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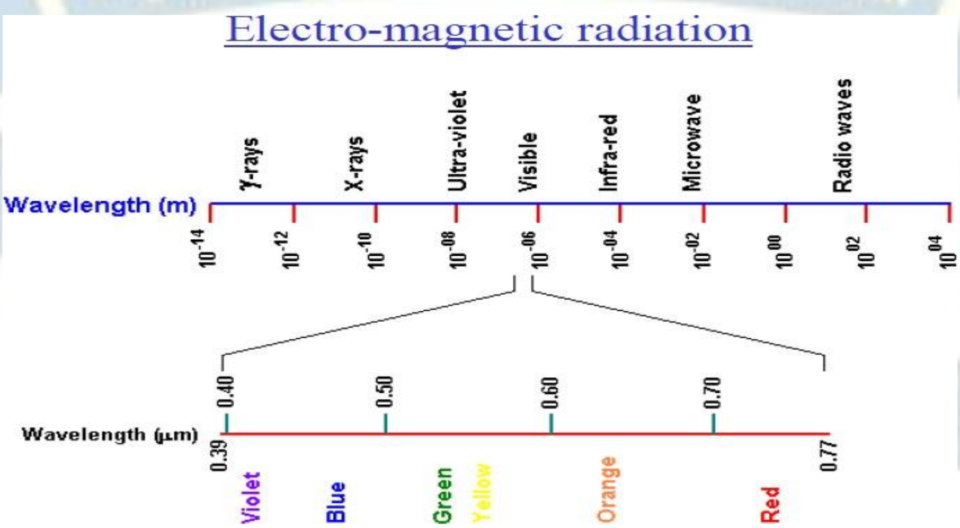
| **Course/Branch** : BE/CSE | **Year / Semester** : I/II | Format No. | NAC/TLP-07a.5 |
| **Subject Code** :PH8252 | **Subject Name** :Physics for Information science | Rev. No. | 02 |
| **Unit No** : 4 | **Unit Name :Optical properties of materials** | Date | 14-11-2017 |

**LECTURE NOTES**

Classification of optical materials – carrier generation and recombination processes - Absorption emission and scattering of light in metals, insulators and Semiconductors (concepts only) - photo current in a P- N diode – solar cell – LED – Organic LED – Laser diodes – Optical data storage techniques.

## INTRODUCTION

- Optical property of a material is defined as its interaction with electromagnetic radiation in the visible.
- Electromagnetic spectrum of radiation spans the wide range from γ-rays with wavelength as $10^{-12}$ m, through x-rays, ultraviolet, visible, infrared, and finally radio waves with wavelengths as along as $10^5$ m.
- Visible light is one form of electromagnetic radiation with wavelengths ranging from 0.39 to 0.77 µm. Light can be considered as having waves and consisting of particles called photons.
- They play an important role due to their physical properties such as electrical properties; thermal properties; magnetic properties; and optical properties.
- The optical properties of engineering materials are useful in different applications. Ex.: domestic, medicine, astronomy, manufacturing.
- Engineering materials are important in everyday life because of their versatile structural properties.

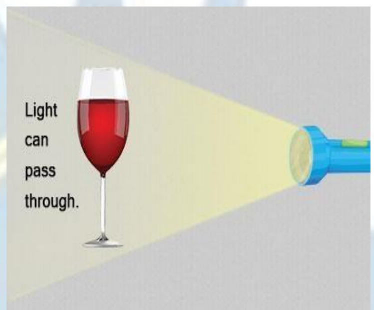


**LECTURE NOTES**

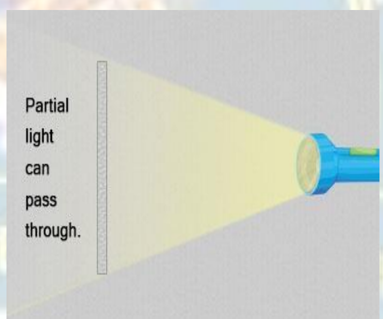
## CLASSIFICATION OF OPTICAL MATERIALS:

Materials are classified on the basis of their interaction with visible light into three categories.

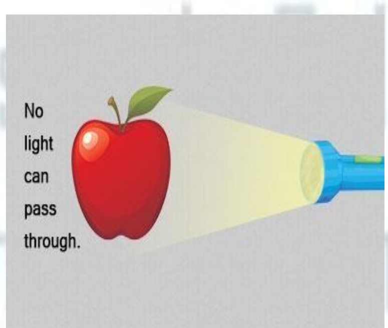
1. **Transparent materials**: Materials that are capable of transmitting light with relatively little absorption and reflection are called transparent materials i.e. we can see through the objects clearly.




2. **Translucent materials:** Translucent materials are those through which light is transmitted diffusely i.e. objects are not clearly distinguishable when viewed through.




3. **Opaque materials:** Those materials that are impervious to the transmission of visible light are termed as opaque materials. These materials absorb all the energy from the light photons.

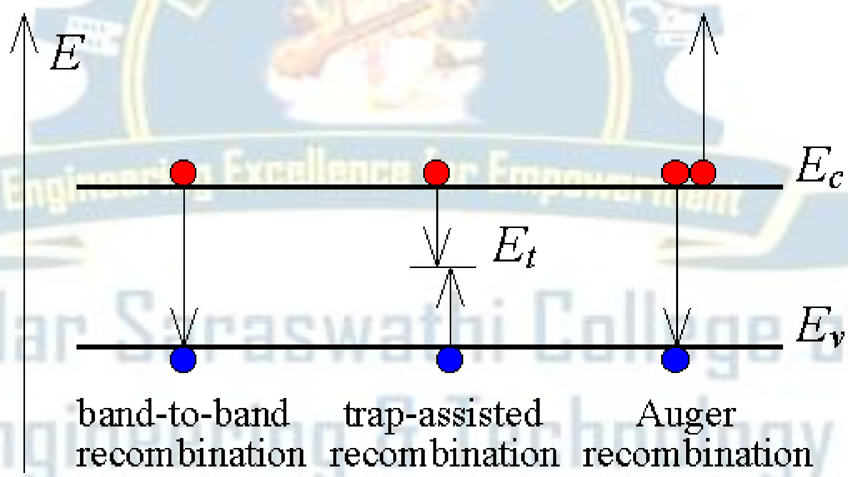


**LECTURE NOTES**

## CARRIER GENERATION AND RECOMBINATION PROCESSES:

### Recombination Processes

- Recombination of electrons and holes is a process by which both carriers annihilate each other: electrons occupy - through one or multiple steps - the empty state associated with a hole.
- Both carriers eventually disappear in the process. The energy difference between the initial and final state of the electron is released in the process.
- This leads to one possible classification of the recombination processes. In the case of radiative recombination, this energy is emitted in the form of a photon.
- In the case of non-radiative recombination, it is passed on to one or more phonons and in the case of Auger recombination it is given off in the form of kinetic energy to another electron.
- Another classification scheme considers the individual energy levels and particles involved.




**Band-to-band recombination** occurs when an electron moves from it conduction band state into the empty valence band state associated with the hole. This band-to-band transition is typically also a radiative transition in direct bandgap semiconductors.

**Trap-assisted recombination** occurs when an electron falls into a "trap", an energy level within the bandgap caused by the presence of a foreign atom or a structural defect. Once the trap is filled it cannot accept another electron.

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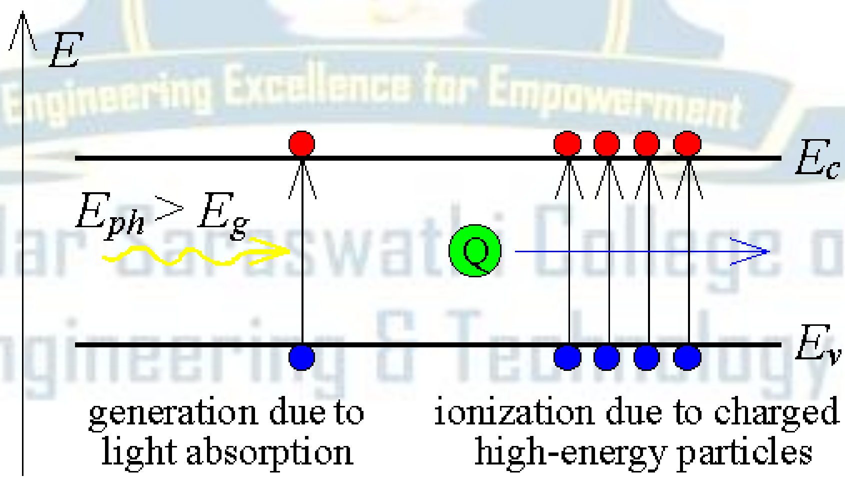
**LECTURE NOTES**

## Auger recombination

This process in which an electron and a hole recombine in a band-to- band transition, but now the resulting energy is given off to another electron or hole. The involvement of a third particle affects the recombination rate so that we need to treat Auger recombination differently from band-to-band recombination. Each of these recombination mechanisms can be reversed leading to carrier generation rather than recombination.

## Carrier Generation Types

In addition, there are generation mechanisms, which do not have an associated recombination mechanism, such as generation of carriers by light absorption or by a high- energy electron/particle beam. These processes are referred to as ionization processes. Impact ionization, which is the generation mechanism associated with Auger recombination, also belongs to this category. The generation mechanisms are illustrated.




Carrier generation due to light absorption occurs if the photon energy is large enough to raise an electron from the valence band into an empty conduction band state, thereby generating one electron-hole pair. The photon energy needs to be larger than the bandgap energy to satisfy this condition. The photon is absorbed in this process and the excess energy, $E_{ph} - E_g$, is added to the electron and the hole in the form of kinetic energy.

**LECTURE NOTES**

## OPTICAL PROPERTIES OF MATERIALS:

- When a light beam in impinged of a material surface, portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material.

- Bouguer's law : The fraction of beam that is absorbed is related to the thickness of the materials and manner in which the photons interact with the materials structure.

$$I = I_0 \exp( -\alpha.X)$$

- Absorption occurs by two mechanisms: Reyleigh scattering and Compton scattering.

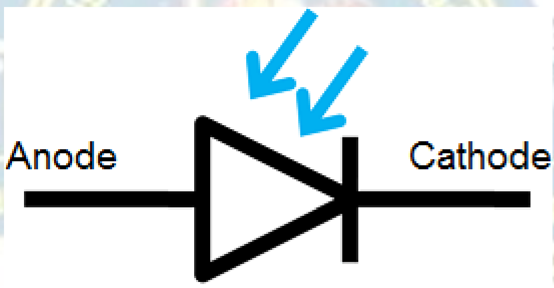
## MATERIALS FOR COLORED LEDs :

| Wave length (nm) | Color | Material |
|---|---|---|
| - | Infra-red | GaAs |
| 660 | Red | $GaP_{0.40}As_{0.60}$ *or* $Al_{0.25}Ga_{0.75}As$ |
| 635 | Orange | $GaP_{0.65}As_{0.35}$ |
| 578 | Yellow | $GaP_{0.85}As_{0.15}$ |
| 556 | Green | GaP ($GaP_{1.00}As_{0.00}$) |
| - | Blue | $Ga_{0.94}NIn_{0.06}$ |

## PHOTOCURRENT IN P-N- JUNCTION DIODE:

- A photodiode is a PN-junction diode that consumes light energy to produce electric current. Sometimes it is also called as photo-detector, a light detector, and photo-sensor.
- These diodes are particularly designed to work in reverse bias condition, it means that the P-side of the photodiode is associated with the negative terminal of the battery and n-side is connected to the positive terminal of the battery.

- This diode is very complex to light so when light falls on the diode it easily changes light into electric current. The solar cell is also branded as large area photodiode because it converts solar energy into electric energy. Though, solar cell works only in bright light.
- A photodiode is one type of light detector, used to convert the light into current or voltage based on the mode of operation of the device.
- It comprises of optical filters, built-in lenses and also surface areas.
- These diodes have a slow response time when the surface area of the photodiode increases.
- Photodiodes are alike to regular semiconductor diodes, but that they may be either visible to let light reach the delicate part of the device.
- Several diodes intended for use exactly as a photodiode will also use a PIN junction somewhat than the usual PN junction




Photodiode symbol

- Some photodiodes will look like a light emitting diode. They have two terminals coming from the end.
- The smaller end of the diode is the cathode terminal, while the longer end of the diode is the anode terminal. See the following schematic diagram for the anode and cathode side.
- Under forward bias condition, conventional current will flow from the anode to the cathode, following the arrow in the diode symbol. Photocurrent flows in the reverse direction.

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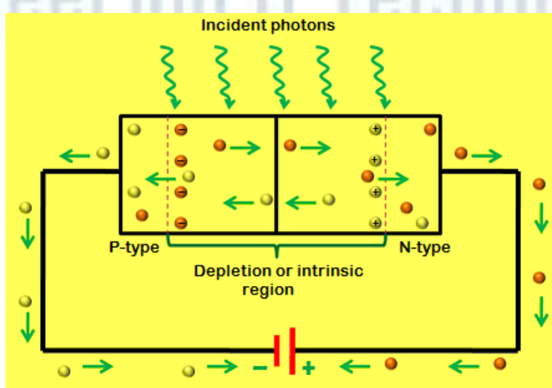
**LECTURE NOTES**

**Photodiode**

## Types of Photodiode

- Although there are numerous types of photodiode available in the market and them all works on the same basic principles, though some are improved by other effects.
- The working of different types of photodiodes work in a slightly different way, but the basic operation of these diodes remains the same. Photodiodes can be classified based on its construction and functions as follows.
  - PN Photodiode
  - Schottky Photo Diode
  - PIN Photodiode
  - Avalanche Photodiode

These diodes are widely used in the applications where the detection of the presence of light, color, position, intensity is required. The main features of these diodes include the following.




**PN Junction Diode**

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**LECTURE NOTES**

**Modes of Operation**

There are three operating modes of the photodiode namely

(i) Photovoltaic mode

(ii) Photoconductive mode

(iii) Avalanche diode mode

**Photovoltaic Mode:**

This mode also known as zero bias mode, in which a voltage is produced by the lightened photodiode. It gives a very small dynamic range & non-linear necessity of the voltage formed.

**Photoconductive Mode:**

The photodiode used in this photoconductive mode is more usually reverse biased. The reverse voltage application will increase the depletion layer's width, which in turn decreases the response time & the junction capacitance. This mode is too fast and displays electronic noise

**Avalanche Diode Mode:**

Avalanche diodes operate in a high reverse bias condition, which permits multiplication of an avalanche breakdown to each photo-produced electron-hole pair. This outcome in an internal gain in the photodiode, which slowly increases the device response.

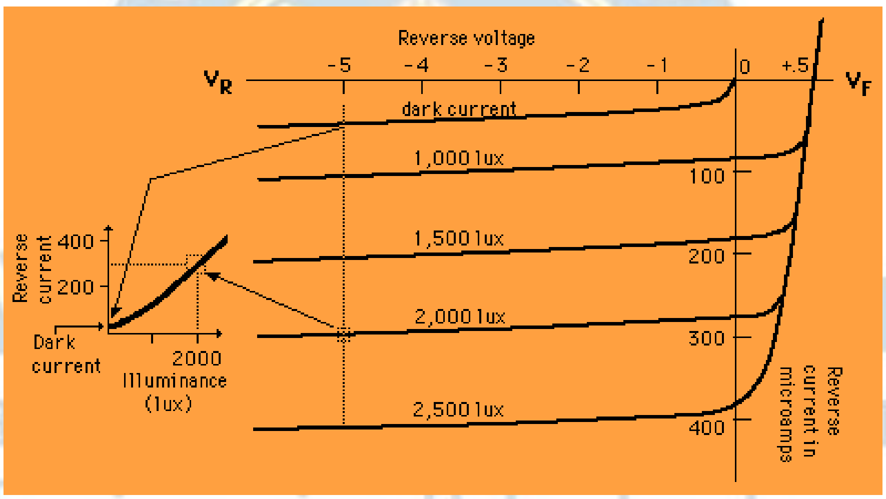
**Applications of Photodiode**

- Photodiodes are used in photo detectors like charge-coupled devices, photoconductors, and photomultiplier tubes.
- These diodes are used in consumer electronics devices like smoke detectors, compact disc players, and televisions and remote controls in VCRs.
- Consumer devices like clock radios, camera light meters, and street lights, photoconductors are more frequently used rather than photodiodes.
- Photodiodes are frequently used for the measurement of intensity of light in science & industry.
- These are widely used in various medical applications like instruments to analyze samples, detectors for computed tomography and are also used in blood gas monitors.

- These diodes are faster & more complex than normal PN junction diodes.
- Photodiodes are frequently used for lighting regulation and in optical communications

**V-I Characteristics of Photodiode**

- A photodiode continually activates in a reverse bias mode. The characteristics of the photodiode are shown in the figure,
- The photocurrent is independent of reverse bias voltage which is applied. For zero luminance, the photocurrent is almost zero excluding for small dark current in the order of nano amperes.
- As the optical power rises the photo current also rises linearly. The max photocurrent is incomplete by the power dissipation of the photo diode.

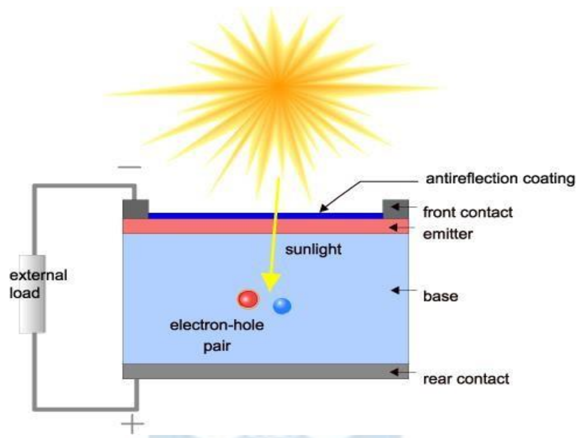



**V-I Characteristics**

## SOLAR CELLS:

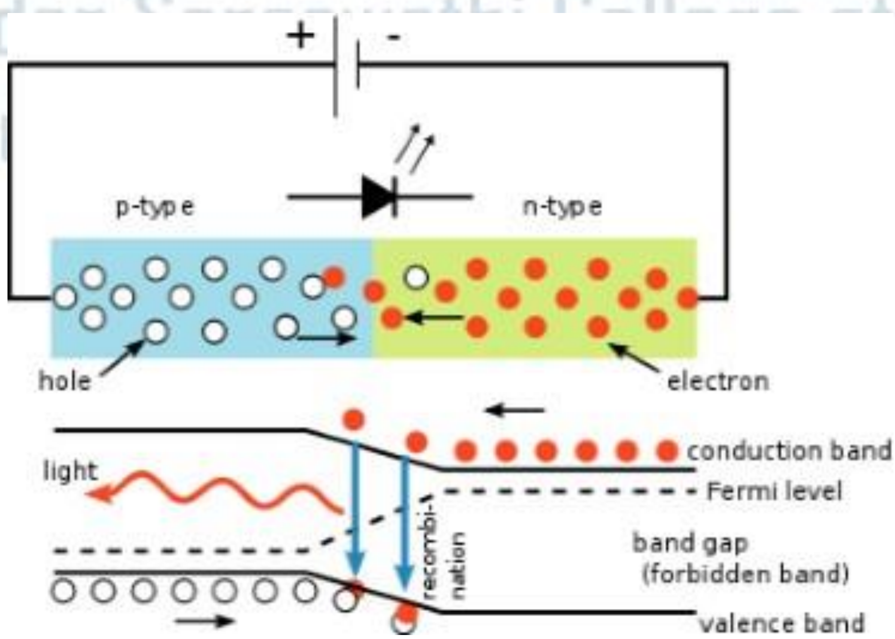
- Solar cells and photodetectors are devices that convert an optical input into current. A solar cell is an example of a photovoltaic device, i.e., a device that generates voltage when exposed to light.
- The first photovoltaic device was built, using a Sipn junction, by Russell Ohl in 1939.
- The functioning of a solar cell is similar to the photodiode (photo detector).
- It is a photodiode that is unbiased and connected to a load.

- There are three qualitative differences between a solar cell and photo detector.
- A photodiode works on a narrow range of wavelength while solar cells need to work over a broad spectral range (solar spectrum).
- Solar cells are typically wide area devices to maximize exposure.
- In photodiodes the metric is quantum efficiency, which defines the signal to noise ratio, while for solar cells, it is the power conversion efficiency, and which is the power delivered per incident solar energy.
- Usually, solar cells and the external load they are connected to are designed to maximize the delivered power.
- A simple solar cell is a pn junction diode. The n region is heavily doped and thin so that the light can penetrate through it easily.
- The p region is lightly doped so that most of the depletion region lies in the p side. The penetration depends on the wave-length and the absorption coefficient increases as the wavelength decreases.
- Electron hole pairs (EHPs) are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to then region and the holes to the p region.
- When an external load is applied, the excess electrons travel through the load to recombine with the excess holes. Electrons and holes are also generated with the p and n regions, as seen from figure.
- The shorter wavelengths (higher absorption coefficient) are absorbed in the n region and the longer wavelengths are absorbed in the bulk of the p region. Some of the EHPs generated in these regions can also contribute to the current.




## LIGHT-EMITTING DIODE (LED)

- A **light-emitting diode** (**LED**) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons. This effect is called electroluminescence.
- The color of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor.
- White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor on the semiconductor device.



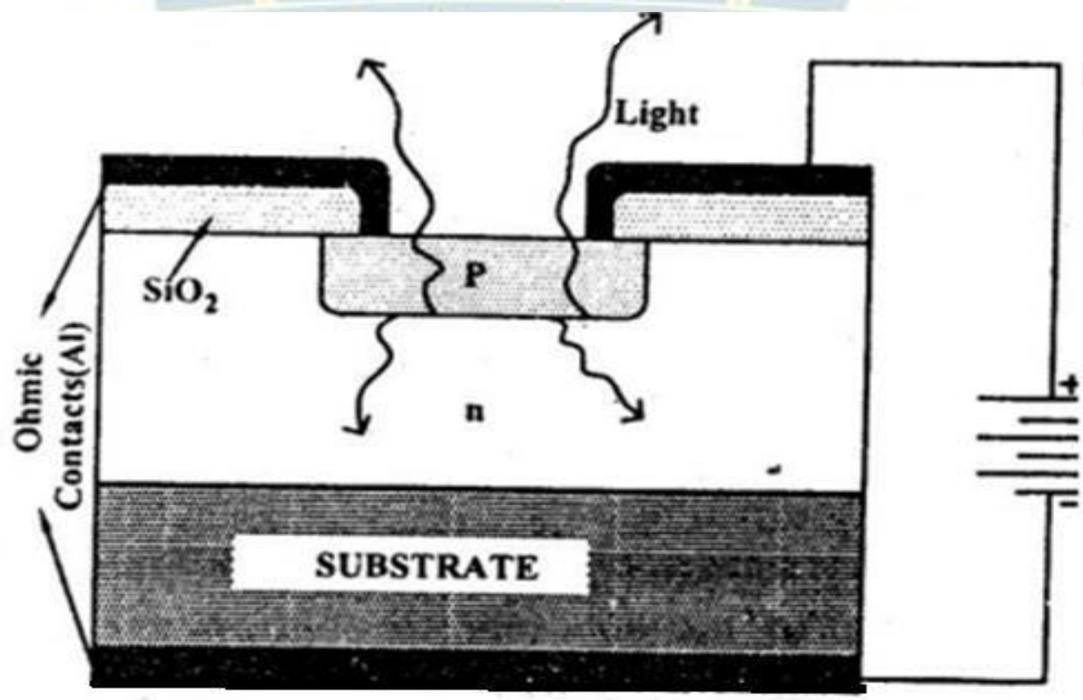
**LECTURE NOTES**

**Working of LED**

- Light emitting device convert the electrical energy into light energy. When it is forward biased, the majority charge carriers of electrons from n-type and holes from p-type are diffuse into each other.
- At the junction the electron hole recombination process takes place and energy is emitting in the form of visible light and IR region.

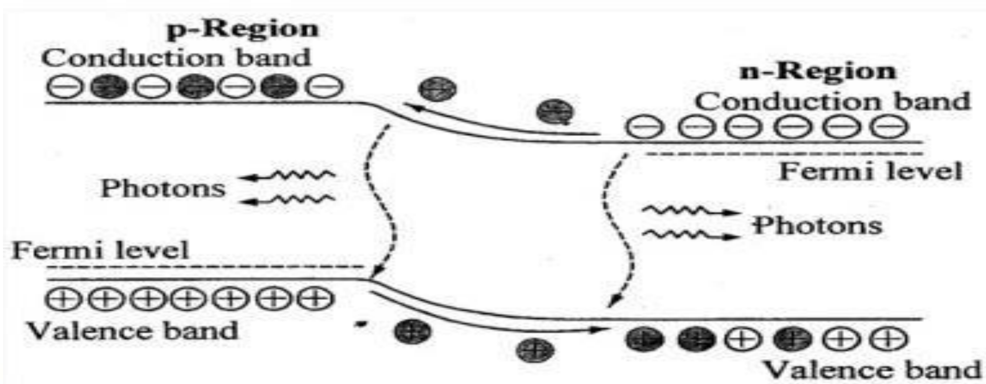
**CONSTRUCTION:**

- The light emitting diode is made by Gallium Arsenide semiconductors. First the PN Junction is formed by epitaxial growth technique. Si+Ga = n-type; Si+As = p-type.
- The thickness of the n-layer is always larger than the p-layer, because of increasing the radiative recombination. Proper electric connection (forward bias) given to the semiconductor through aluminium contact. P-jn is slightly open for out coming light rays.



**WORKING:**

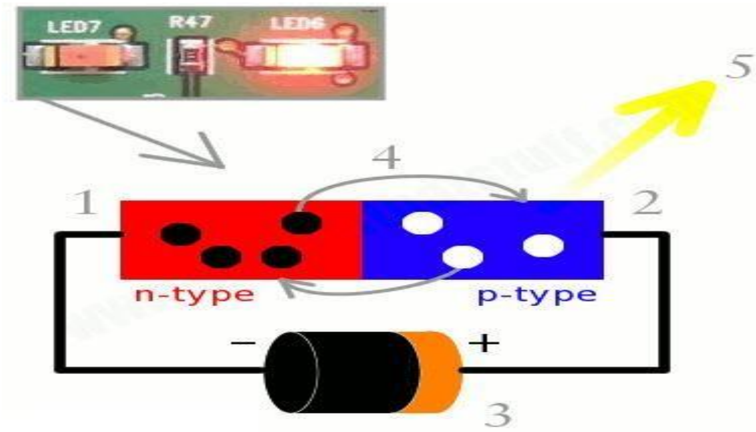
- When the p-n junction diode is forward biased, the barrier width is reduced, raising the potential energy on the n-side and lowering that on the p-side.
- The free electrons and holes have sufficient energy to move into the junction region.
- If a free electron meets a hole, it recombines and releases a photon. Thus, light radiation from the LED is caused by the recombination of holes and electrons that are injected into the junction by a forward bias voltage.




**Types of Light Emitting Diodes:**

There are different types of light emitting diodes present and some of them are mentioned below.

- Gallium Arsenide (GaAs) – infra-red
- Gallium Arsenide Phosphide (GaAsP) – red to infra-red, orange.
- Aluminium Gallium Arsenide Phosphide (AlGaAsP) – high-brightness red, orange-red, orange, and yellow
- Gallium Phosphide (GaP) – red, yellow and green
- Aluminium Gallium Phosphide (AlGaP) – green
- Gallium Nitride (GaN) – green, emerald green.
- Galium Indium Nitride (GaInN) – near ultraviolet, bluish-green and blue
- Silicon Carbide (SiC) – blue as a substrate
- Zinc Selenide (ZnSe) – blue

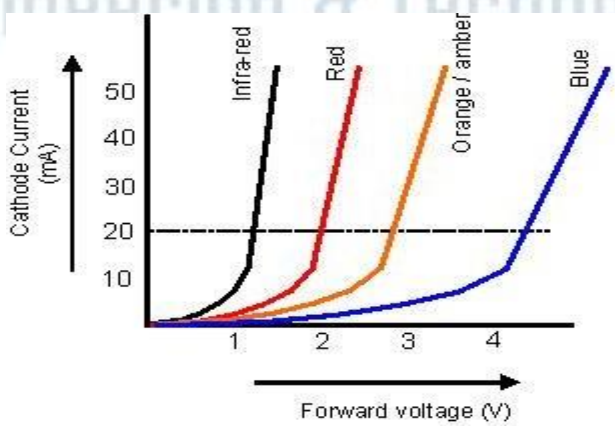



## I-V Characteristics of LED:

- There are different types of light emitting diodes are available in the market and there are different LED characteristics which include the color light, or wavelength radiation, light intensity.

- The important characteristic of the LED is color. In the starting use of LED, there is the only red color.

- As the use of LED is increased with the help of the semiconductor process and doing the research on the new metals for LED, the different colors were formed.

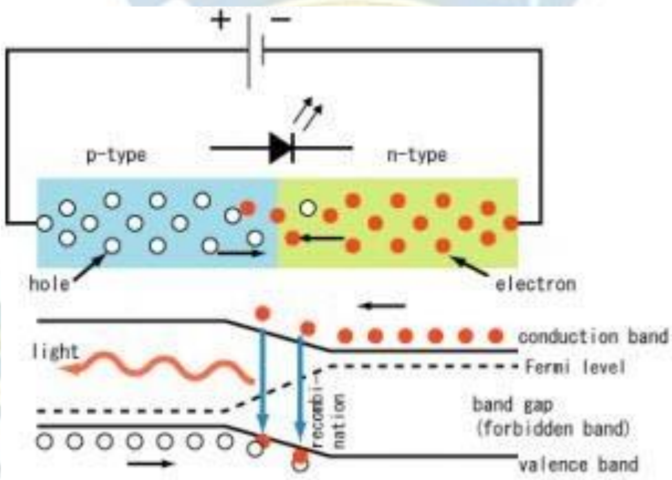



**I-V Characteristics of LED**

The following graph shows the approximate curves between the forward voltage and the current. Each curve in the graph indicates the different color. The table shows the summary of the LED characteristics.

The working principle of the Light emitting diode is based on the quantum theory. The quantum theory says that when the electron comes down from the higher energylevel to the lower energy level then, the energy emits from the photon.

The photon energy is equal to the energy gap between these two energy levels. If the PN-junction diode is in the forward biased, then the current flows through the diode.




**Working Principle of LED**

- The flow of current in the semiconductors is caused due to the flow of holes in the opposite direction of current and flow of electrons in the direction of the current.
- Thus there occurs recombination due to the flow of these charge carriers. The recombination indicates that the electrons in the conduction band jump down to the valence band.
- When the electrons jump from one band to another band the electrons emit the electromagnetic energy in the form of photons and the photon energy is equal to the forbidden energy gap.

- For example, consider the quantum theory, the energy of the photon is the product of both Planck constant and frequency of electromagnetic radiation. The mathematical equation is shown

$$Eq = h\upsilon$$

- Where h is known as a Planck constant, and the velocity of electromagnetic radiation is equal to the speed of light c. i.e. The frequency radiation is related to the velocity of light as a $f = c / \lambda$, λ is denoted as a wavelength of an electromagnetic radiation and the above equation will become as a

$$Eq = hc / \lambda$$

- From the above equation, it is inferred that the wavelength of electromagnetic radiation is inversely proportional to the forbidden gap. In silicon, germanium semiconductors this forbidden energy gap lies in between the condition and valence bands.
- Due to this reason, the total radiation of electromagnetic wave during recombination is in the form of the infrared radiation. The wavelength of infrared are out of visible range.
- The infrared radiation is said to be as a heat because the silicon and the germanium semiconductors are not direct gap semiconductors rather these are indirect gap semiconductors.
- But in the direct gap semiconductors, the maximum energy level of the valence band and minimum energy level of conduction band does not occur at the same moment of electrons.
- Therefore, during the recombination of electrons and holes are a migration of electrons from the conduction band to valence band the momentum of electron band will be changed.

**ORGANIC LED (OLED):**

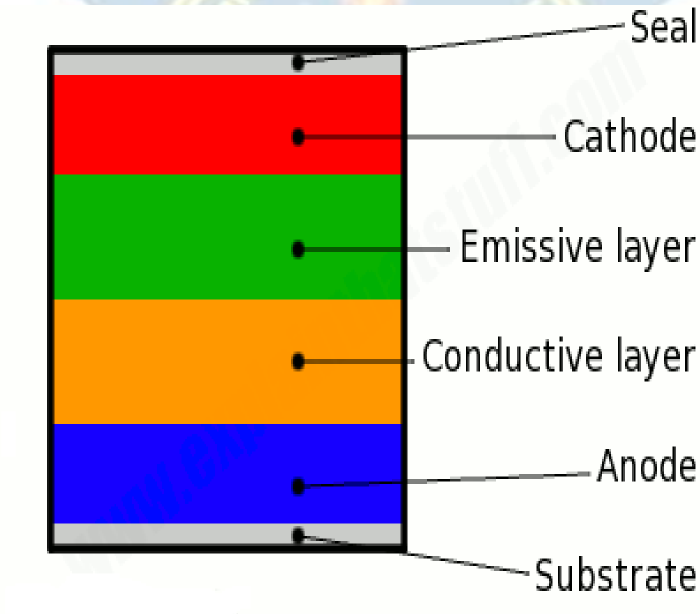
An **organic light-emitting diode** (**OLED**) is a light-emitting diode (LED) in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current.

This organic layer is situated between two electrodes; typically, at least one of these electrodes is transparent. OLEDs are used to create digital displays in devices such as television screens, computer monitors, portable systems such as smartphones, handheld game consoles and PDAs. White OLED devices are used in solid-state lighting applications.

The components in an OLED differ according to the number of layers of the organic material. There is a basic single layer OLED, two layer and also three layer OLED's. As the number of layers increase the efficiency of the device also increases.

The increase in layers also helps in injecting charges at the electrodes and thus helps in blocking a charge from being dumped after reaching the opposite electrode. Any type of OLED consists of the following components.

1. An emissive layer
2. A conducting layer
3. A substrate
4. Anode and cathode terminals.




As the emissive layer and the conducting layer is made up of organic molecules (both being different), OLED is considered to be an organic semi-conductor, and hence its name.

The organic molecules have the property of conducting electricity and their conducting levels can be varied form that of an insulator to a conductor. The emissive layer used in an OLED is made up of organic plastic molecules, out of which the most commonly used is polyfluorene.

The conducting layer is also an organic molecule, and the commonly used component is polyaniline. The substrate most commonly used may be a plastic, foil or even glass. The anode component should be transparent. Usually indium tin oxide is used.

This material is transparent to visible light. It also has a great work function which helps in injecting holes into the different layers. The cathode component depends on the type of OLED required. Even a transparent cathode can be used.

Usually metals like calcium and aluminium used because they have lesser work functions than anodes which helps in injecting electrons into the different layers.

**TYPES:**

1. **Active Matrix OLED (AMOLED)**

This type of OLED is suitable for high resolution and large size display. Though the manufacturing process is the same, the anode layers have a Thin-film transistor (TFT) plane in parallel to it so as to form a matrix.

This helps in switching each pixel to it's on or off state as desired, thus forming an image. This is the least power consuming type among others and also has quicker refresh rates which makes them suitable for video as well.

2. **Passive Matrix OLED (PMOLED)**

The design of this type of OLED makes them more suitable for small screen devices like cell phones, MP3 players and so on. Though this type is less power consuming than an LCD and LED (even if connected to other external circuitry's), it is the most power consuming comparative to other OLED's.

This type is very easy to make as strips of anode and cathode are kept perpendicular to each other. When they are both intersected light is produced. As there are strips of anode and cathode, current is applied to the selected strips and is applied to them. This helps in determining the on or off pixels

3 **Inverted OLED**

This type uses a bottom cathode, which is connected to the drain end of an n-channel TFT backplane. This method is usually used for producing low cost OLED with little applications.

## 4 Foldable OLED

This type is mainly used in devices which have more chance of breaking. As this material is strong it reduces breakage and therefore is used in cell phones, computer chips, GPS devices and PDA's.

They are also flexible, durable and lightweight. As its name explains, these OLED's are foldable and can also be connected to clothes. They use different types of substrates like flexible metallic foils, plastics and so on.

## 5 Top Emitting OLED

This type of OLED is integrated with a transistor backplane that is not transparent. Such devices are suitable for matrix applications like smart cards. The substrate used for this device is of the opaque/reflective type.

As a transparent substrate is used the electrode used is either semi-transparent or fully transparent. Otherwise the light will not pass through the transparent substrate.

## 6 Transparent OLED

This device has a good contrast even in bright sunlight so it is applicable in head-up displays, mobile phones, smart windows and so on. In this device, the entire anode, cathode and the substrate are transparent.

When they are in the off position, they become almost completely transparent as their substrate. This type of OLED can be included in both the active and passive matrix categories.

## 7 White OLED

This device creates the brightest light of all. They are manufactured in large sheets. Thus they can easily replace fluorescent lamps. They are also cost-effective and also consumes less power.

## 8 Stacked OLED

This device uses the composite colors as sub pixels and also on top of each other. This causes the reduction in pixel gap and also an increase in color depth. Thus they are being introduced as television displays.

**TECHNIQUES:**

**1. Inkjet Printing Technique** – This is the cheapest and most commonly used technique. The method is same as the paper printing mechanism where the organic layers are sprayed onto the substrates. This method is also highly efficient and they can be used for printing very large displays like billboards and also big TV screens.

**2. Organic Vapour Phase Deposition (OVPD)** – This is also an efficient technique which can be carried out at a low cost. A cooled substrate is being hit by the organic molecules, which was evaporated in a low pressure, high temperature chamber. The gas is carried onto the substrate with the help of a carrier gas.

**3. Vacuum Thermal Evaporation (VTE)** – This method is also commonly known as vacuum deposition method. This operation is carried out by gently heating the organic molecules so that they evaporate and subside on the substrates. As the heating method is complicated and the strictness of parameters should be highly accurate, this method is economical as well.

**Advantages of OLED's:**

The manufacture of OLEDD is highly economical and is more efficient than LCD and flat panel screens.

- It will be a great surprise to see displays on our clothing and fabrics. This technology will help in carrying huge displays in our hands.
- There is much difference in watching a high-definition TV to a OLED display. As the contrast ratio of OLED is very high (even in dark conditions), it can be watched from an angle of about 90 degrees without any difficulty.
- No backlight is produced by this device and the power consumption is also very less.
- OLED has a refresh rate of 100,000 Hz which is almost 9900 HZ greater than an LCD display.
- The response time is less than 0.01 ms. LCD needs a response time of 1 ms.

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**LECTURE NOTES**

## Disadvantages of OLED:

- The power consumption of this device depends upon the colour that is displayed on the screen. Less than 50% power is only consumed when a black image is displayed, compared to an LCD. But the percentage increases to almost three times when a bright image such as a white colour is displayed. Thus, this device is disadvantageous for mobile applications.
- The OLED technology is only rising and due to this, the commercial availability of OLED products are very less. Though they can be easily made the fabrication process is considered expensive and thus the initial amount is expensive.
- As there is no reflective light technology used in such a device it has a very poor reading effect in bright light surroundings. Even if this is to be overcome additional power should be used.
- With time, the brightness of the OLED pixels will fade.
- The images displayed in this device are created by an artificial light source. So, the whole electricity has to be used to perform such an operation. LCD's, on the other hand use some percentage of light from sunlight and also e-ink.
- The device is not at all water resistant. The lifetime of this device is much lesser when compared with an LCD or LED

## Applications of OLED:

OLED's are used as mobile phone screens, MP3 players, digital cameras, car radios, PDA's and so on.