Light Emitting Diodes (LEDs)
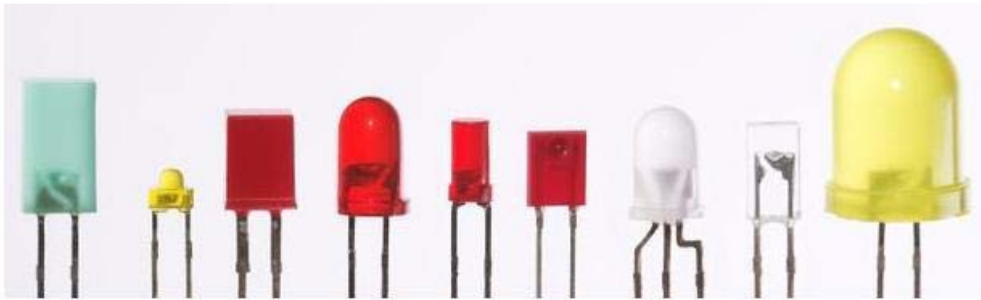
ELE 432 Assignment # 3
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Synopsis:
To explain the theory and the underlying principle behind the functioning of an LED

Brief History:

- The first known report of a light-emitting solid-state diode was made in 1907 by the British experimenter H. J. Round.

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y.   H. J. ROUND.

H.J.Round, Electrical World, 49,309, 1907

**(material.eng.usm.my/stafhome/zainovia/EBB424e/LED1.ppt)**

- In the mid 1920s, Russian Oleg Vladimirovich Losev independently created the first LED, although his research was ignored at that time.
- In 1955, Rubin Braunstein of the Radio Corporation of America reported on infrared emission from gallium arsenide (GaAs) and other semiconductor alloys.
- Experimenters at Texas Instruments, Bob Biard and Gary Pittman, found in 1961 that gallium arsenide gave off infrared radiation when electric current was applied. Biard & Pittman received the patent for the infrared light-emitting diode.
- In 1962, Nick Holonyak Jr., of the General Electric Company and later with the University of Illinois at Urbana-Champaign, developed the first practical visible-spectrum LED. He is seen as the "father of the light-emitting diode".
- In 1972, M. George Craford, Holonyak's former graduate student, invented the first yellow LED and 10x brighter red and red-orange LEDs.
- Shuji Nakamura of Nichia Corporation of Japan demonstrated the first high-brightness blue LED based on InGaN. The 2006 Millennium Technology Prize was awarded to Nakamura for his invention.

Schematic:
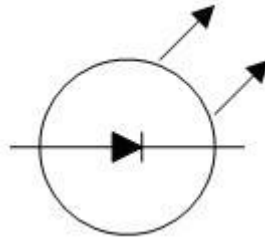
Theory:
A Light emitting diode (LED) is essentially a pn junction diode. When carriers are injected across a forward-biased junction, it emits incoherent light. Most of the commercial LEDs are realized using a highly doped n and a p Junction.
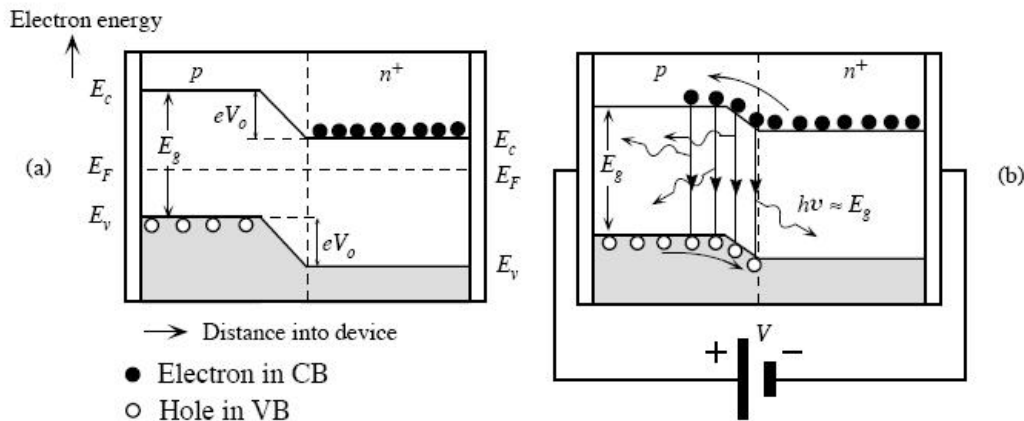
(a) The energy band diagram of a pn^+ (heavily n-type doped) junction without any bias. Built-in potential V_o prevents electrons from diffusing from n^+ to p side. (b) The applied bias reduces V_o and thereby allows electrons to diffuse or be injected into the p-side. Recombination around the junction and within the diffusion length of the electrons in the p-side leads to photon emission.

Figure 1: p-n+ Junction under Unbiased and biased conditions.

(pn Junction Devices and Light Emitting Diodes by Safa Kasap)

To understand the principle, let's consider an unbiased pn+ junction (Figure1 shows the pn+ energy band diagram). The depletion region extends mainly into the p-side. There is a potential barrier from E_c on the n-side to the E_c on the p-side, called the built-in voltage, V_0. This potential barrier prevents the excess free electrons on the n+ side from diffusing into the p side.
When a Voltage V is applied across the junction, the built-in potential is reduced from V_0 to $V_0 - V$. This allows the electrons from the n+ side to get injected into the p-side. Since electrons are the minority carriers in the p-side, this process is called minority carrier injection. But the hole injection from the p side to n+ side is very less and so the current is primarily due to the flow of electrons into the p-side.
These electrons injected into the p-side recombine with the holes. This recombination[(see Appendix 1)] results in spontaneous emission of photons (light). This effect is called injection

electroluminescence. These photons should be allowed to escape from the device without being reabsorbed.

The recombination can be classified into the following two kinds
- Direct recombination
- Indirect recombination

Direct Recombination:
In direct band gap materials, the minimum energy of the conduction band lies directly above the maximum energy of the valence band in momentum space energy (Figure 2 shows the E-k plot[see Appendix 2] of a direct band gap material). In this material, free electrons at the bottom of the conduction band can recombine directly with free holes at the top of the valence band, as the momentum of the two particles is the same. This transition from conduction band to valence band involves photon emission (takes care of the principle of energy conservation). This is known as direct recombination. Direct recombination occurs spontaneously. GaAs is an example of a direct band-gap material.
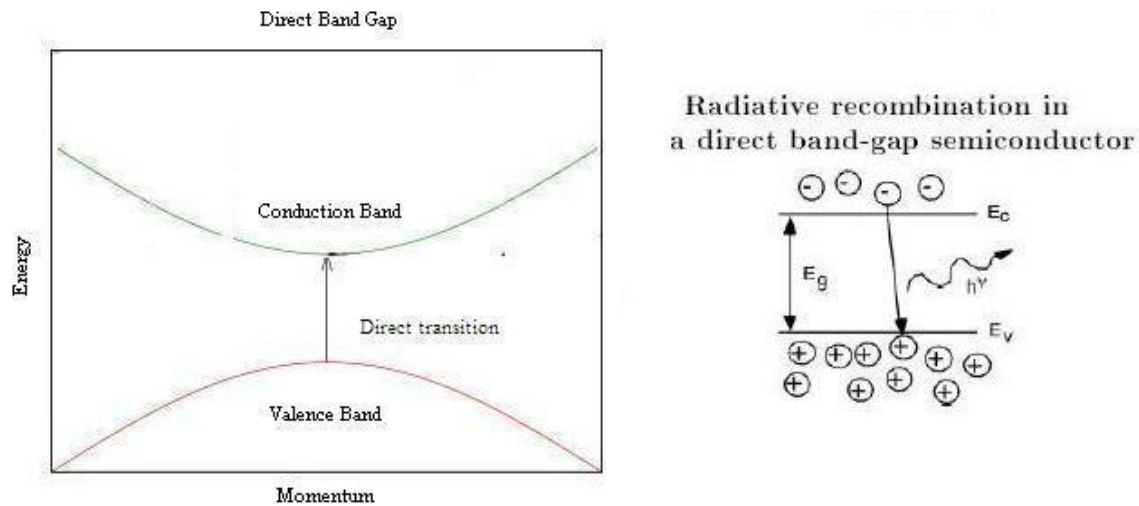

Figure 2: Direct Bandgap and Direct Recombination

Indirect Recombination:
In the indirect band gap materials, the minimum energy in the conduction band is shifted by a k-vector relative to the valence band. The k-vector difference represents a difference in momentum. Due to this difference in momentum, the probability of direct electron-hole recombination is less.
In these materials, additional dopants(impurities) are added which form very shallow donor states. These donor states capture the free electrons locally; provides the necessary momentum shift for recombination. These donor states serve as the recombination centers. This is called Indirect (non-radiative) Recombination.
Figure3 shows the E-k plot of an indirect band gap material and an example of how Nitrogen serves as a recombination center in GaAsP. In this case it creates a donor state, when SiC is doped with Al, it recombination takes place through an acceptor level.

The indirect recombination should satisfy both conservation energy, and momentum. Thus besides a photon emission, phonon[See Appendix 3] emission or absorption has to take place.
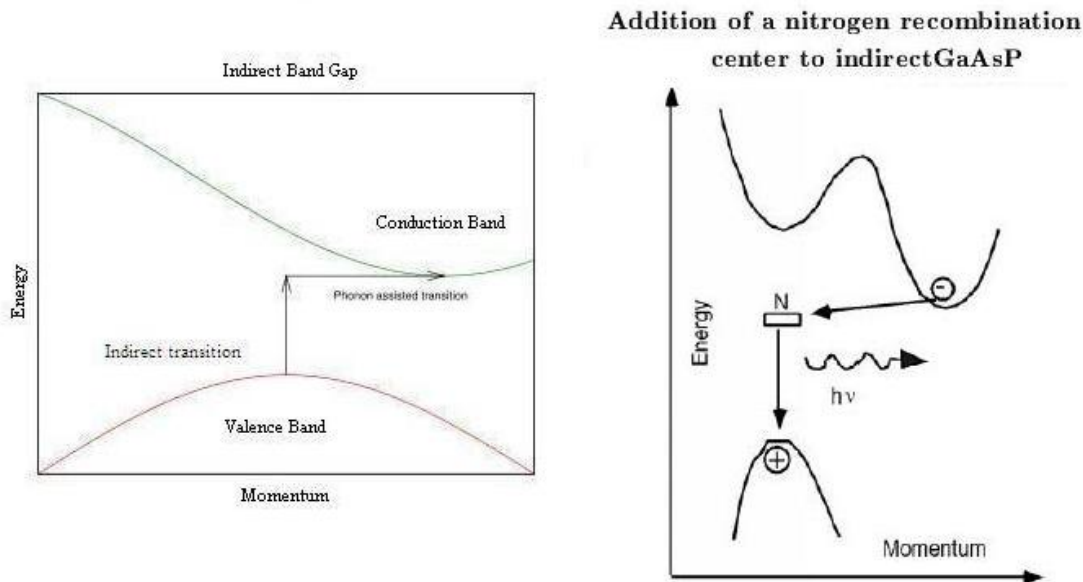GaP is an example of an indirect band-gap material.

Figure 3: Indirect Bandgap and NonRadiative recombination

The wavelength of the light emitted, and hence the color, depends on the band gap energy of the materials forming the p-n junction.
The emitted photon energy is approximately equal to the band gap energy of the semiconductor. The following equation relates the wavelength and the energy band gap.

$$h\nu = E_g$$
$$hc/\lambda = E_g$$

$$\lambda = hc/E_g$$

Where h is Plank's constant, c is the speed of the light and E_g is the energy band gap
Thus, a semiconductor with a 2 eV band-gap emits light at about 620 nm, in the red. A 3 eV band-gap material would emit at 414 nm, in the violet. Appendix 4 shows a list of semiconductor materials and the corresponding colors.

LED Materials:
An important class of commercial LEDs that cover the visible spectrum are the III-V[see Appendix 5]. ternary alloys based on alloying GaAs and GaP which are denoted by $GaAs_{1-y}P_y$. InGaAlP is an example of a quarternary (four element) III-V alloy with a direct band gap.
The LEDs realized using two differently doped semiconductors that are the same material is called a homojunction. When they are realized using different bandgap materials they are called a heterostructure device[see Appendix 7]. A heterostructure LED is brighter than a homoJunction LED.

LED Structure:

The LED structure plays a crucial role in emitting light from the LED surface. The LEDs are structured to ensure most of the recombinations takes place on the surface by the following two ways.

- By increasing the doping concentration of the substrate, so that additional free minority charge carriers electrons move to the top, recombine and emit light at the surface.
- By increasing the diffusion length $L = \sqrt{D\tau}$, where D is the diffusion coefficient and τ is the carrier life time. But when increased beyond a critical length there is a chance of re-absorption of the photons into the device.

The LED has to be structured so that the photons generated from the device are emitted without being reabsorbed. One solution is to make the p layer on the top thin, enough to create a depletion layer. Following picture shows the layered structure. There are different ways to structure the dome for efficient emitting[See Appendix 6].
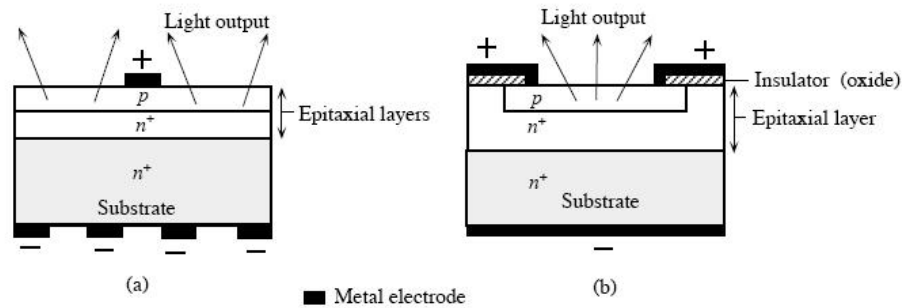
A schematic illustration of typical planar surface emitting LED devices. (a) *p*-layer grown epitaxially on an *n+* substrate. (b) First *n+* is epitaxially grown and then *p* region is formed by dopant diffusion into the epitaxial layer.

Figure 4: LED structure

(pn Junction Devices and Light Emitting Diodes by Safa Kasap)

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.

LED efficiency:

A very important metric of an LED is the external quantum efficiency η_{ext}. It quantifies the efficeincy of the conversion of electrical energy into emitted optical energy. It is defined as the light output divided by the electrical input power. It is also defined as the product of Internal radiative efficiency and Extraction efficiency.

$$\eta_{ext} = P_{out}(optical) / IV$$

For indirect bandgap semiconductors η_{ext} is generally less than 1%, where as for a direct band gap material it could be substantial.

$$\eta_{int} = \text{rate of radiation recombination/ Total recombination}$$

The internal efficiency is a function of the quality of the material and the structure and composition of the layer.

Applications: LED have a lot of applications. Following are few examples.
- Devices, medical applications, clothing, toys
- Remote Controls (TVs, VCRs)
- Lighting
- Indicators and signs
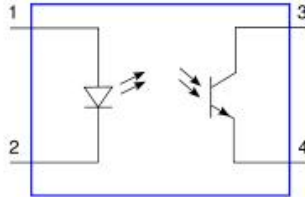- Optoisolators and optocouplers

Figure 5: Optocoupler schematic showing LED and phototransistor (Wikipedia)

- Swimming pool lighting[see Appendix 9].

Advantages of using LEDs
- LEDs produce more light per watt than incandescent bulbs; this is useful in battery powered or energy-saving devices.
- LEDs can emit light of an intended color without the use of color filters that traditional lighting methods require. This is more efficient and can lower initial costs.
- The solid package of 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.
- When used in applications where dimming is required, LEDs do not change their color tint as the current passing through them is lowered, unlike incandescent lamps, which turn yellow.
- LEDs are ideal for use in applications that are subject to frequent on-off cycling, unlike fluorescent lamps that burn out more quickly when cycled frequently, or High Intensity Discharge (HID) lamps that require a long time before restarting.
- LEDs, being solid state components, are difficult to damage with external shock. Fluorescent and incandescent bulbs are easily broken if dropped on the ground.
- LEDs can have a relatively long useful life. A Philips LUXEON k2 LED has a life time of about 50,000 hours, whereas Fluorescent tubes typically are rated at about 30,000 hours, and incandescent light bulbs at 1,000–2,000 hours.
- LEDs mostly fail by dimming over time, rather than the abrupt burn-out of incandescent bulbs.
- LEDs light up very quickly. A typical red indicator LED will achieve full brightness in microseconds; Philips Lumileds technical datasheet DS23 for the Luxeon Star states "less than 100ns." LEDs used in communications devices can have even faster response times.
- LEDs can be very small and are easily populated onto printed circuit boards.
- LEDs do not contain mercury, unlike compact fluorescent lamps.

Disadvantages:
- LEDs are currently more expensive, price per lumen, on an initial capital cost basis, than more conventional lighting technologies. The additional expense partially stems from the relatively low lumen output and the drive circuitry and power supplies needed. However, when considering the total cost of ownership (including energy and maintenance costs), LEDs far surpass incandescent or halogen sources and begin to threaten the future existence of compact fluorescent lamps.
- LED performance largely depends on the ambient temperature of the operating environment. Over-driving the LED in high ambient temperatures may result in overheating of the LED package, eventually leading to device failure. Adequate heat-sinking is required to maintain long life [See Appendix8 9].
- LEDs must be supplied with the correct current. This can involve series resistors or current-regulated power supplies.
- LEDs do not approximate a "point source" of light, so they cannot be used in applications needing a highly collimated beam. LEDs are not capable of providing divergence below a few degrees. This is contrasted with commercial ruby lasers with divergences of 0.2 degrees or less. However this can be corrected by using lenses and other optical devices.
- There is increasing concern that blue LEDs and white LEDs are now capable of exceeding safe limits of the so-called blue-light hazard as defined in the eye safety specifications for example ANSI/IESNA RP-27.1-05: Recommended Practice for Photobiological Safety for Lamp and Lamp Systems.

LEDs in the future: LEDs have come a long way and currently they are widely used in many applications. In future, I believe research will continue for high intenisty LEDs, eventhough heat dissipation is an issue[see appendix8 9]

References:
- Discussions with Dr Fischer.
- ELE 432 Notes and Solid State Electronic Devices Ben G Streetman, Sanjay K Banerjee.
- Wikipedia.org (http://en.wikipedia.org/wiki/Led)
- http://www.ialb.uni-bremen.de/downloads/Semiconductor%20Device.pdf
- material.eng.usm.my/stafhome/zainovia/EBB424e/**LED**1.ppt
- pn Junction Devices and Light Emitting Diodes by Safa Kasap University of Saskatchewan Canada.
- Solid State Light Emitters, Light Emitting Diodes, Dr. János Schanda ,Colour and Multimedia Laboratory of the University of Veszprém.
- Light Emitting Diode, Bill Wilson

Future Reading:

LEDs are very interesting and involved. It's difficult to summarize all the information in one report. If interested, additional information can be obtained from the above references.

Acknowledgements:

I would like to take this opportunity to thank Dr Fischer and others who have assisted me in editing this report.

Appendix:

1) Recombination of an electron hole pair (EHP) involves and electron in the conduction band occupying a hole in the valence band. This results in the annihilation of the electron-hole pair.

2) Energy- k plot: Ek plot is a different way of describing the material characteristics. The effects of the crystal lattice are included by defining effective mass m*. From the plot the effective mass can be calculated $m^* = \hbar^2/ (d^2E/dk^2)$, where $\hbar$ is the Plank's constant ($h/2\pi$) and d^2E/dk^2 gives the curvature. The effective mass can be positive, negative or infinity.

   - Infinity means particle cant be accelerated by external forces
   - Negative means the object reacts to an attractive force as if it would experience a repulsive force.

3) Phonons: Phonons are a quantum mechanical version of a special type of vibrational motion, known as normal modes in classical mechanics, in which each part of a lattice oscillates with the same frequency. These normal modes are important because any arbitrary vibrational motion of a lattice can be considered as a superposition of normal modes with various frequencies according to classical mechanics. In this sense, the normal modes are the elementary vibrations of the lattice. Although normal modes are wave-like phenomena in classical mechanics, they acquire certain particle-like properties when the lattice is analysed using quantum mechanics. They are then known as phonons. The properties of long-wavelength phonons give rise to sound in solids -- hence the name phonon from the Greek φωνή (phonē) = voice

4) Following is a list of semiconductor materials and the corresponding colors:

   - Aluminium gallium arsenide (AlGaAs) — red and infrared
   - Aluminium gallium phosphide (AlGaP) — green
   - Aluminium gallium indium phosphide (AlGaInP) — high-brightness orange-red, orange, yellow, and green
   - Gallium arsenide phosphide (GaAsP) — red, orange-red, orange, and yellow
   - Gallium phosphide (GaP) — red, yellow and green
   - Gallium nitride (GaN) — green, pure green (or emerald green), and blue also white (if it has an AlGaN Quantum Barrier)
   - Indium gallium nitride (InGaN) — 450 nm - 470 nm — near ultraviolet, bluish-green and blue
   - Silicon carbide (SiC) as substrate — blue
   - Silicon (Si) as substrate — blue (under development)
   - Sapphire (Al_2O_3) as substrate — blue
   - Zinc selenide (ZnSe) — blue
   - Diamond (C) — ultraviolet
   - Aluminium nitride (AlN), aluminium gallium nitride (AlGaN), aluminium gallium indium nitride (AlGaInN) — near to far ultraviolet (down to 210 nm)

Band gaps of some Common Semiconductors relative to the optical spectrum
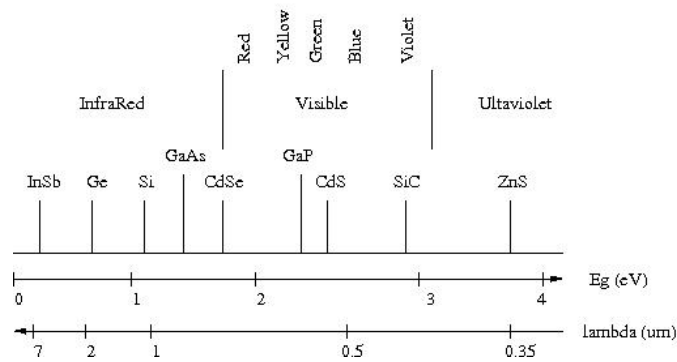
Solid State Electronic Devices Ben G Streetman, Sanjay K Banerjee
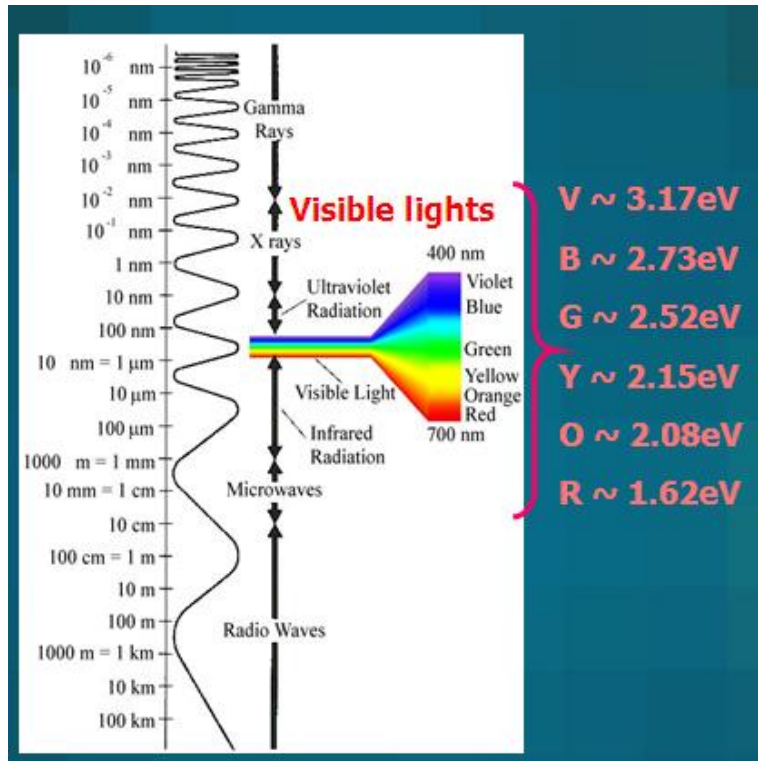

(material.eng.usm.my/stafhome/zainovia/EBB424e/LED1.ppt)

5) Semiconductors in the periodic table: The following table shows the semiconductors in the periodic table. An example of III-V components is GaP or GaAs.

II	III	IV	V	VI
	B	C		
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te

6) LED dome shapes: The LED domes are constructed such most of the light gets emitted efficiently. Following picture shows the two different kinds of domes.
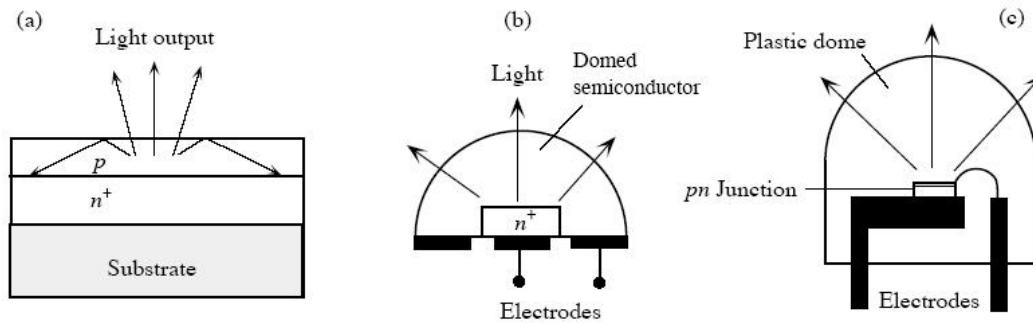
(a) Some light suffers total internal reflection and cannot escape. (b) Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle. (b) An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome.

(pn Junction Devices and Light Emitting Diodes by Safa Kasap)

7) Heterojunction High intensity LEDs:
A semiconductor device that has junctions between different bandgap materials is called a heterostructure device. Following picture shows an example
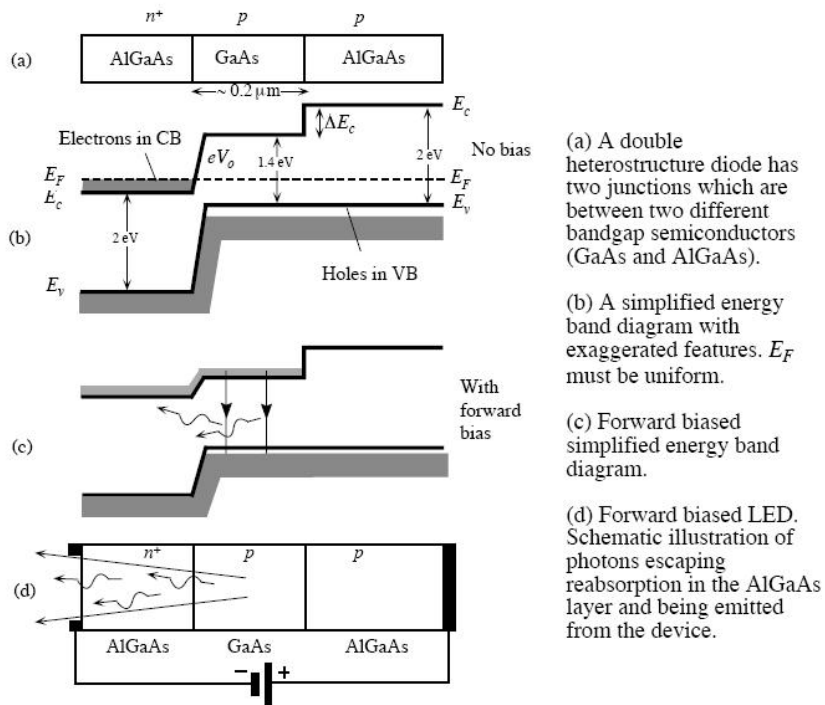
(a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs).

(b) A simplified energy band diagram with exaggerated features. E_F must be uniform.

(c) Forward biased simplified energy band diagram.

(d) Forward biased LED. Schematic illustration of photons escaping reabsorption in the AlGaAs layer and being emitted from the device.

(pn Junction Devices and Light Emitting Diodes by Safa Kasap)

8) Luminous Intensity over the year:
The following graph shows the improvement of luminous intensity of LEDs over the years.
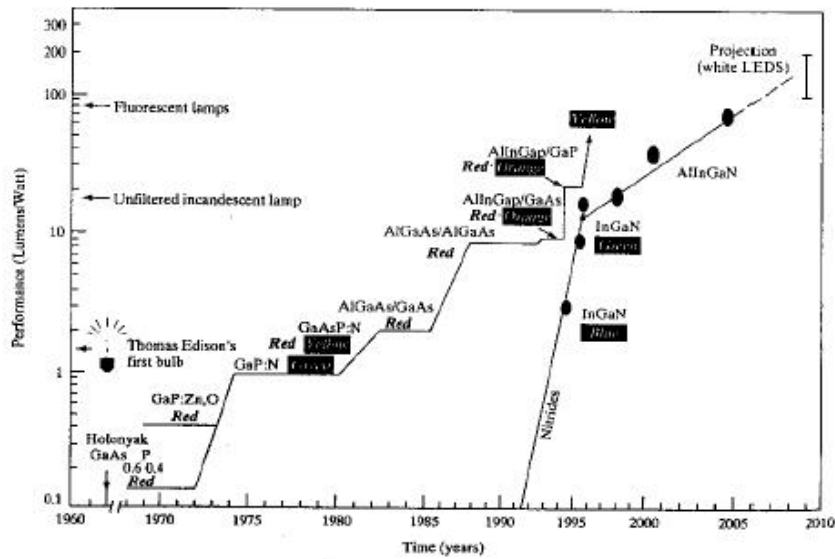
Figure 8–10
Improvement of luminous intensity of LEDs over time. [Modified from M. G. Craford, *IEEE Circuits and Devices*, p. 24, Sept. 1992.]

(Solid State Electronic Devices Ben G Streetman, Sanjay K Banerjee)

The following graph shows how the efficacy of III-V compound LEDs could be increased by introducing new compositions. The first visible light emitting diodes were fabricated using a GaAsP alloy.
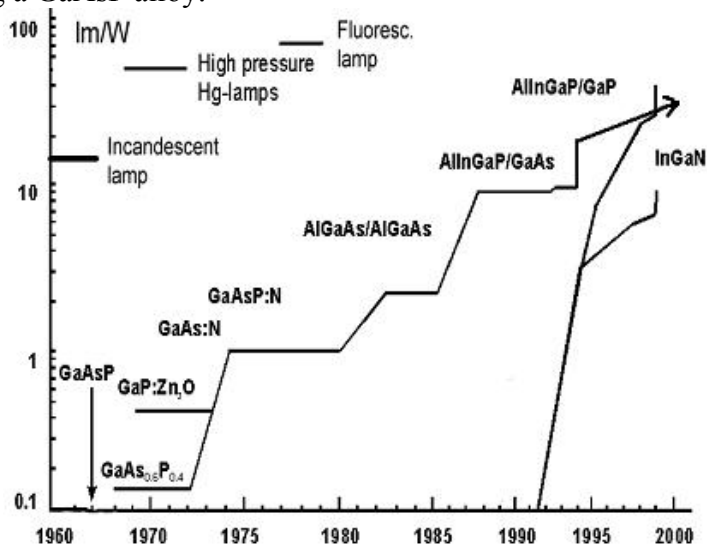
**(Solid State Light Emitters, Light Emitting Diodes, Dr. János Schanda)**

9) Different Types of LEDs:
There are 3 main types of LEDs: miniature LEDs, alphanumeric LEDs, and lighting LEDs. The following picture shows some through hole LEDs.

(Wikipedia)

Most LEDs were made in the very common 5 mm T1-3/4 and 3 mm T1 packages, but with higher power, it has become increasingly necessary to eliminate the heat, therefore the packages have become more complex and adapted for heat dissipation. Packages for state-of-the-art high power LEDs bear little resemblance to early LEDs. For example, the following picture shows a Philips Lumiled LUXEON K2.
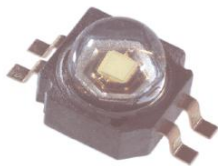
LUXEON® K2 is available in white, green, blue, royal blue, cyan, red, red-orange and amber.

PHILIPS

LUMILEDS
LIGHT FROM SILICON VALLEY

Following pictures shows Color Logic, a Goldline Controls Product (company I work with). Color Logic is used to light up the swimming pool with different colors. The board uses about 25 LEDs (Philips Lumiled LUXEON K2).

Currently Heat dissipation is issue. When closely seen, (picture on the right shows an enlarged view) a lot of copper is placed underneath these LEDs for better heat dissipation in to the board and to the heat sink.
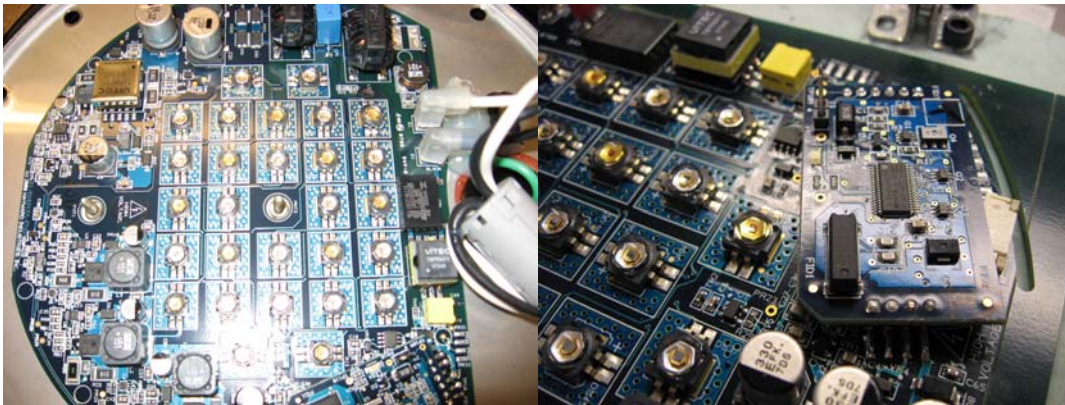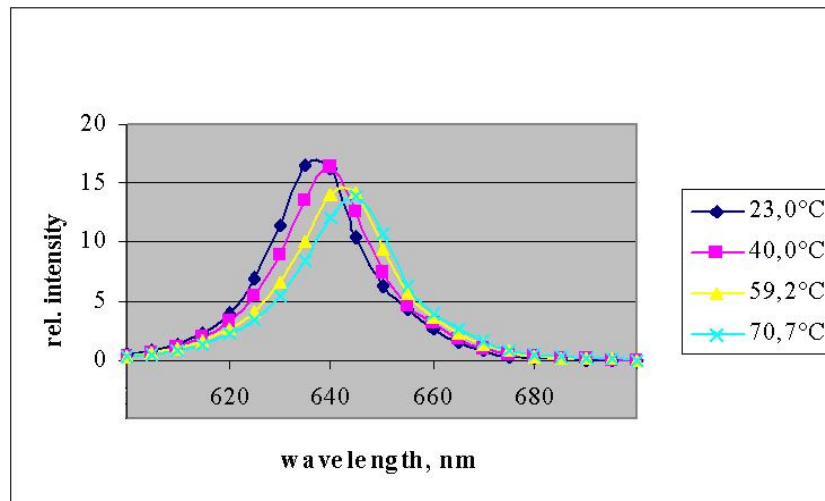

Following is a new version of the board. This board uses even smaller, but brighter LEDs. Heat dissipation is even more crucial. It can be seen that there is even more amount of copper and the LEDs are separated a little bit.
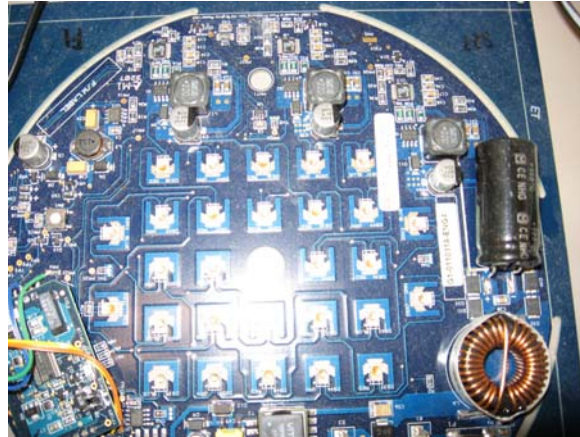
9) Temperature effects on LEDs
Following picture shows the effect of temperature on LEDs.

(Solid State Light Emitters, Light Emitting Diodes, Dr. János Schanda ,Colour and Multimedia Laboratory of the University of Veszprém)