintenance of White Luxeon Power Light Sources, http://www.lumileds.com/pdfs/AB07.PDF, Accessed November 4, 2002.

3. Pang, Grantham; Kwan, Thomas; Liu Hugh; Chan, Chi-Ho, "LED traffic light as as communications device", University of Hong Kong ,Hong Kong, 1999, p 789

4. Data Display Products, http://www.ddp-leds.com/applicationnotes.htm, Accessed November 10, 2002

5. Callister, William D., Fundamentals of Material Science and Engineering / An Interactive e-text, John Wiley & Sons, Inc. New York. 2001. p. 377

6. Callister, William D., Fundamentals of Material Science and Engineering / An Interactive e-text, John Wiley & Sons, Inc. New York. 2001. p. 378

7. LED Device Structure, StarNine Technologies, http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/leds.html, Accessed 30 November 2001

8. Barrett C., Nix W., Tetelman A., The Principles of Engineering Materials , Prentice-Hall, Inc. New Jersey 1973. p. 371

9. S.O. Kasap, Principles of Electrical Engineering Materials and Devices, McGrawHill. New York. 2002   p. 481

10. Atkins, Peter; de Paula Julio, Physical Chemistry 7th Ed., W.H. Freeman and Company, New York. p.299

11. S.O. Kasap, Principles of Electrical Engineering Materials and Devices, McGrawHill. New York. 2002   p. 425

12. Kotz, John C.; Treichel, Paul Jr. , Chemistry & Chemical Reactivity 4th Ed. , Saunders College Publishing, Florida 1999. p.300

13. Kotz, John C.; Treichel, Paul Jr. , Chemistry & Chemical Reactivity 4 ed. , Saunders College Publishing, Florida 1999. p.295

14. Mining and Chemical Products Limited (MCP), http://www.mcp-group.co.uk/metals/mc_gal.html, Accessed November 8, 2002.

15. Pang, Grantham; Kwan, Thomas; Liu Hugh; Chan, Chi-Ho, "Optical wireless based on high brightness visible LEDs", University of Hong Kong ,Hong Kong, 1999, p 1693-1699

16. Pang, Grantham; Kwan, Thomas; Liu Hugh; Chan, Chi-Ho, "Optical wireless based on high brightness visible LEDs", University of Hong Kong ,Hong Kong, 1999, p 1696

17. IBM Corporation, http://www.almaden.ibm.com/st/projects/oleds/ , Accessed November 8, 2002.

18. McGraw, Daniel, Medical Applications of Light Emitting Diodes, Photonics East, Boston MA, 2000, http://www.spie.org/web/meetings/programs/pe00/courses/SC195.html, Accessed November 8, 2002.

19. S.O. Kasap, Principles of Electrical Engineering Materials and Devices, McGrawHill. New York. 2002   p. 484 Table 6.2

20. Light Emitting Diodes (LED), Australian Photonics CRC, http://www.vislab.usyd.edu.au/photonics/devices/semicdev/led0.html, Accessed November 10, 2002

21. Data Display Products, http://www.ddp-leds.com/applicationnotes.htm, Accessed November 10, 2002

22. Data Display Products, http://www.ddp-leds.com/applicationnotes.htm, Accessed November 10, 2002

23. Hongxing Jiang, Researchers fabricate blue micro light-emitting diodes, paving the way for future miniature displays , Kansas State University, http://www.globaltechnoscan.com/3rdOct-9thOct01/light-emitting-diodes.htm, Accessed November 8, 2002.

24. Fernelius, N.C.; "Properties of gallium selenide single crystal", Progress in Crystal Growth and Characterization of Materials, v28, n4, 1994, p 275-353, Pergamon Press Inc. New York

25. Reid, D.T.; Padgett M.; McGowan C.; Sleat, W.E.; Sibett, W., "Light Emitting Diodes as measurement devices for femtosecond laser pulses", Optic Letters Feb. 16, 1996. v22 n4. p. 233.

26. Robinson, K. , Which direction are Laser and Light Emitting Diodes Headed? , Frost & Sullivan, New York ,

http://www.frost.com/prod/news.nsf/3fcc3449277e0b738025695d006cfe7f/f4c7bbd624d6cbf
f86256b180000d725?OpenDocument, Accessed November 8, 2002.

27. Light Emitting Diodes (LED), Australian Photonics CRC,
http://www.vislab.usyd.edu.au/photonics/devices/semicdev/led0.html, Accessed November
10, 2002

28. Data Display Products, http://www.ddp-leds.com/applicationnotes.htm, Accessed
November 10, 2002

29. The LED Light, http://www.theledlight.com/, Accessed November 5, 2002

30. The LED Light, http://www.theledlight.com/, Accessed November 5, 2002

31. Robinson, K. , <u>Which direction are Laser and Light Emitting Diodes Headed?</u> , Frost &
Sullivan, New York,
http://www.frost.com/prod/news.nsf/3fcc3449277e0b738025695d006cfe7f/f4c7bbd624d6cbf
f86256b180000d725?OpenDocument, Accessed November 8, 2002.

Appendix A

Material	Band Gap (eV)	Electrical Conductivity $[(\Omega\text{-m})^{-1}]$	Electron Mobility $(m^2/V\text{-s})$	Hole Mobility $(m^2/V\text{-s})$
Elemental				
Si	1.11	4×10^{-4}	0.14	0.05
Ge	0.67	2.2	0.38	0.18
III-V Compounds				
GaP	2.25	-	0.05	0.002
GaAs	1.42	10^{-6}	0.85	0.45
InSb	0.17	2×10^4	7.7	0.07
II-VI Compounds				
CdS	2.40	-	0.03	-
ZnTe	2.26	-	0.03	0.01

Table 12.2*
Band Gap Energies, Electron and Hole Mobilities, and Intrinsic Electrical Conductivities at
Room Temperature for Semiconducting Materials

Appendix B

Semiconductor	Direct Bandgap or Indirect Bandgap	λ (nm)	η external (%)	Comments
GaAs	D	870-900	10	Infrared LEDs
$Al_xGa_{1-x}As$ (0<x<0.4)	D	640-870	5-20	Red to IR LEDs, DH
$In_{1-x}Ga_xAs_yP_{1-y}$ (y≈2.20x, 0<x<0.47)	D	1000-1600	>10	LEDs in communications
InGaN alloys	D	430-460 500-530	2 3	Blue LED Green LED
SiC	I	460-470	0.02	Blue LED, low efficiency
$In_{0.49}Al_xGa_{0.51-x}P$	D	590-630	1-10	Amber, Green, Red LEDs
$GaAs_{1-y}P_y$(y<0.45)	D	630-870	<1	Red to IR LEDs
$GaAs_{1-y}P_y$(y>0.45) (N or Zn, O doping)	I	560-700	<1	Red, Orange, Yellow LEDs
GaP (Zn-O)	I	700	2-3	Red LED
GaP (N)	I	565	<1	Green LED

Table 6.2*

Selected LED semiconductor materials

*NOTE: Optical communication channels are at 850nm (local network) and at 1.3 and 1.55 μm (long distance)

DH=double heterostructure

$\eta_{external}$ is typical and may vary substantially depending on the device structure.

$\eta_{external}$ or external efficiency is given by the following expression

$$\eta_{external} = P_o (optical) / (IV) \times 100\%$$

where P_o is the optical power emitted by the device

I is the current

V is the voltage

* S.O. Kasap, <u>Principles of Electrical Engineering Materials and Devices</u>, McGrawHill. New York. 2002   p. 484 Table 6.2