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Module 2

Opto Electronic Devices

Introduction

* There are wide variety of very interesting and useful device functions involving the interaction of photons with semiconductors.

* These devices provide the optical sources and detectors that allow broadband telecommunications and data transmission over optical fibers. This area of device applications is called optoelectronics.

Photodiodes

* Semiconductor samples can be used as photoconductors by providing a change in conductivity proportional to an optical generation rate.

* Junction devices can be used to improve the speed of response and the sensitivity of detectors of optical or high energy radiation.

* Two Terminal devices designed to respond to photon absorption are called photodiodes. They have extremely high sensitivity and response speed.

* Since modern electronics often involves optical as well as electrical signals, photodiodes serve important functions as electronic devices.

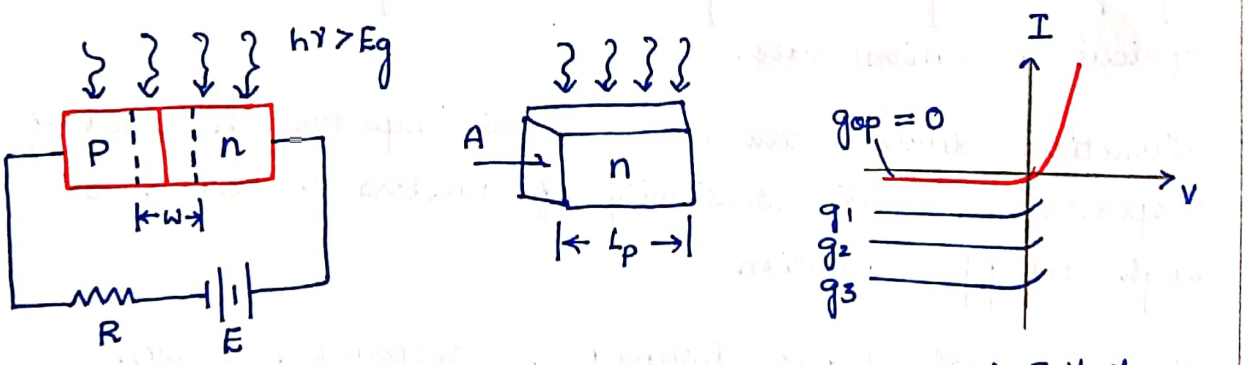
Current and Voltage in an illuminated Junction.

* W.K.T the current due to drift of minority carriers across a junction as a generation current.

* Minority carriers generated thermally within a diffusion length of each side of the junction diffuse to the depletion region and are swept to the other side by the electric field.

* carriers generated within the depletion region W are separated by the junction field, electrons being collected in the n region and holes in the p region.

* If junction is uniformly illuminated by photons with $h\nu > E_g$, an added generation rate g_{op} (EHP/cm^3-s) participates in this current.



(a) absorption of light by the device

(b) Iop resulting from EHP generation within diffusion length of the junction on n-side

fig c) I-V charac of illuminated junction

fig : optical generation of carriers in a pn junction.

* The no. of holes created per second with in a diffusion Length of the transition region on the n side is $A L_p g_{op}$. Similarly $A L_n g_{op}$ electrons are generated per second within L_n on p-side and $A W g_{op}$ carriers are generated with W

* the resulting current due to the collection of these optically generated carriers by the junction is

$$I_{op} = q A g_{op} L_p + q A g_{op} L_n + q A g_{op} W$$

$$\boxed{I_{op} = q A g_{op} [L_p + L_n + W]} \longrightarrow (1)$$

* Now total reverse current is given by

$$I = I_{th} (e^{qV/KT} - 1) - I_{op} \longrightarrow (2)$$

where I_{th} is thermally generated current
I_{op} is optically generated current which is directed from n to p.

$$\therefore I = I_{th} (e^{qV/KT} - 1) - q A g_{op} [L_p + L_n + W] \longrightarrow (3)$$

where $I_{th} = q A \left(\frac{L_p}{\tau_p} P_n + \frac{L_n}{\tau_n} n_p \right) \longrightarrow (4)$

Substituting eq^n (4) in eq^n (3)

$$I = q A \left(\frac{L_p}{\tau_p} P_n + \frac{L_n}{\tau_n} n_p \right) (e^{qV/KT} - 1) - q A g_{op} [L_p + L_n + W] \longrightarrow (5)$$

* I-V curve is lowered by an amount proportional to the generation rate. Eq^n (5) can be considered in two parts the current described by the usual diode eq^n and current due to optical generation.

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* When the device is short circuited ($V=0$), the current eq^n is given by

$$I = qA\left(\frac{L_p}{\tau_p}p_n + \frac{L_n}{\tau_n}n_p\right)\left(\cancel{e^{q(0)/KT}}^{1} - 1\right) - qAg_{op}(L_p + L_n + W)$$

$$I_{sc} = -I_{op}$$

There is a short circuit current from n to p equal to I_{op}.

* When there is an open circuit across the device, $I=0$ and the voltage $V = V_{oc}$ is

$$V_{oc} = \frac{KT}{q}\ln\left[\frac{I_{op}}{I_{th}} + 1\right]$$

$$= \frac{KT}{q}\ln\left[\frac{L_p + L_n + W}{\left(\frac{L_p}{\tau_p}\right)p_n + \left(\frac{L_n}{\tau_n}\right)n_p}g_{op} + 1\right]$$

for a symmetrical junction $p_n = n_p$ and $\tau_p = \tau_n$, thermal generation rate $\frac{p_n}{\tau_n} = g_{th}$.

$$\therefore V_{oc} = \frac{KT}{q}\ln\left[\left(\frac{L_p + L_n + W}{L_p + L_n}\right)\frac{g_{op}}{g_{th}} + 1\right]$$

Neglecting generation within W,

$$V_{oc} = \frac{KT}{q}\ln\left(\frac{g_{op}}{g_{th}}\right) \qquad \text{for } g_{op} >> g_{th}$$

* The term $g_{th} = \frac{p_n}{\tau_n}$ represents the equilibrium thermal generation-recombination rate. As minority carrier concentration is increased by optical generation of EHPs, the lifetime τ_n becomes shorter and $\frac{p_n}{\tau_n}$ becomes larger. Therefore V_{oc} cannot increase indefinitely with increased generation rate and V_{oc} is limited to contact potential $V_{oc} = V_0$

* The contact potential is the maximum forward bias that can appear across a junction. The appearance of a forward voltage across an illuminated junction is known as the photovoltaic effect.

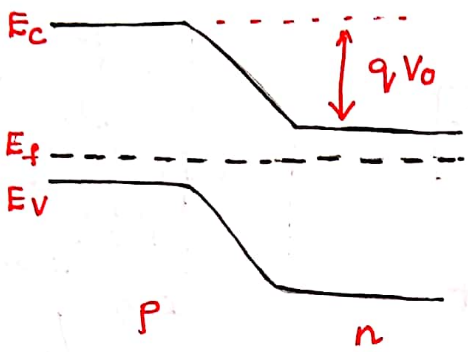


fig : junction at equillibrium

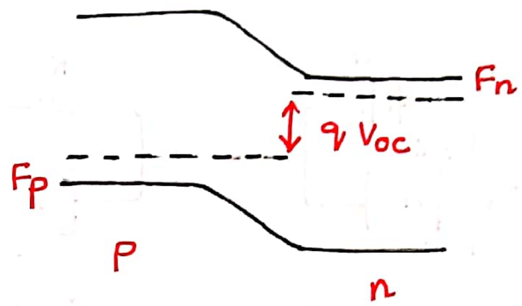


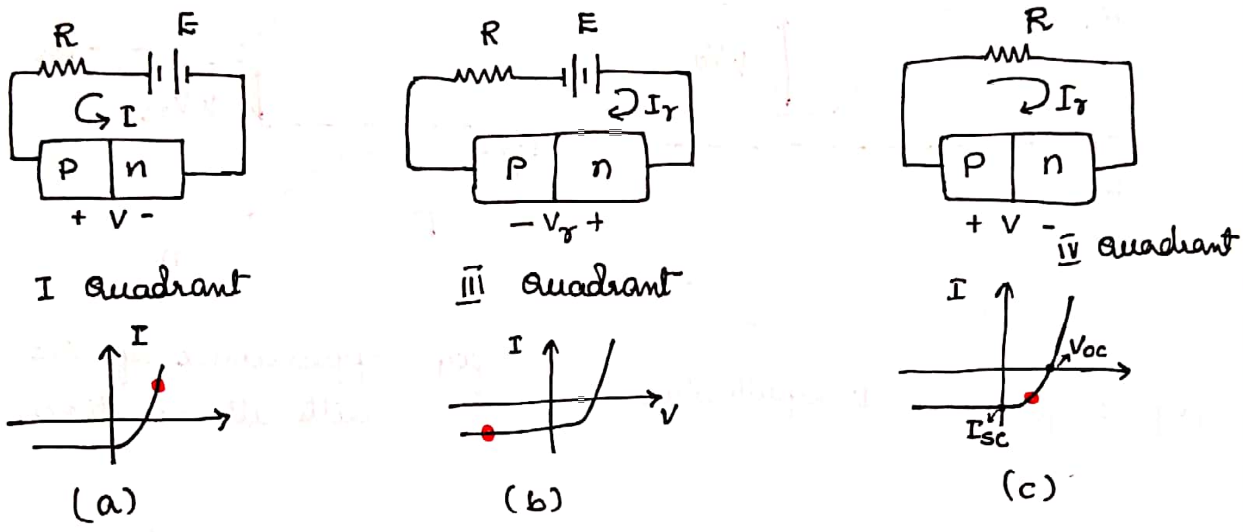
fig : appearance of V_{oc} with illumination.

* depending on the intended application, the photodiode can be operated in either the third or fourth quadrants of its I - V characteristics.

* Fig illustrates, power is delivered to the device from the external circuit when the current and junction voltage are both positive or both negative (first or third quadrants).

* In the fourth quadrant, the junction voltage is positive and the current is negative. In this case power is delivered from the junction to the external circuit (In fourth quadrant the current flows from the negative side of V to the positive side as in a battery)

* If power is to be extracted from the device, the fourth quadrant is used; on the other hand, in applications as a photodetector, junction is reverse biased and operated in third quadrant.



In (a) & (b) power is delivered to the device by the external circuit.

(c) the device delivers power to the load.

Solar Cells

* Since power can be delivered to an external circuit by an illuminated junction, it is possible to convert solar energy into electrical energy.

* In the fourth quadrant of IV characteristics of diode, more power cannot be delivered by an individual device. where voltage is restricted to value less than the contact potential which is less than the bandgap voltage i.e $\frac{E_g}{q}$ [because $E_g = qV_0$, $\therefore V_0 = \frac{E_g}{q}$]

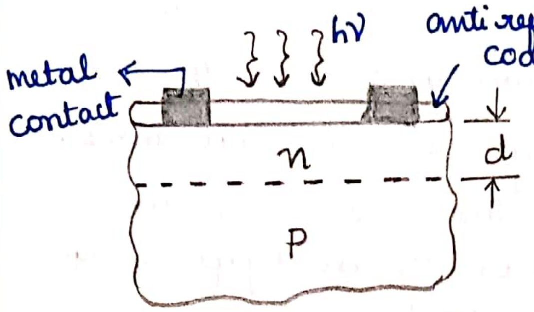
* For Si, the voltage V_{oc} is less than about 1V, the current generated depends on the illuminated area typically I_{op} in the range of 10-100mA for a junction within an area of about $1cm^2$. If many such devices are used, the resulting power can be significant.

* In fact, arrays of p-n junction solar cells are currently used to supply electrical power for many space satellites

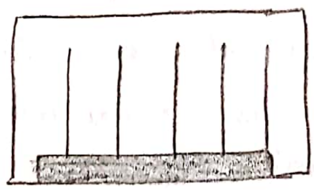
* Solar cells can supply power for the electronic equipment abroad a satellite over a long period which is a distinct advantage over batteries.

* The array of junctions can be distributed over the surface of the satellite or can be contained in solar cell 'paddles' attached to the main body of the satellite.

* To utilize a maximum amount of available optical energy, it is necessary to design a solar cell with a large area junction located near the surface of the device.



(a) Enlarged view of the planar junction



(b) top view showing metal contact 'fingers'

fig : Configuration of a solar cell

* The planar junction is formed by diffusion or ion implantation and the surface is coated with appropriate materials to reduce reflection and to decrease surface recombination.

* Many compromises must be made in solar cell design. for example in the above fig,

① Junction depth d must be less than L_p in the n-material to allow holes generated near the surface to diffuse to the junction before recombination takes place.

Similarly thickness of the p-region must be such that electrons generated in the region can diffuse to the junction before recombination takes place.

This requirement implies a proper match between the L_n and thickness of p-region and the mean optical penetration depth $1/\alpha$.

(2) It is desirable to have a large contact potential V_0 to obtain a large photovoltage and therefore heavy doping is indicated.

On the other hand, long lifetimes are desirable and these are reduced by doping too heavily.

* It is important that the series resistance of the device be very small so that the power is not lost to heat due to ohmic losses in the device itself.

A series resistance of only a few ohms can reduce output power of a solar cell. Since the area is large the resistance of the p-type body of the device can be made small. However contacts to the thin N region require special design.

If this region is contacted at the edge current must flow along the thin N region to the contact resulting in a large series resistance. To prevent this effect, the contact can be distributed over the n surface by providing small contact fingers as in fig b. These narrow contacts serve to reduce the series resistance without interfering appreciably with the incoming light.

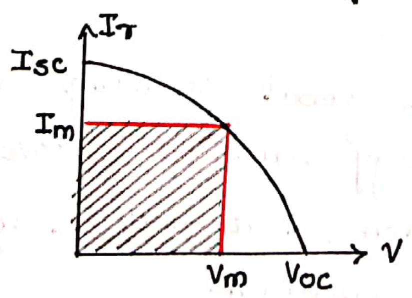


fig : I-V charac of an illuminated cell.

* A well made Si cell can have about 25% efficiency for solar energy conversion providing about $\sim 250\ W/m^2$ of electrical power under full illuminations.

* The cost and scalibility of photovoltaic technology are of great importance for terrestrial applications.

* To obtain more power per cell is to focus considerable light onto the cell with the use of mirrors.

At high temperatures Si cells lose efficiency. GaAs or related compounds can be used at $100^{\circ}C$ or higher. For example GaAs - AlGaAs heterojunction all provides good conversion efficiency and operates at elevated temperatures that are common in solar concentration systems.

Problem.

A Si solar cell has a short-circuited current of 100 mA and an open-circuited voltage of 0.8 V under full solar illumination. The fill factor is 0.7. What is the maximum power delivered to a load by this cell?

Soln : Given : $V_{oc} = 0.8V$, $I_{sc} = 100mA$, $ff = 0.7$

$$\therefore P_{max} = (ff)\ I_{sc}\ V_{oc}$$

$$= (0.7)(100)(0.8)$$

$$\boxed{P_{max} = 56\ mW}$$

Photodetectors

* When the photodiode is operated in the third quadrant of its I-V characteristics, the current is essentially independent of voltage but is proportional to the optical generation rate.

Such a device provides a useful means of measuring illumination levels or of converting time varying optical signals into electrical signals.

Response Speed (or) Bandwidth

* In most optical detection applications the detector's speed of response or bandwidth is critical.

For ex, if the photodiode is to respond to a series of light pulses 1 ns apart, the photogenerated minority carriers must diffuse to the junction and be swept across to the other side in a time much less than 1 ns.

The carrier diffusion step in this process is time consuming and should be eliminated if possible.

∴ It is desirable that the width of the depletion region W be large enough so that most of the photons are absorbed within W rather than in the neutral p & n regions and generate more EHPs.

Since this carrier drift occurs in a very short time, the response of the photodiode can be quite fast. When the carriers are generated primarily within the depletion layer W, the detector is called a Depletion Layer Photodiode

When W can be chosen appropriately a compromise between sensitivity and speed of response.

If W is wide, most of the incident photons will be absorbed in the depletion region leading to a high sensitivity but it will produce small junction capacitance, thereby reducing the

RC time constant of the detector circuit.

When W is not be so wide that the time required for drift of photogenerated carriers out of the depletion region is excessive, leading to low bandwidth.

P-i-n photodetector :

* This is one of the convenient method of controlling the width of the depletion region.
* The 'i' region need not be truly intrinsic as long as the resistivity is high.
* When the device is reverse biased, the applied voltage appears almost entirely across the 'i' region. If the carrier lifetime within the i region is long compared with the drift time, most of the photogenerated carriers will be collected by the n and p regions.

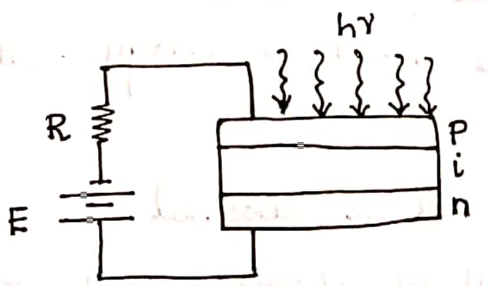


fig : p.i.n photodiode

* An important figure of merit for a photodetector is the <u>external quantum efficiency</u> (η_Q), defined as number of carriers that are collected for every photon impinging on the detector.

For a photocurrent density J_{op}, we collect J_{op}/q carriers per unit area per second. For an incident optical power density of P_{op}, the no. of photons shining on the detector per unit area per second is $P_{op}/h\nu$. Therefore,

$$\eta_q = \frac{\left(\frac{J_{op}}{q}\right)}{(P_{op}/h\nu)}$$

* For a photodiode that has no current gain, the maximum η_q is unity. If low level optical signal are to be detected, it is often desirable to operate the photodiode in avalanche region of its characteristic. In this mode, each photogenerated carrier results in a significant change in the current because of avalanche multiplication, leading to gain and external quantum efficiencies of greater than 100%. Avalanche photodiodes (APDs) are useful as detectors in fiber-optic systems.

* Types of photodiodes: If the photodiode is sensitive to photons with energies near the bandgap energy. It is called <u>intrinsic detectors</u>

  If $h\nu < E_g$ → no photons will be absorbed.

  If $h\nu >> E_g$ then they will be absorbed very near the surface, where recombination rate is high.

* It is necessary to choose a photodiode material with bandgap corresponding to a particular region of the spectrum.

* If the photo diode is sensitive to longer wavelengths such that photons can excite electrons into or out of impurity levels, they are called as extrinsic detector.

* But sensitivity of extrinsic detectors is much less than intrinsic detectors, where EHPs are generated by excitation across the bandgap.

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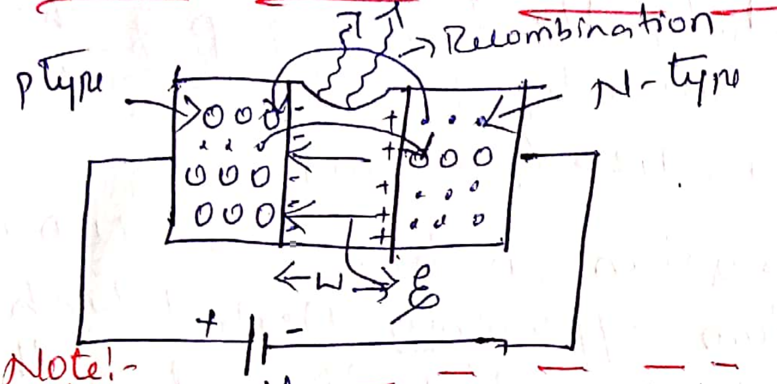
Light Emitting Diodes:-

→ V_{BR} Value for LED is $\simeq 5V$



→ Note:-

1) $E_g > 1.8\,eV$ for emitting Visible Light. (R-to-Violet)

2) light Color depends on frequency of photon.

Note:-
GaAs → 1.8 eV → Infrared (Remote Control (TV))
Si & Ge Not be used for LED.

When Carriers are injected across a forward-biased junction, the Current is usually accounted for by recombination in the transition region & in the neutral regions near the junction.

In a Semiconductor with an indirect band gap, such as Si or Ge, the recombination releases heat to the lattice. On the other hand, in a material characterized by direct recombination, Considererable light may be given off from the junction under forward bias. This effect, Called injection electroluminescence, provides an important application of diodes as generators of light.

The use of LED in digital displays is well known. There are also other important applications, in traffic and automotive Signals and in illumination.

Another important device making use of radiative recombination in a forward-biased p-n Junction is the Semiconductor Laser.

For LEDs, the frequency (color) of the photon is governed by the band gap of the Semiconductor as given by the planck relation, $h\nu = E_g$. ($E_g(eV) = 1.24/\lambda\ (\mu m)$).

A very important metric of an LED is the external quantum efficiency η_{ext}, which is defined as the light output divided by the electrical input power.

$$\eta_{ext} = \left[\text{Internal radiative efficiency}\right] \times \left[\text{Extraction efficiency}\right]$$

The internal efficiency is a function of the quality of the material and the structure and composition of the layer. Defects in the material will clearly lead to nonradiative recombination.

However, even if the internal efficiency is high, not all emitted photons are extracted from the LED. The emitted photons from an LED have a wide angular distribution, unlike those in a laser.

Light - Emitting Materials:-

There is a wide variation in band gaps and therefore, in available photon energies, extending from the ultraviolet (GaN, 3.4eV) into the infrared (InSb, 0.18eV).

The variation in photon energy obtainable from the compound semiconductors is the ternary alloy gallium arsenide-phosphide, which is shown below graph.

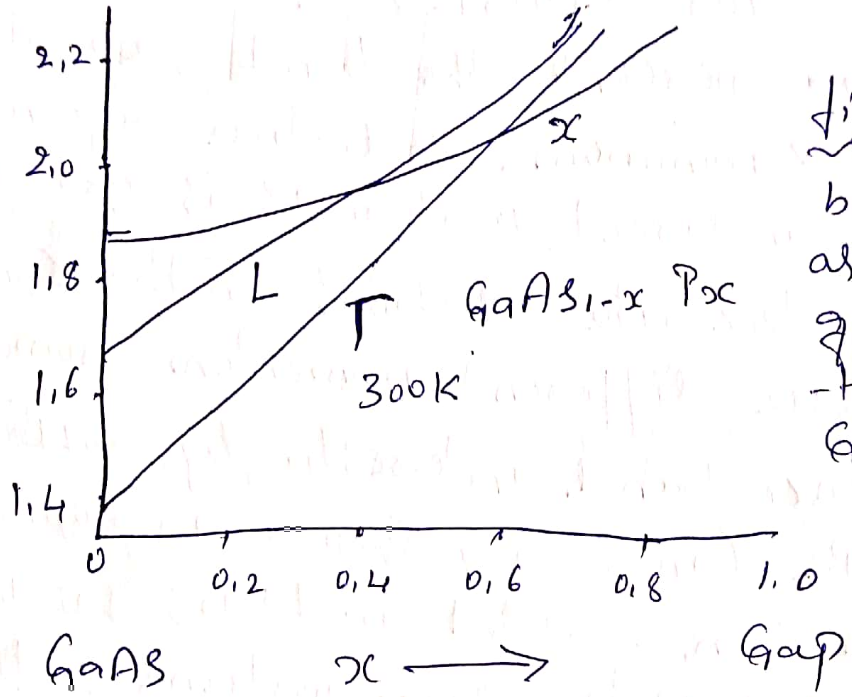


fig: Conduction band energies as a function of alloy composition for $GaAs_{1-x}P_x$.

When the percentage of As is reduced and P is increased in this material, the resulting band gap varies from the direct 1,43 eV gap of GaAs (infrared) to the indirect 2,26 eV gap of GaP (green).

The band gap of $GaAs_{1-x}P_x$ varies almost linearly with x until the 0,45 composition is reached, and electron-hole recombination is direct over this range. The most common alloy composition used in red LED displays is $x \simeq 0.4$. For this composition the band gap is direct, since the Γ minimum (at $k=0$) is the lowest part of the conduction band.

This results in efficient radiative recombination and the emitted photons (~1.9 eV) are in the red portion of the spectrum.

For $GaAs_{1-x}P_x$ with P concentrations above 45 percent, the band gap is due to the indirect X minimum. Radiative recombination in such indirect materials is generally unlikely because electrons in the conduction band have different momentum from holes in the valence band. Interestingly, however, indirect $GaAs_{1-x}P_x$ (including GaP, $x=1$) doped with Nitrogen can be used in LEDs with light o/p in the yellow to green portions of the spectrum.

In many applications light from a laser or an LED need not be visible to the eye. Infrared emitters such as GaAs, InP & mixed alloys of these compounds are particularly well suited to fiber-optical communication system or TV remote controls.

By varying the current through the diode, the light o/p can be modulated such that analog or digital information appears in the optical signal directed at the detectors.

A semiconductor laser-photodetector

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- arrangement can be used in a compact disc or DVD system for reading digital information from the spinning disc.

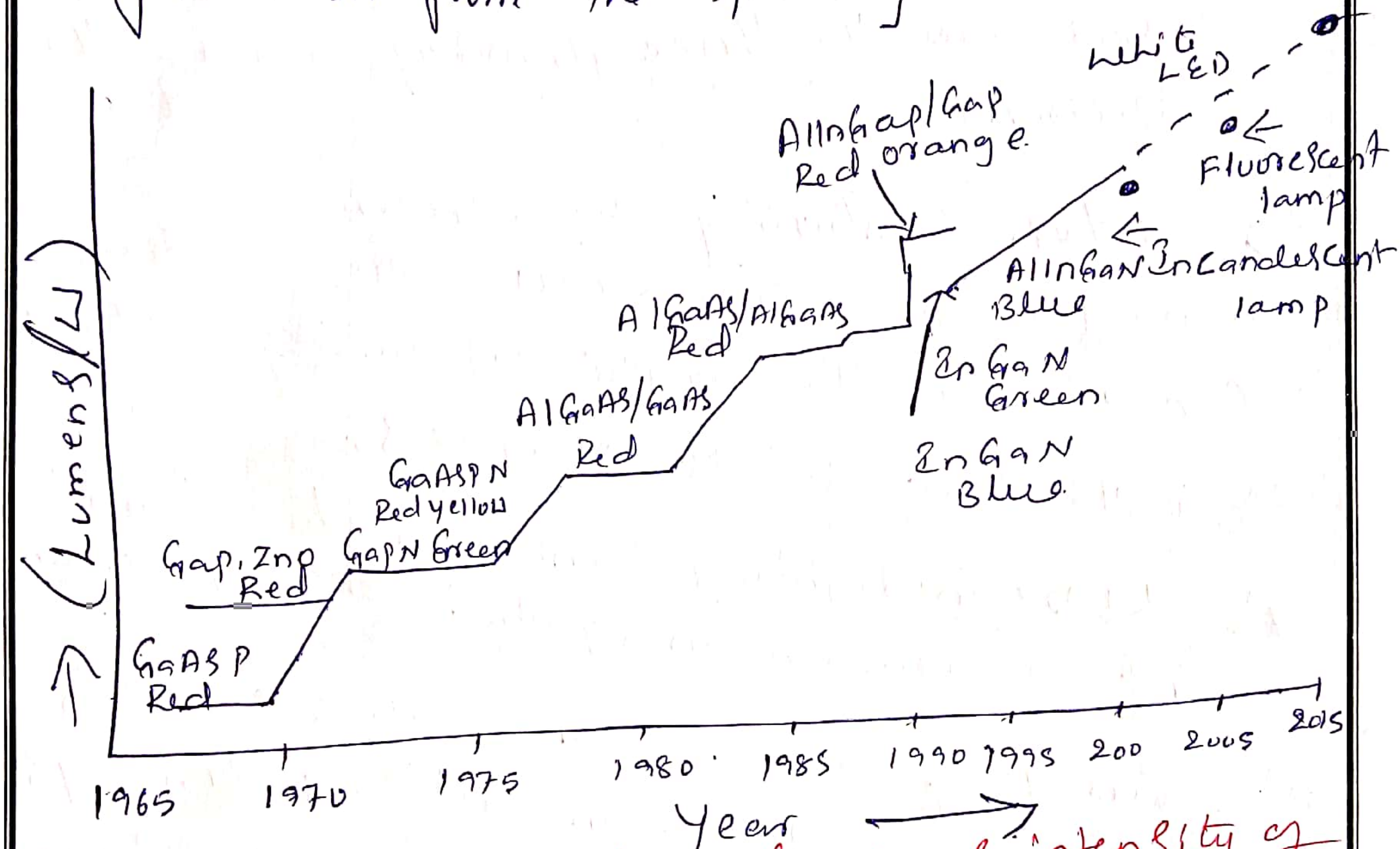

fig:- Improvement of luminous intensity of LED

*) The InAlGaP system is useful for red, yellow orange wavelengths.

*) AlGaInN is a strong emitter in the blue & green.

*) moderate efficiency (~10 lumens/watt) Red, Green & yellow-green LEDs have existed for a long time in the GaAsP system.

*) In mid-1990s much higher brightness & efficiency (~30 lumens/W) red-orange-yellow LEDs based on the InAlGaP system have been developed.

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*) A major goal of the optoelectronics Community has been the achievement of high-efficiency red, green & blue emitters, because those Colour are the three primary colour of the Spectrum.

*) When Combining Red, Green & Blue Color for producing a new Colour & also Can increase the longer lifetime of the LEDs

*) The Cost is also very less,

*) LEDs in lighting Can lead to a significant reduction in global energy demand.

*) Arrays of red, green & blue emitters are being used in outdoor displays and TV screens, as well as in automotive signal lights.

One problem that is faced with LEDs is that many of the photons that are generated Cannot be extracted from the device if it is a planar structure. The reason is that the semiconductor has a higher refractive index than the surrounding (air) medium, and for a light ray impinging on the surface at greater than the Critical angle, it undergoes total internal reflection & is re-absorbed.