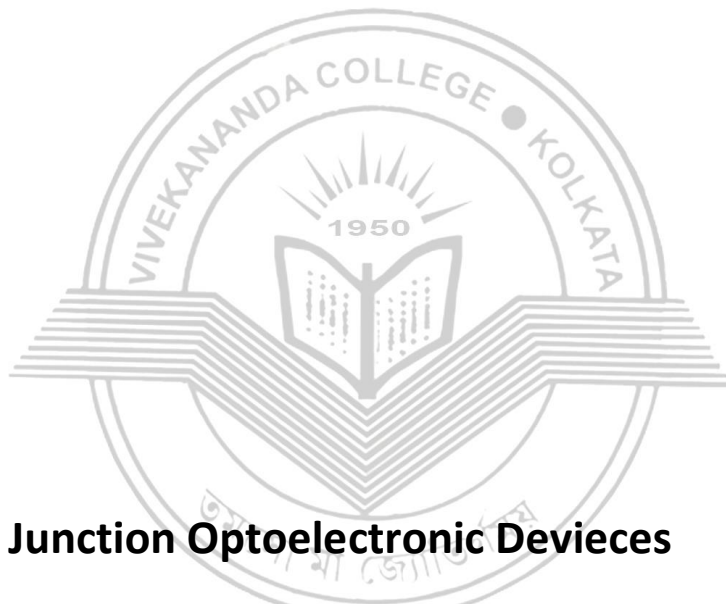


**VIVEKANANDA COLLEGE
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Topic: P-N Junction Optoelectronic Devices

Course Title: Analog Systems and Applications

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Name of the Teacher: SUBHAYAN BISWAS

Name of the Department: PHYSICS

Introduction to optoelectronic devices:-

In modern electronic system conversion of electrical signal to optical signal and vice versa is very important. Now, optoelectronics is a vast subject. In this section we shall only consider **photodiode**, **solar cell** and **light emitting diode (LED)**. In a photodiode optical signal is converted to an electrical signal. And in a LED electrical signal is converted to optical signal. So both photodiode and LED are important in modern fiber optic communication And in a solar cell light energy is converted to electrical energy. At the end I should introduce about **Tunneldiode**.

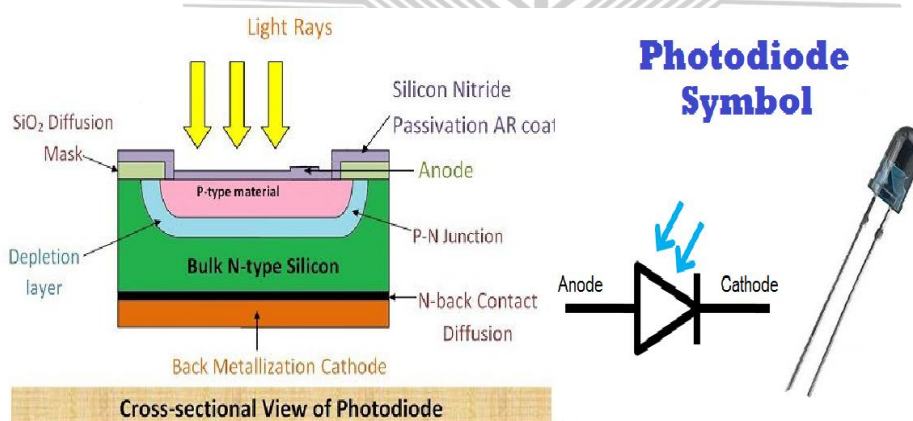
Photodiode: Photodiode is the two terminal passive element which converts light in to electrical current. The basic construction of the Photodiode is similar to that of the simple PN junction diode however it is optimized to respond to light. As described earlier that the PN junction is sensitive to light thus the PN junction of the photodiode is exposed to light, it is covered with the transparent window thus the light can reach the photo sensitive part of the PN junction.

Working principle of photo diode: The photodiode works on the photoelectric effect; that is when the photon of the sufficient energy is absorbed an electron-hole pair is formed.

Photocurrent: When the photon of sufficient energy is absorbed an electron-hole is generated and if the absorption occurred near the depletion region or one diffusion length from the depletion region the electrons move towards the cathode and holes towards the anode due to inner electric field This current is called the photocurrent.

Dark Current: Dark current is the current that flows through the photodiode in the absence of light. There are many reasons for it, I will not discuss them here as it is out of the scope of this article. It is desirable to keep the dark current as low as possible.

An important point to notice here is that the photodiode not only detect the visible light but some photodiodes are also capable detecting electromagnetic waves out of the visible spectrum.



Consider a single-crystal p-n junction made of such a semiconductor which absorbs the incident light. This absorption of light photon is possible only when the energy of the

photon is greater than the energy gap E_g and its energy is within the range of energy from V_B to C_B . The absorption of a photon causes generation of an electron-hole pair (EHP) within the semiconductor. (Now for a reverse bias junction illuminated by such photons will increase the generation rate of EHPs in the transition region causing an increase in reverse current through the diode.) Let us assume that the intensity of light is such that the generation rate is g_{op} . Therefore, the number of holes generated within the diffusion length of the transition region in n-side is $A \cdot L_p \cdot g_{op}$ and number of electrons generated within the diffusion length of the transition region in p-side is $A \cdot L_n \cdot g_{op}$. So, the resultant current due to these optically generated carriers is given by to

$$i_{op} = q \cdot A \cdot g_{op} (L_p + L_n) \text{-----(1)}$$

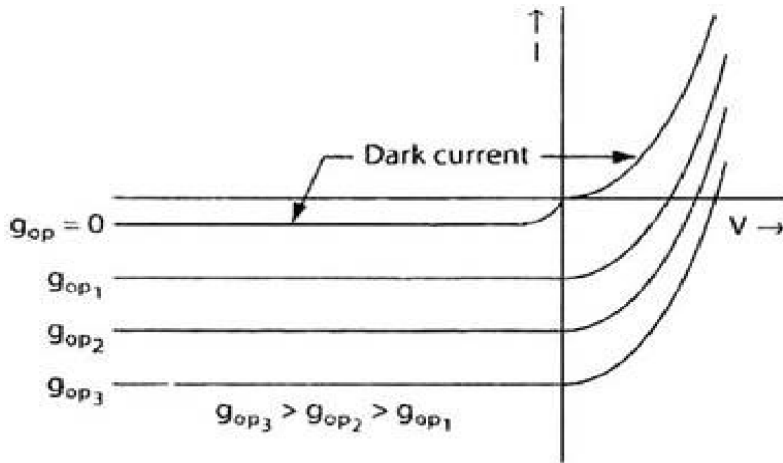
We have current due to diffusion of e^- and hole is given before in my class as

$$I_D = q.A.\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)(e^{qV/kT} - 1) \text{-----(2)}$$

we obtain the total current through the diode as

$$I = I_D - i_{op} = q.A.\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)(e^{qV/kT} - 1) - q.A.g_{op}(L_p + L_n). \text{-----(3)}$$

The I-V characteristics of an illuminated junction with different light intensity i.e., with different generation rate g_{op} has been shown in FIG 2. From this figure it is clear that in the reverse biased



condition the diode current gives a measurement of the light intensity. So, it is possible to convert a light signal of varying intensity to an electrical signal of similar form' by a reverse biased illuminated diode. Now, in the open-circuit condition the current through the diode $I = 0$, and we can find the open-circuit voltage V_{oc} across the diode from equation (3). So,

FIG 2 I-V characteristics of photodiode in the dark and illuminated condition.

$$q.A.\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)(e^{qV_{oc}/kT} - 1) - q.A.g_{op}(L_p + L_n) = 0$$

$$(e^{qV_{oc}/kT} - 1) = \frac{q.A.g_{op}(L_p + L_n)}{q.A.\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)}$$

$$qV_{oc}/kT = \ln \left[1 + \frac{g_{op}(L_p + L_n)}{\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)} \right]$$

$$V_{oc} = \frac{kT}{q} \ln \left[1 + \frac{g_{op}(L_p + L_n)}{\left(\frac{L_p}{\tau_p} p_n + \frac{L_n}{\tau_n} n_p\right)} \right] \text{-----(4)}$$

Considering a symmetrical junction in which $p_n = n_p$ and $\tau_p = \tau_n$, one finds

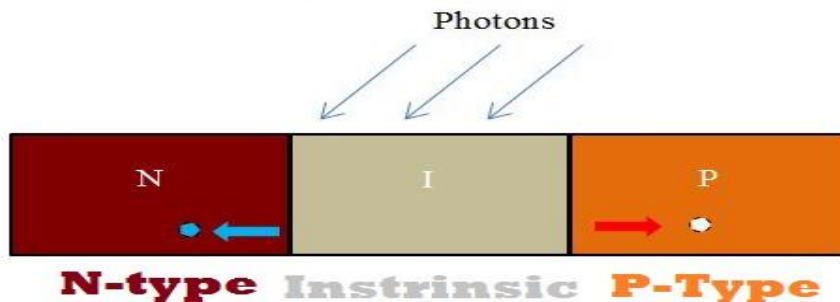
$$V_{oc} = \frac{kT}{q} \ln \left[1 + \frac{g_{op}}{\frac{p_n}{\tau_p}} \right] \text{-----(5)}$$

Now, $\frac{p_n}{\tau_p}$ is the thermal generation rate g_{th} , assuming $g_{op} \gg g_{th}$, one obtains the open circuit voltage as

$$V_{oc} = \frac{kT}{q} \ln \frac{g_{op}}{g_{th}} \text{-----(6)}$$

However, this V_{oc} cannot increase indefinitely as with increased light intensity. As increased generation rate of EHPs decreases the carrier lifetime τ_p and τ_n , so in consequence $\frac{p_n}{\tau_p} (=g_{th})$ increases (however, p_n is fixed as it depends on N_D and temperature T). Thus, there is an appearance of forward voltage in illuminated junction diode if the semiconductor absorbs the light, this effect is called photovoltaic effect.

PIN Junction



The photodiodes have a quite slow response thus most of the Photodiodes are now manufactured with PIN Junction instead of the PN junction in order to improve the response time.

Now in FIG 2, we can see the product of current (I) and voltage (V) is positive when it is operated in 3rd or 1st quadrant, but this product is negative when it is operated in the fourth quadrant (i.e., voltage positive, current negative). Or in other words the energy will be delivered to the junction when the product is positive and will be absorbed when the product is negative. That is when product is negative, energy will be absorbed in the junction and will be delivered to the external load.

These situations have been shown elaborately in FIG 4.

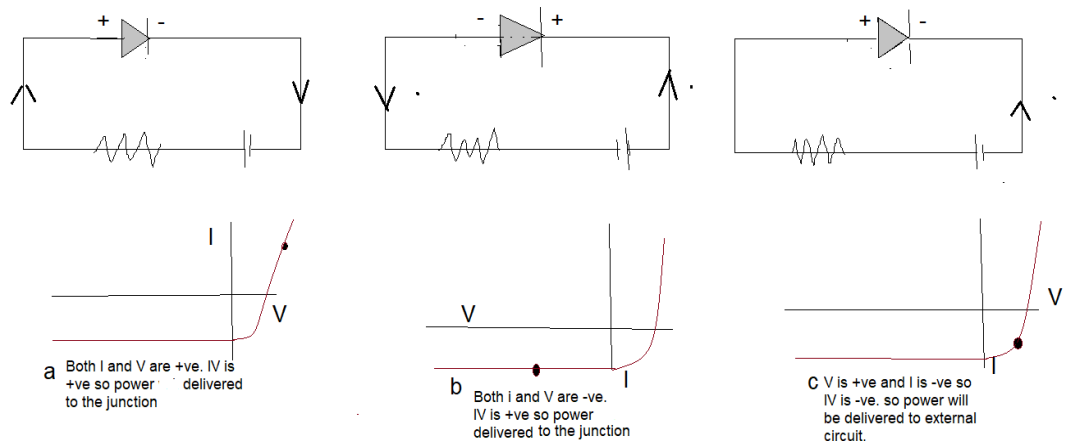


FIG.4

Operation of illuminated p-n junction in different region of characteristics.

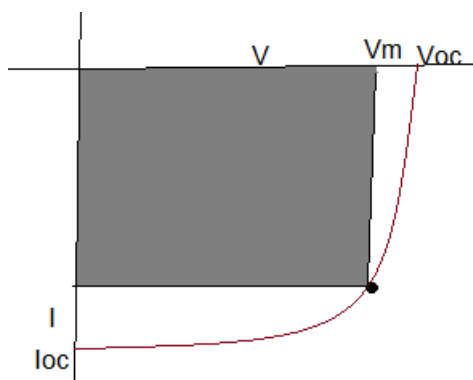
The + and – sign on the diode is indicating biasing voltage applied to the diode and current flowing is due to external battery. In 3rd diagram biasing voltage is greater than external battery.

- (a) Both I and V are positive. IV positive so power delivered to the junction
- (b) Both I and V are negative. IV positive so power delivered to the junction
- (c) V positive and i negative. IV negative so power delivered to the external circuit

Therefore, if we want to extract energy from the device, it is to be operated in the fourth quadrant. Such energy converters are used to convert sunlight to electrical energy. And then it is called a solar battery or solar cell. It is extensively used in artificial satellite as power source.

Solar cells Solar Cells We know that the power will be delivered to an external circuit if we operate an illuminated p-n junction diode in the fourth quadrant?

Now let us calculate the possible output power from such a cell V . From the previous section we came to know that V_{oc} cannot be increased indefinitely. It can be shown that maximum possible



limit of V_{oc} is barrier voltage. And the maximum limit of barrier voltage is energy gap voltage (E_G/q). And maximum possible current in an illuminated junction lies in the range 10-100 mA/cm². Referred to FIG 5 in which I-V characteristics has been redrawn, the maximum possible power that can be extracted from the cell is $V_m \cdot I_m$. The ratio $V_m \cdot I_m / V_{oc} \cdot I_{oc}$ is called the fill factor of the solar cell.

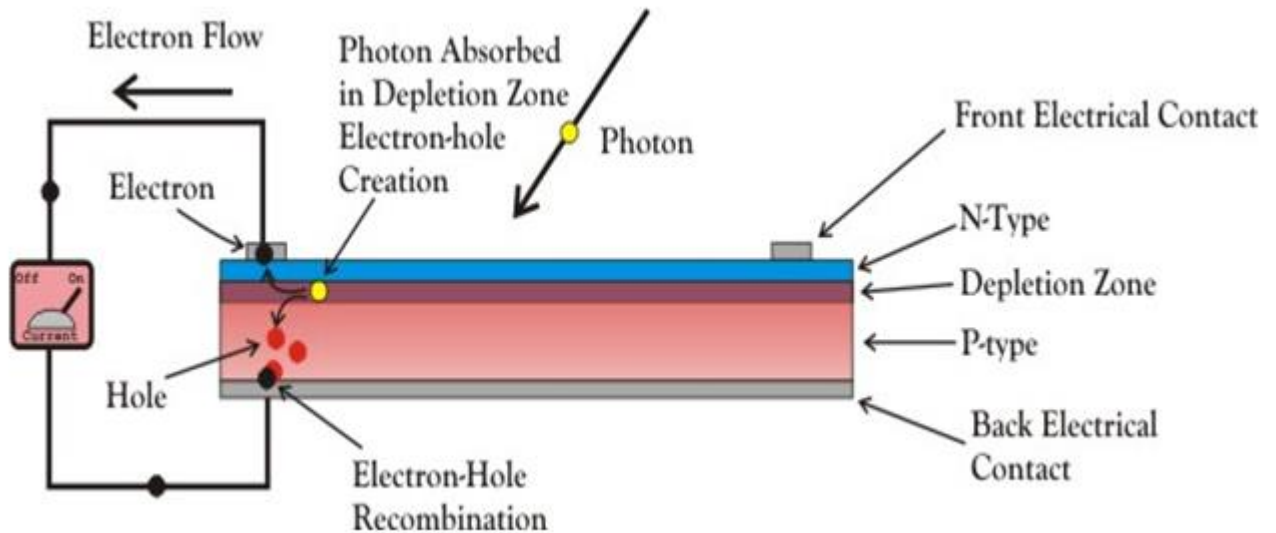
Definition: A solar cell (also known as a photovoltaic cell or PV cell) is defined as an electrical device that converts light energy into electrical energy through the photovoltaic

effect. A solar cell is basically a p-n junction diode. Solar cells are a form of photoelectric cell, defined as a device whose electrical characteristics – such as current, voltage, or resistance – vary when exposed to light. Individual solar cells can be combined to form modules commonly known as solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. By itself this isn't much – but remember these solar cells are tiny. When combined into a large solar panel, considerable amounts of renewable energy can be generated.

Construction of Solar Cell

A solar cell is basically a junction diode, although its construction it is little bit different from conventional p-n junction diodes. A very thin layer of p-type semiconductor is grown on a relatively thicker n-type semiconductor. We then apply a few finer electrodes on the top of the p-type semiconductor layer.

These electrodes do not obstruct light to reach the thin p-type layer. Just below the p-type layer there is a p-n junction. We also provide a current collecting electrode at the bottom of the n-type layer. We encapsulate the entire assembly by thin glass to protect the solar cell from any mechanical shock.



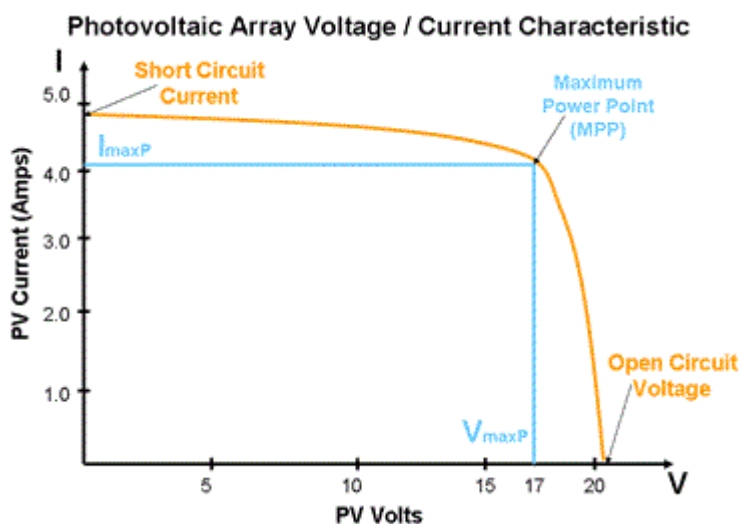
Working Principle of Solar Cell

When light reaches the p-n junction, the light photons can easily enter in the junction, through very thin p-type layer. The light energy, in the form of photons, supplies sufficient energy to the junction to create a number of electron-hole pairs. The incident light breaks the thermal equilibrium condition of the junction. The free electrons in the depletion region can quickly come to the n-type side of the junction.

Similarly, the holes in the depletion can quickly come to the p-type side of the junction. Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.

Similarly, the newly created holes once come to the p-type side cannot further cross the junction because of same barrier potential of the junction. As the concentration of electrons becomes higher in one side, i.e. n-type side of the junction and concentration of holes becomes more in another side, i.e. the p-type side of the junction, the p-n junction will behave like a small battery cell. A voltage is set up which is known as photo voltage. If we connect a small load across the junction, there will be a tiny current flowing through it.

V-I Characteristics of a Photovoltaic Cell (converted into 1st coordinate)



Materials Used in Solar Cell

The materials which are used for this purpose must have band gap close to 1.5eV. Commonly used materials are-

Silicon, GaAs, CdTe, CuInSe₂

Criteria for Materials to be Used in Solar Cell

1. Must have band gap from 1eV to 1.8eV.
2. It must have high optical absorption.
3. It must have high electrical conductivity.
4. The raw material must be available in abundance and the cost of the material must be low.

Advantages of Solar Cell

1. No pollution associated with it.
2. It must last for a long time.
3. No maintenance cost.

Disadvantages of Solar Cell

1. It has high cost of installation.
2. It has low efficiency.
3. During cloudy day, the energy cannot be produced and also at night we will not get solar energy.

Uses of Solar Generation Systems

1. It may be used to charge batteries.
2. Used in light meters.
3. It is used to power calculators and wrist watches.
4. It can be used in spacecraft to provide electrical energy.

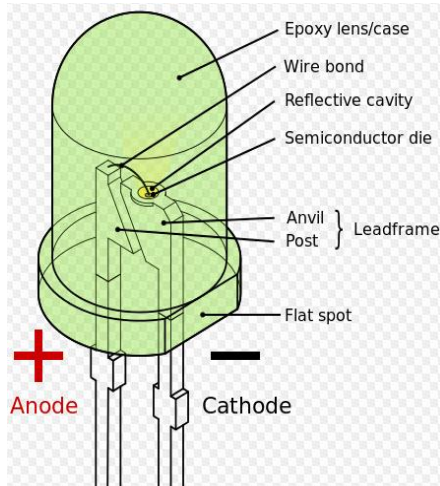
Conclusion: Though solar cell has some disadvantage associated with it, but the disadvantages are expected to overcome as the technology advances, since the technology is advancing, the cost of solar plates, as well as the installation cost, will decrease down so that everybody can effort to install the system. Furthermore, the government is laying much emphasis on the solar energy so after some years we may expect that every household and also every electrical system is powered by solar or the renewable energy source.

Light Emitting Diode (LED):-

The Light emitting diode is a two-lead semiconductor light source. In 1962, **Nick Holonyak** has come up with an idea of light emitting diode, and he was working for the general electric company. The LED is a special type of diode and they have similar electrical characteristics of a PN junction diode. Hence the LED allows the flow of current in the forward direction and blocks the current in the reverse direction. The LED occupies the small area which is less than the 1 mm². The applications of LEDs used to make various electrical and electronic projects. In this article, we will discuss the working principle of the LED and its applications.

What is a Light Emitting Diode?

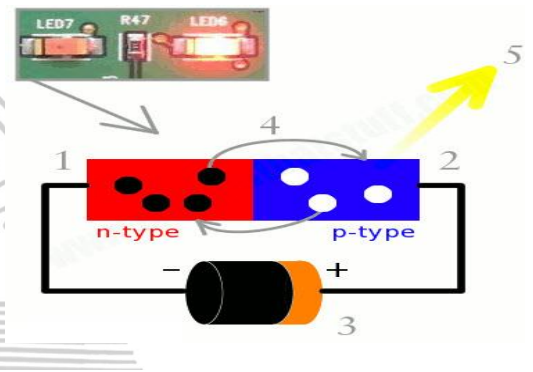
The lighting emitting diode is a p-n junction diode. It is a specially doped diode and made up of a special type of semiconductors. When the light emits in the forward biased, then it is called as a light emitting diode.



How does the Light Emitting Diode work?

The light emitting diode simply, we know as a diode. When the diode is forward biased, then the electrons & holes are moving fast across the junction and they are combining constantly, removing one another out. Soon after the electrons are moving from the n-type to the p-type silicon, it combines with the holes, then it disappears. Hence it makes the complete atom & more stable and it gives the little burst of energy in the form of a tiny packet or photon of light.

- From the diagram, we can observe that the N-type silicon is in red color and it contains the electrons, they are indicated by the black circles.
- The P- type silicon is in the blue color and it contains holes, they are indicated by the white circles.
- The power supply across the p-n junction makes the diode forward biased and pushing the electrons from n-type to p-type. Pushing the holes in the opposite direction.
- Electron and holes at the junction are combined.
- The photons are given off as the electrons and holes are recombined.



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
- Gallium Indium Nitride (GaInN) – near ultraviolet, bluish-green and blue
- Silicon Carbide (SiC) – blue as a substrate
- Zinc Selenide (ZnSe) – blue
- Aluminium Gallium Nitride (AlGaN) – ultraviolet

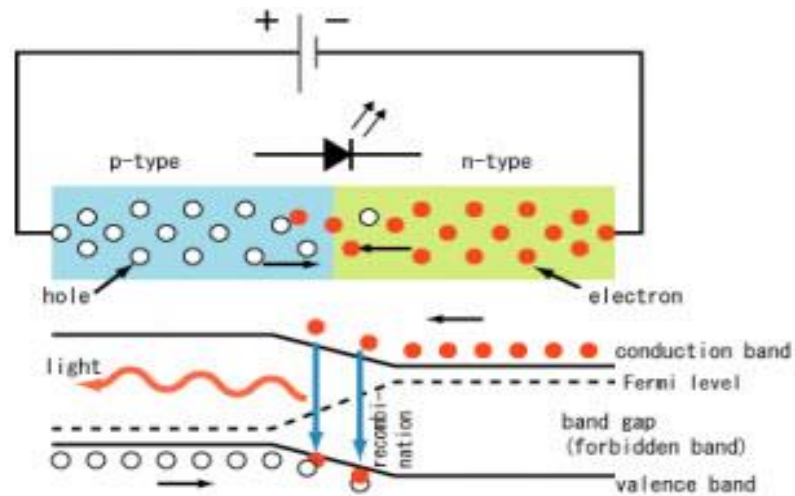
Working Principle of LED

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 energy level 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.

The flow of current in the semiconductors is caused by the both flow of holes in the opposite direction of current and flow of electrons in the direction of the current. Hence there will be 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 will emit the electromagnetic energy in the form of photons and the photon energy is equal to the forbidden energy gap.



For an example, let us 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

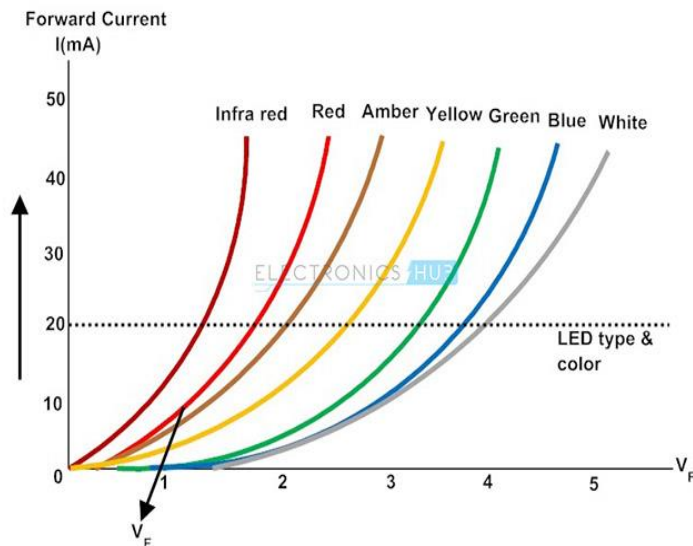
$$E_q = h\nu$$

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

$$E_q = hc / \lambda$$

From the above equation, we can say that the wavelength of electromagnetic radiation is inversely proportional to the forbidden gap. In general silicon, germanium semiconductors this forbidden energy gap is between the condition and valence bands are such that the total radiation of electromagnetic wave during recombination is in the form of the infrared radiation. We can't see the wavelength of infrared because they are out of our 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.



I-V Characteristics of LED

There are different types of light emitting diodes 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.

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.

Color	Wavelength [nm]	Voltage drop [ΔV]	Semiconductor material
Infrared	$\lambda > 760$	$\Delta V < 1.63$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	$1.9^{[66]} < \Delta V < 4.0$	Traditional green: Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP) Pure green: Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate—under development
Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm) ^[67] Boron nitride (215 nm) ^{[68][69]} Aluminium nitride (AlN) (210 nm) ^[70] Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN)—down to 210 nm ^[71]
Pink	multiple types	$\Delta V \sim 3.3^{[72]}$	Blue with one or two phosphor layers: yellow with red, orange or pink phosphor added afterwards, or white phosphors with pink pigment or dye over top. ^[73]
White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Applications of Light Emitting Diodes

There are many applications of the LED and some of them are explained below.

- LED is used as a bulb in the homes and industries
- The light emitting diodes are used in the motorcycles and cars
- These are used in the mobile phones to display the message
- At the traffic light signals led's are used

Advantages of LED's

- The cost of LED's is less and they are tiny.
- By using the LED's the electricity is controlled.
- The intensity of the LED differs with the help of the microcontroller.

