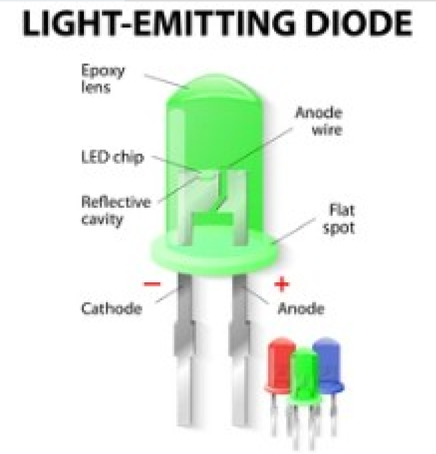
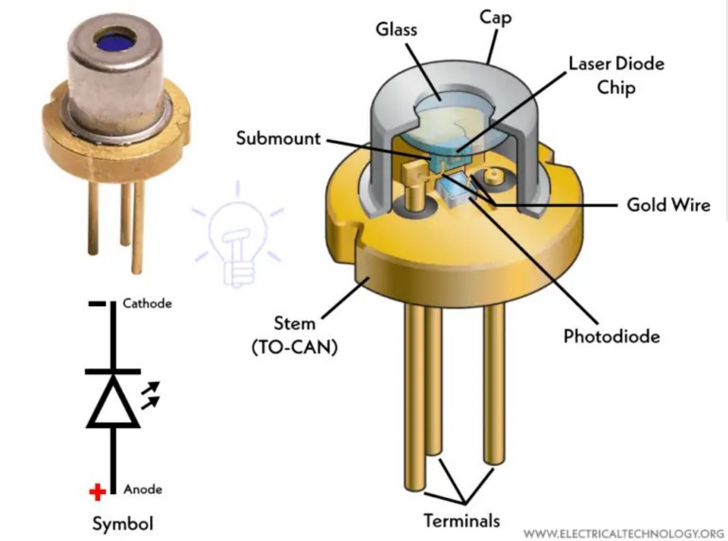
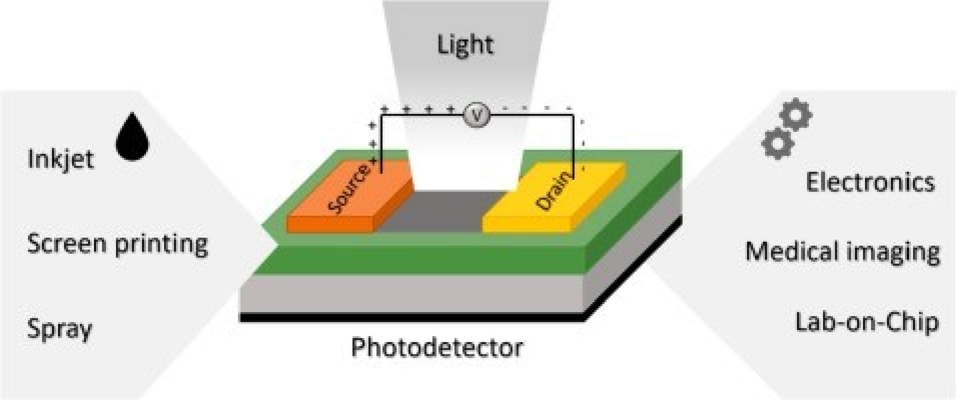
Module – 7

Module:7	Optoelectronic devices	6 hours
Introduction to semiconductors - direct and indirect bandgap – Sources: LED and laser diode, Photodetectors: PN and PIN.		



Laser diode





Photodetector

Dr. Pankaj Sheoran
SAS

Introduction to semiconductors

Semiconductor are materials whose electrical conductivity lies between **conductor** and an **insulator.**

- **Semiconductors** can be compounds such as **gallium arsenide or** pure elements, such as **germanium or silicon**.
- **Silicon** is **used in electronic circuit fabrication** and **gallium arsenide** is **used in solar cells, laser diodes**, etc.

Energy band gap in materials

- **Metals:** have no energy gap (i.e. valence band and conduction band overlap)

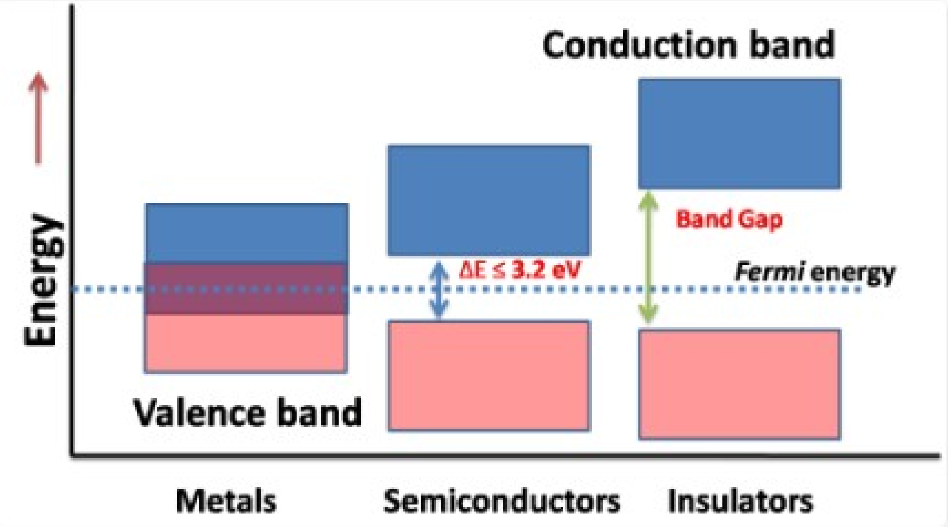
➢ Result: current flows easily

- **Insulator**: have a large energy gap

➢ Result: no current flows

- **Semiconductor**: have a medium energy gap

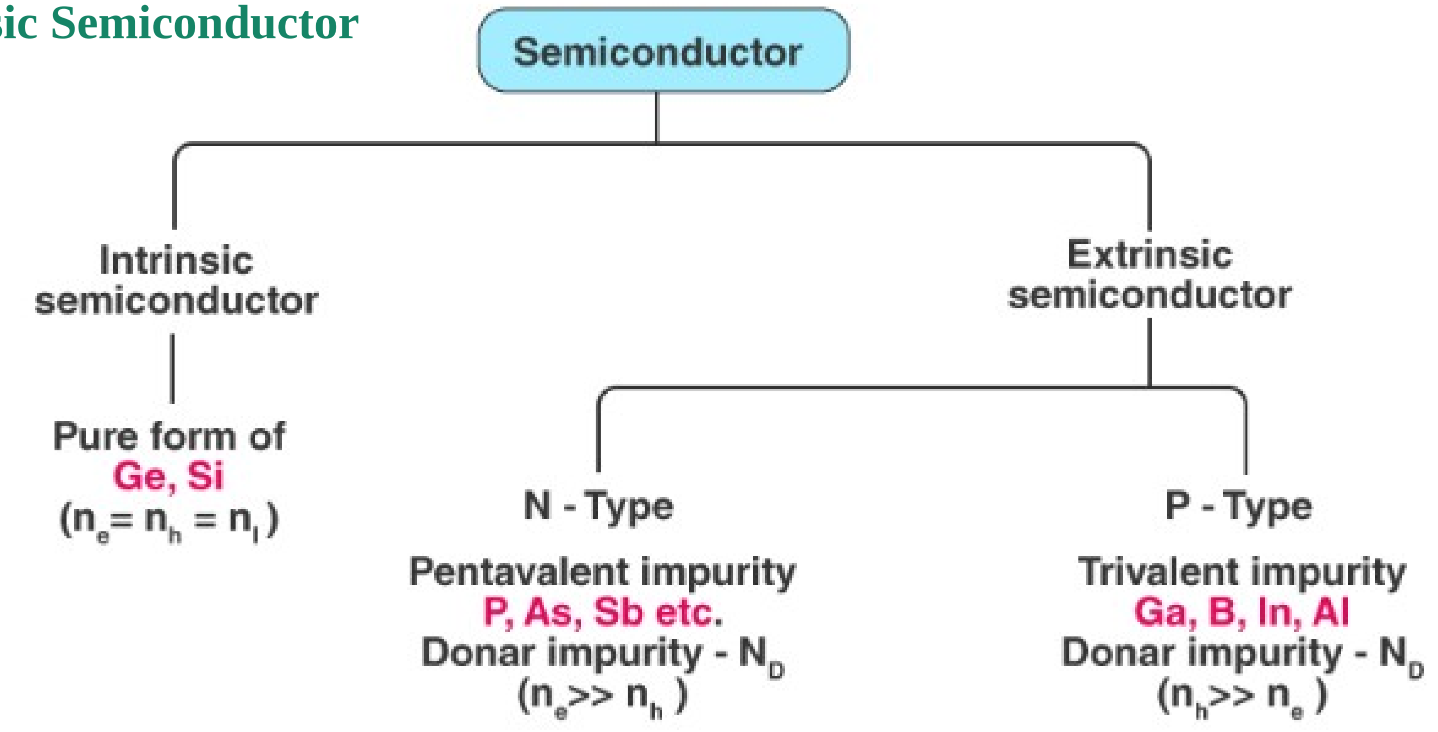
➢ Result: only a small amount of current can flow



Types of Semiconductors

Semiconductors can be **classified as:**

- **Intrinsic Semiconductor**
- **Extrinsic Semiconductor**



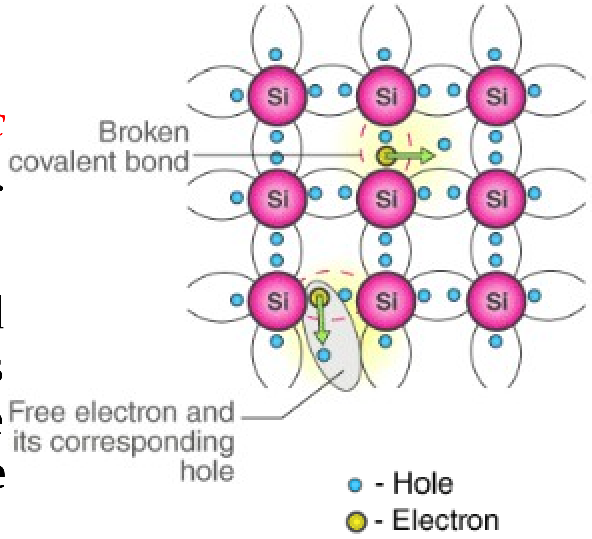
Intrinsic Semiconductor

An **intrinsic type** of semiconductor material is made to be very pure chemically. It is **made up of only a single type of element**.

Germanium (Ge) and Silicon (Si) are the most c*ommon type of intrinsic semiconductor elements*. They **have four valence electrons (tetravalent)**. They are *bound to the atom by covalent bond at absolute zero temperature*.

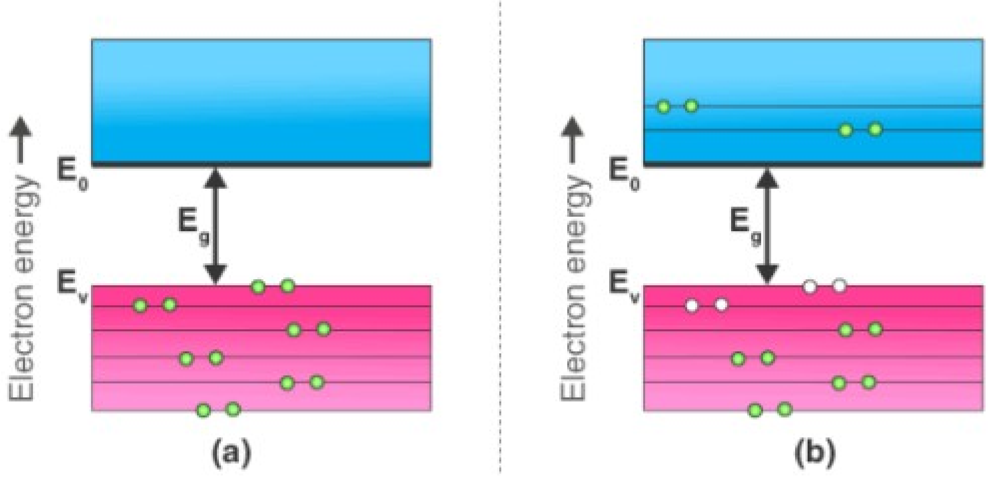
When the temperature rises, due to collisions, few electrons are unbounded and become free to move through the lattice, thus creating an absence in its original position (hole). These free electrons and holes contribute to the conduction of electricity in the semiconductor. **The negative and positive charge carriers are equal in number.**

The thermal energy is capable of ionizing a few atoms in the lattice, and hence their conductivity is less.



The Lattice of Pure Silicon Semiconductor at Different Temperatures

- **At absolute zero Kelvin temperature:** At this temperature, the covalent bonds are very strong and there are no free electrons and the semiconductor behaves as a perfect insulator.
- **Above absolute temperature:** With the increase in temperature few valence electrons jump into the conduction band and hence it behaves like a poor conductor.



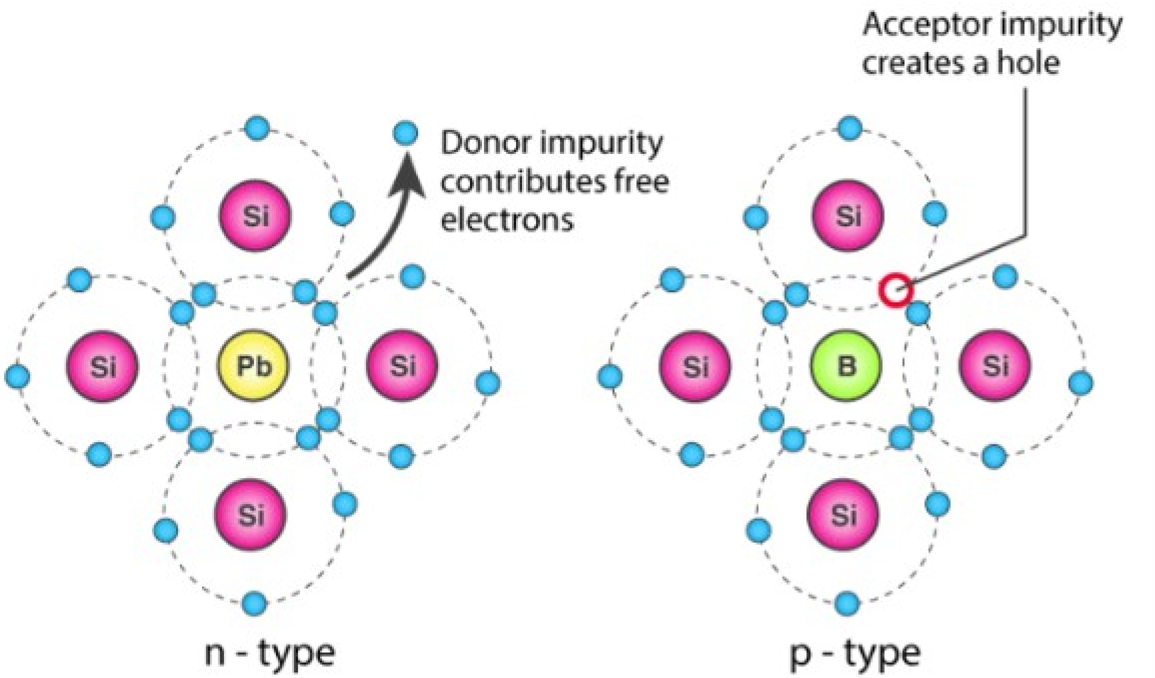
(a) Intrinsic Semiconductor at T = 0 Kelvin, behaves like an insulator (b) At t>0, four thermally generated electron pairs

Extrinsic Semiconductor

The **conductivity of semiconductors can be greatly improved** by **introducing** a small number of **suitable** replacement atoms called **IMPURITIES**. *The process of adding impurity atoms to the pure semiconductor is called **DOPING.*** Usually, only 1 atom in 10^7 is replaced by a dopant atom in the doped semiconductor. An extrinsic semiconductor can be further classified into:

N-type Semiconductor

P-type Semiconductor



Difference Between Intrinsic and Extrinsic Semiconductors

Intrinsic Semiconductor	Extrinsic Semiconductor
Pure semiconductor	Impure semiconductor
Density of electrons is equal to the density of holes	Density of electrons is not equal to the density of holes
Electrical conductivity is low	Electrical conductivity is high
Dependence on temperature only	Dependence on temperature as well as on the amount of impurity
No impurities	Trivalent impurity, pentavalent impurity

Classification of Semiconductor by Bandgap

Classification of s/c

(depends on how the electron recombining in the s/c)

Semiconductor

Direct Bandgap s/c

Indirect Bandgap s/c

Graph……E-k Diagram

E-K diagram ?

Direct and Indirect band gap

- Based on the their band structure, materials are characterised with a direct band gap or indirect band gap.
- In the free-electron model, ***"k"*** is the momentum of a free electron and assumes unique values within the Brillouin zone that outlines the periodicity of the crystal lattice.
- *If the* ***momentum of the lowest energy state in the conduction band*** *and* ***the highest energy state of the valence band*** *of a material* ***have the same value****, then the material has a* ***direct bandgap****.*
- ***If they are not the same,*** *then the material has an* ***indirect band gap*** *and the electronic transition must undergo momentum transfer to satisfy conservation.* Such indirect "forbidden" transitions still occur, however at very low probabilities and weaker energy.
- For **materials with a direct band gap**, *valence electrons can be directly excited into the conduction band by a photon whose energy is larger than the bandgap.*
- *In contrast, for materials with an indirect band gap,* ***a photon and phonon must both be involved in a transition*** *from the valence band top to the conduction band bottom,* ***involving a momentum change.***
- Hence, **direct bandgap materials tend to have stronger light emission and absorption properties** and tend to be **better suited** for *photovoltaics (**PVs**), light-emitting diodes (**LEDs**), and* ***laser diodes***; however, ***indirect bandgap materials*** *are frequently used in* ***PVs and LEDs when the materials have other favorable properties.***

E-K Diagram

For a microscopic quantum particle of mass m, momentum, p and energy, E

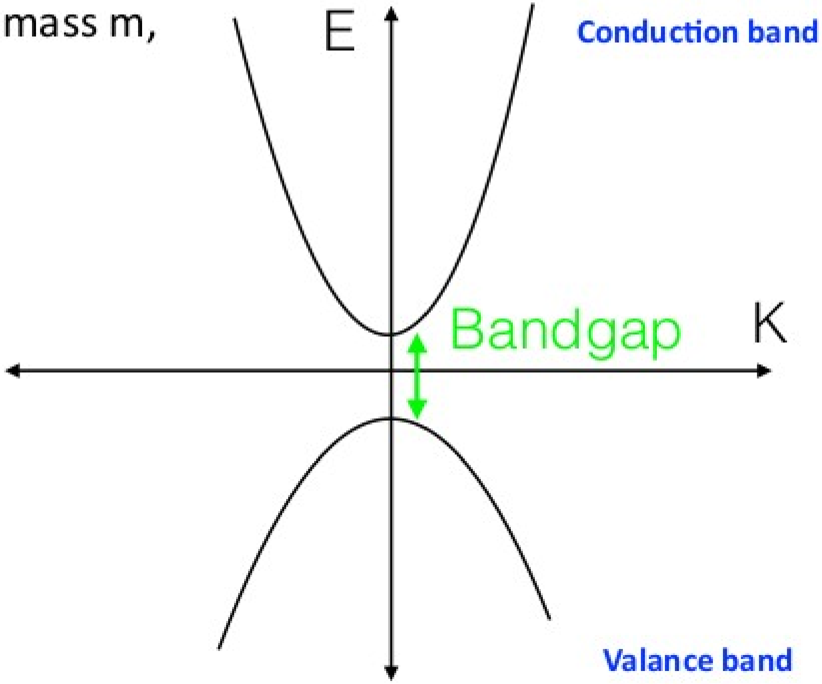
$$p = mv$$

$$E = \frac{1}{2}mv^2$$

the momentum of the particle can be described as :

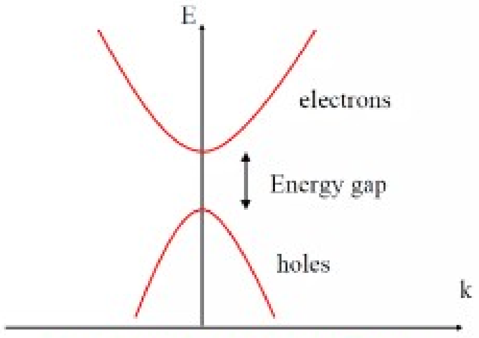
$$p = \hbar k, \; where, \; k = \frac{2\pi}{\lambda}$$

$$\Rightarrow \boxed{E = \frac{\hbar^2 k^2}{2m}}$$

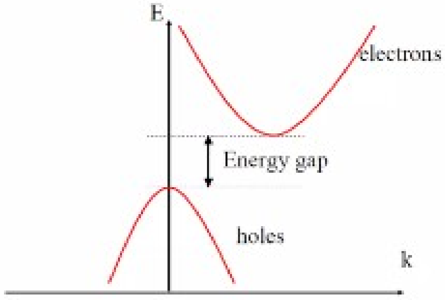


E....directly proportional to K² → Parabola

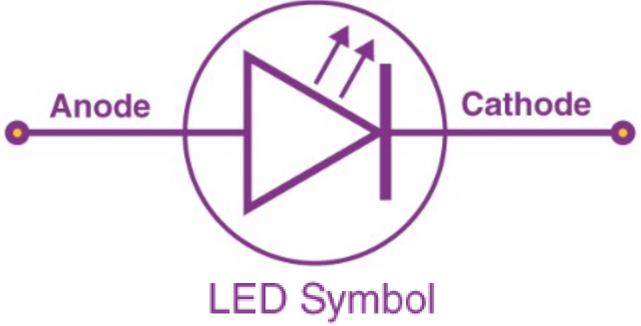
Direct band-gap (DBG) semiconductor	Indirect band-gap (IBG) semiconductor
A direct band-gap (DBG) semiconductor is one in which the maximum energy level of the valence band aligns with the minimum energy level of the conduction band with respect to momentum.	An Indirect band-gap (IBG) semiconductor is one in which the maximum energy level of the valence band and the minimum energy level of the conduction band are misaligned with respect to momentum.
In a DBG semiconductor, a direct recombination takes place with the release of the energy equal to the energy difference between the recombining particles.	In case of a IBG semiconductor, due to a relative difference in the momentum, first, the momentum is conserved by release of energy and only after the both the momenta align themselves, a recombination occurs accompanied with the release of energy.
The probability of a radiative recombination is high.	The probability of a radiative recombination is comparatively low.
The efficiency factor of a DBG semiconductor is higher. Thus, DBG semiconductors are always preferred over IBG for making optical sources.	The efficiency factor of a IBG semiconductor is lower.
Example, Gallium Arsenide (GaAs).	Example, Silicon and Germanium



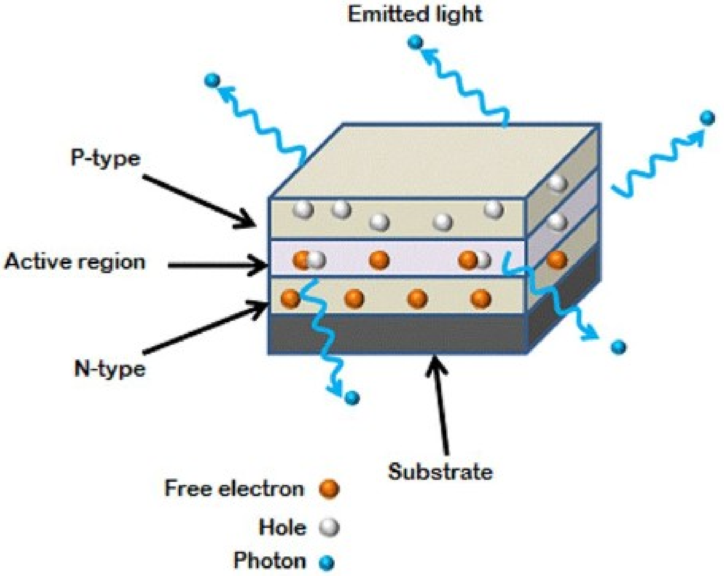
Direct bandgap semiconductors



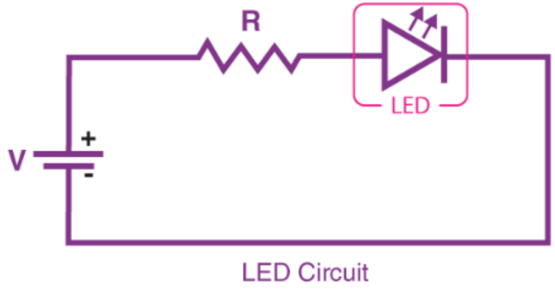
Indirect bandgap semiconductors



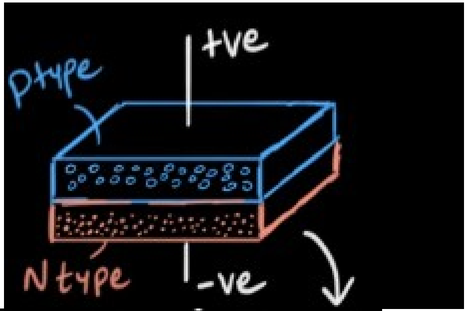
Light Emitting Diodes (LEDs)

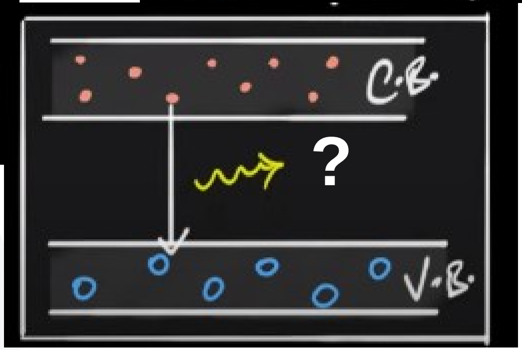


- The **LED structure consists of three semiconductor layers** deposited over the substrate. The **top layer is a P-type region,** the **bottom layer is the n-type region**, and the **central layer is called the active region** of the LED.
- The **P-layer** is ***deposited above*** **the N-layer** because the electron-hole pair **recombination** takes place towards the *p region*
- The **P-type layer is covered with the thin metallic layer** which **provides the anode connections**, and the **N-type region is coated with the thin gold layer, which provides the cathode connection.** *The gold film also acts as a reflective layer in the LED structure.*



Semiconductor materials used for the construction of LEDs

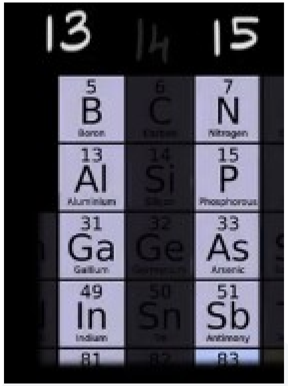




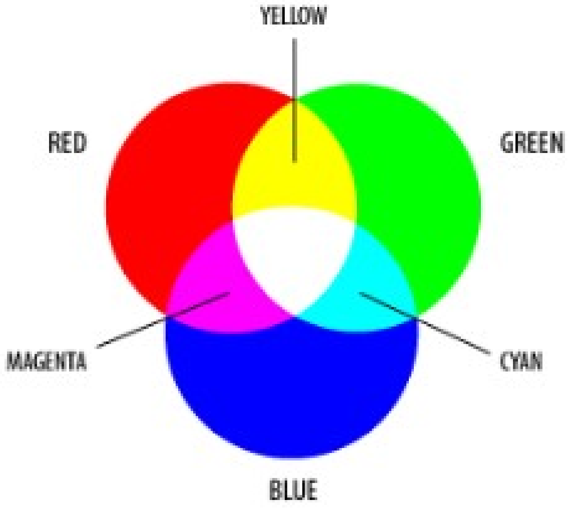
$$E_{photon} = E_{Bandgap}$$

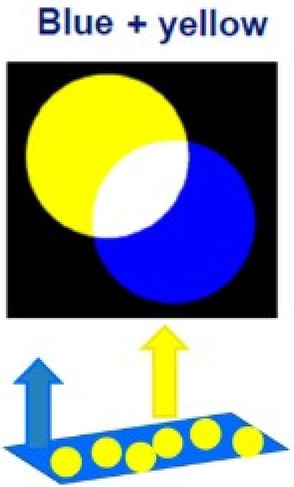
$$\Rightarrow E_{photon} = \underbrace{E_{Bandgap}}_{\text{2eV - 3eV}} = h\nu$$

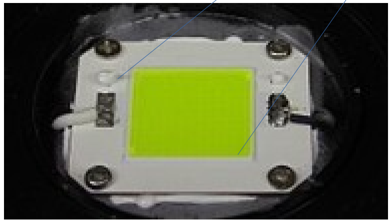
Semiconductor	Bandgap (eV)
Silicon	1.1
Germanium	0.7
Gallium Arsenide	1.4
Gallium phosphide	2.3
Gallium nitride	3.4



2014
Nobel Prize
in Physics

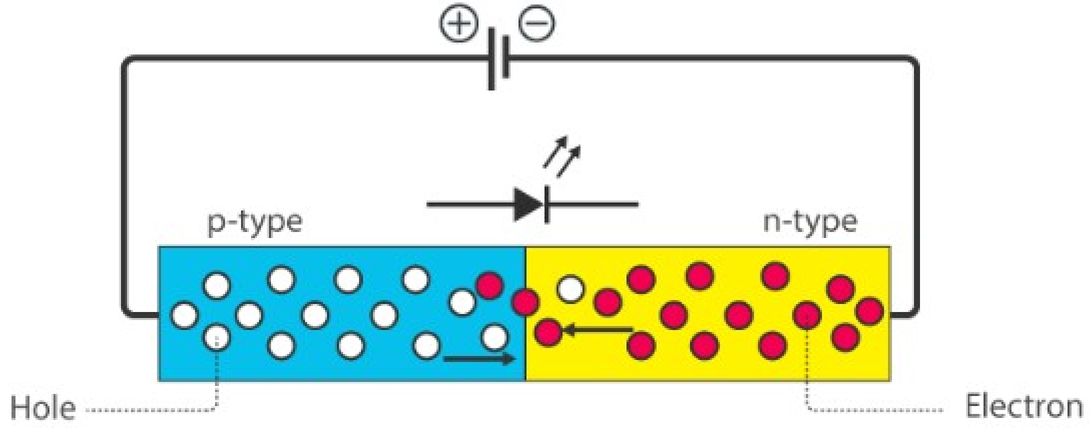


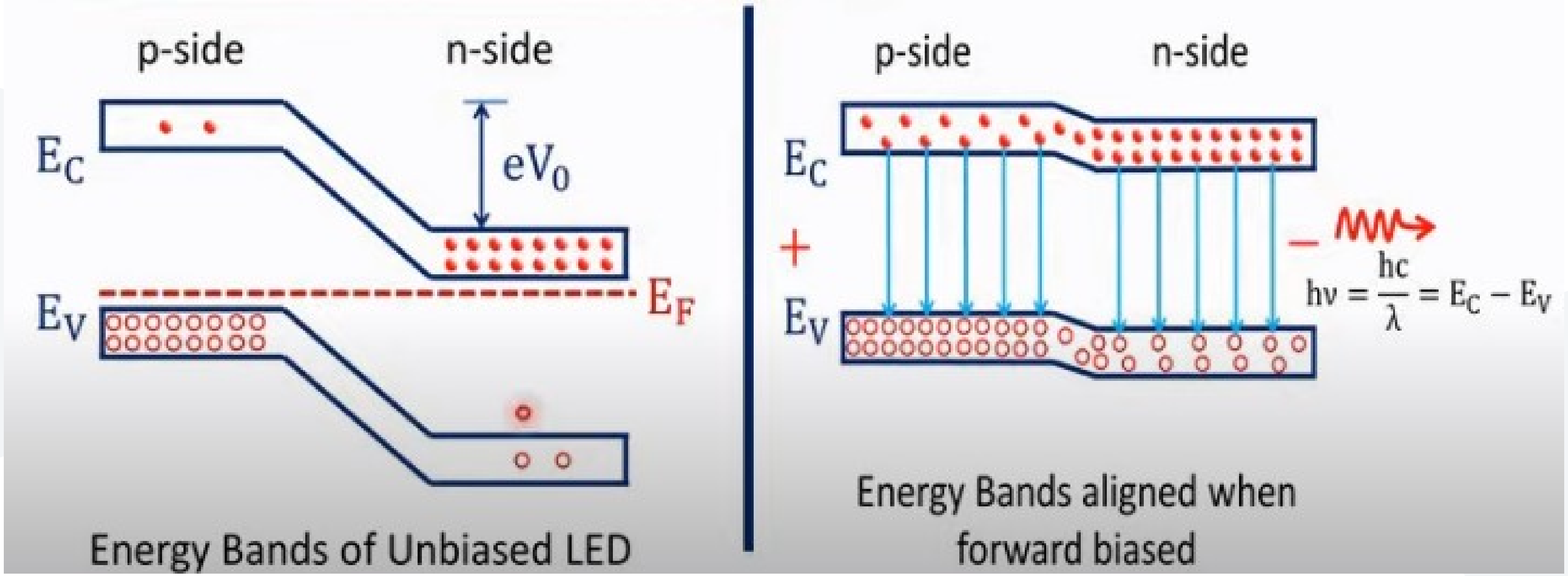




The **semiconductor materials that are commonly** used **for** the construction of **LEDs** are **Gallium Phosphide, Gallium Arsenide, or Gallium Arsenide Phosphide.**

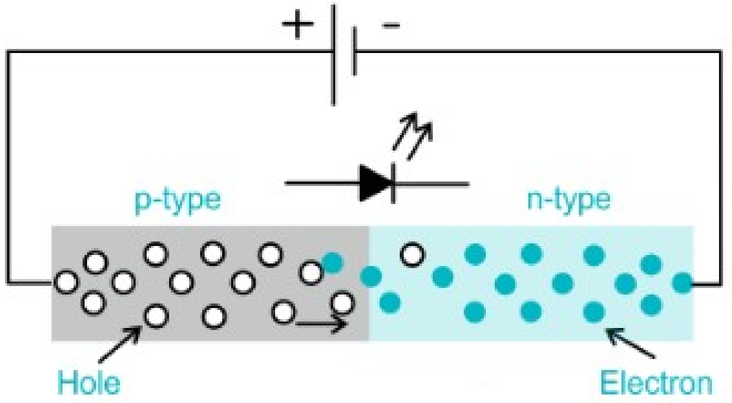
Working of LED

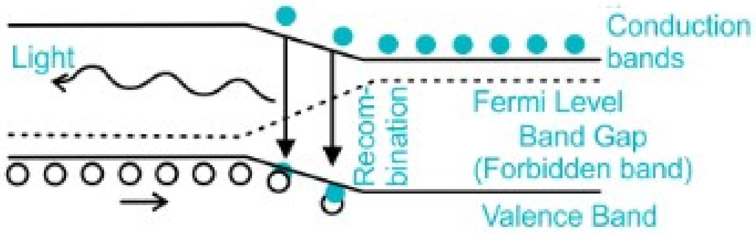




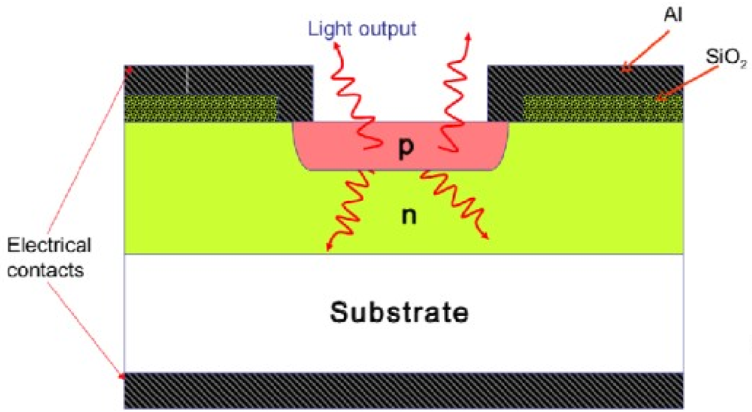
Working Principle of LED

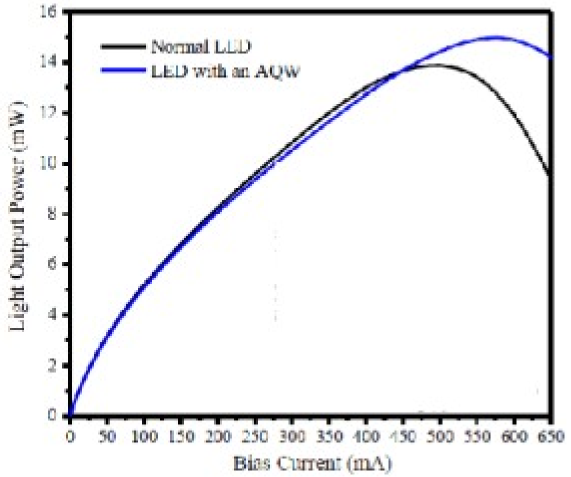
- When P-N junction is forward biased the electron present in the n region are combine with the holes.
- These free electrons occupy in conduction band and at the higher energy level from the holes in the valence band.
- When the recombination takes place, the electrons return back to the valence band which is at a lower energy level than the conduction band.
- While returning back the recombining electrons give away the excess energy in the form of light.



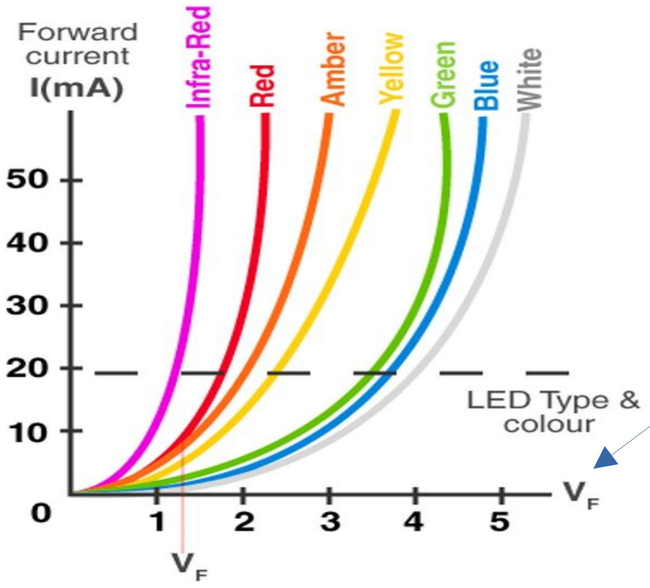


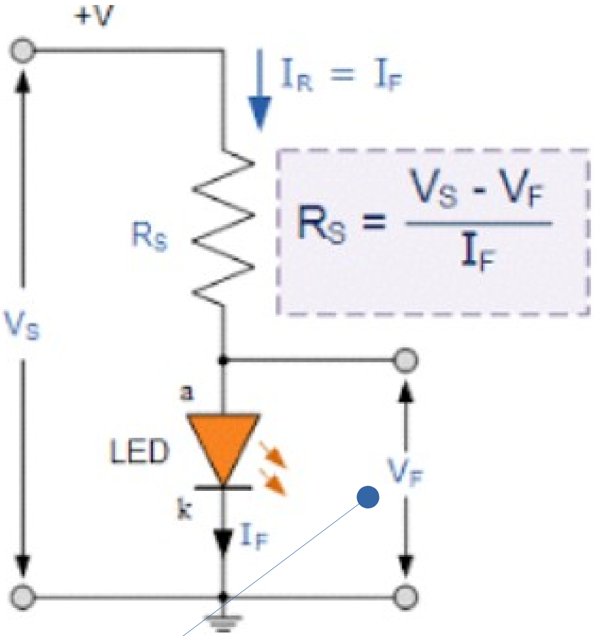
Typical structure of LED





I-P Characteristics of LED





$$P_{out} = \eta_{ext} \frac{1.24}{\lambda} i$$

- Why Silicon and Germanium diodes can not be used to as LED?
  - These are indirect gap semiconductors
  - Energy Gap for Si = 1.1 eV
  - Energy Gap for Ge = 0.7 eV
  - Corresponding values of wavelength do not fall in visible region.

$$\boxed{E_g = E_C - E_V = h\nu = \frac{hc}{\lambda}}$$

- Which materials are used for LED?
  - GaAs, GaAsP, GaP etc. which are obtained by mixing group 3 elements with group 5 elements.
  - These are direct gap semiconductors and the energy gap is such that corresponding wavelength falls in the visible region

Material used in the LEDs

- Gallium arsenide (GaAs)
- Aluminium gallium arsenide (AlGaAs)
- Gallium arsenide phosphide (GaAsP)
- Aluminium gallium indium phosphide (AlGaInP)
- Gallium phosphide (GaP)
- Aluminium gallium phosphide (AlGaP)
- Aluminium nitride (AlN)
- Aluminium gallium nitride (AlGaN)

Advantages and Disadvantages of LEDs

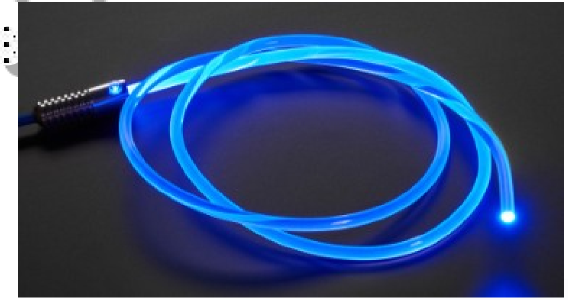
Advantages of LED:

- ✓ Simple design.
- ✓ Ease of manufacture.
- ✓ Low cost.
- ✓ High reliability
- ✓ Light output is proportional to the current: light intensity can be controlled easily
- ✓ LEDs can withstand shocks and vibrations.
- ✓ LEDs can emit light of different colors
- ✓ It has long life time
- ✓ Highly efficient (no heat loss)
- ✓ Operated over a wide range of temperatures.

Disadvantages of LED:

- not suitable for large area display (because of its high cost)
-cannot be used for illumination
- refraction of light at semiconductor/air interface.
- average lifetime of a radiative recombination is only a few nanoseconds, therefore nodulation BW is limited to only few hundred megahertz.
- Low coupling efficiency
- Large chromatic dispersion

Applications of LEDs

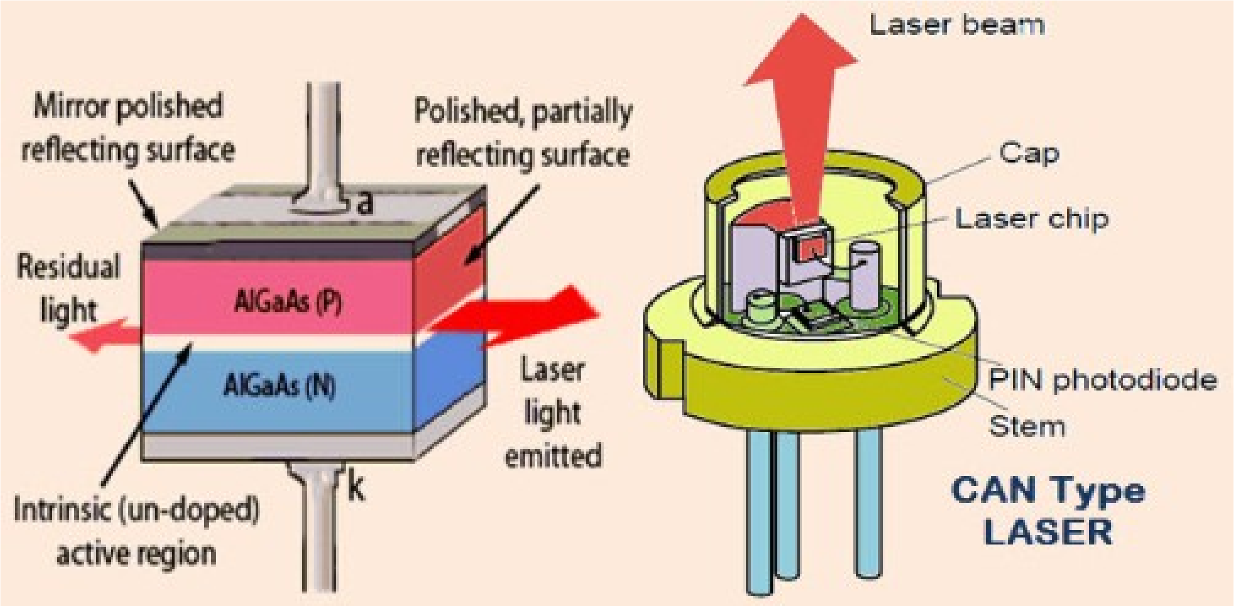


- Digital displays.
- Optical source in fibre optic communication.
- Infrared LEDs used in remote control devices.
- Widely used in automobile industry.

Semiconductor LASER Diodes

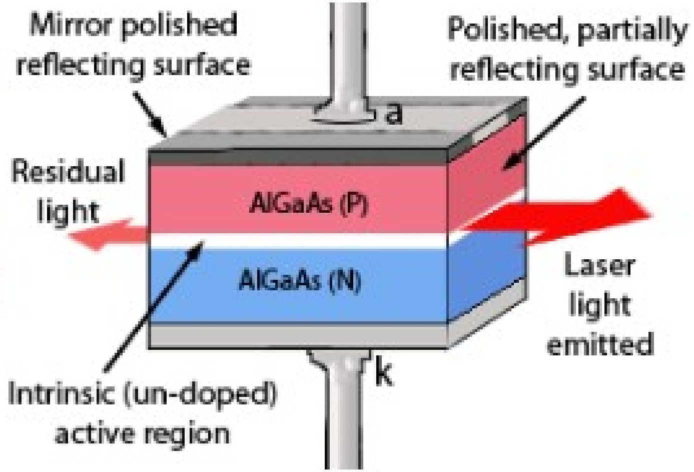
developed by **Robert N. Hall** in early **1960s**

A **Laser Diode** is a **semiconductor device** similar to a LED that **emits monochromatic coherent** (same frequency and phase) **light.** It uses p-n junction and the coherent light is produced **by** the **"Light Amplification by Stimulated Emission of Radiation".**



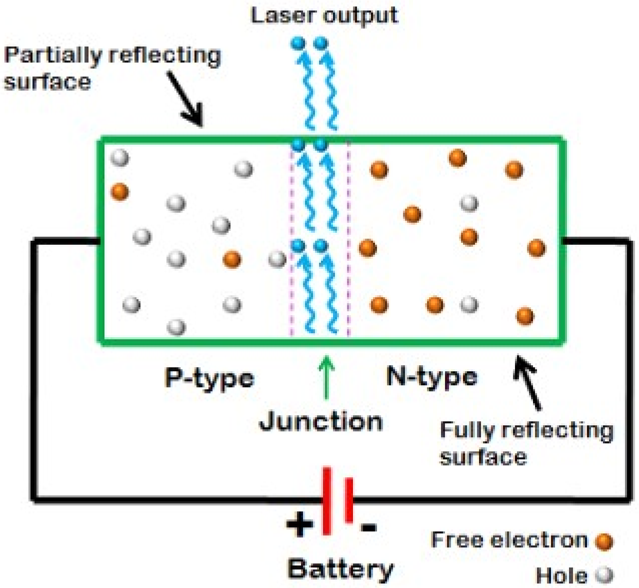
LASER Diode: Construction

- The **construction** of laser diodes is **similar to LED.**
- It is **made by** an **n-type** and a **p-type semiconductor of gallium arsenide (GaAs)** **doped** with **aluminium or silicon.**
- Generally, both p-type and n-type regions are heavily doped to increase the amount of electron-hole recombination
- The **lasing action takes place in the active region** (depletion layer) of the laser diode.
- The **end faces of the junction diode are well-polished** *and* **reflective surface Highly reflective surface parallel to each other.** They act as optical resonators through which the emitted light comes out.
- **One side is fully reflective**, and t**he other side is partially reflective** for the laser to out from the device.
- *Metal contacts on both sides are made to supply the voltage.*

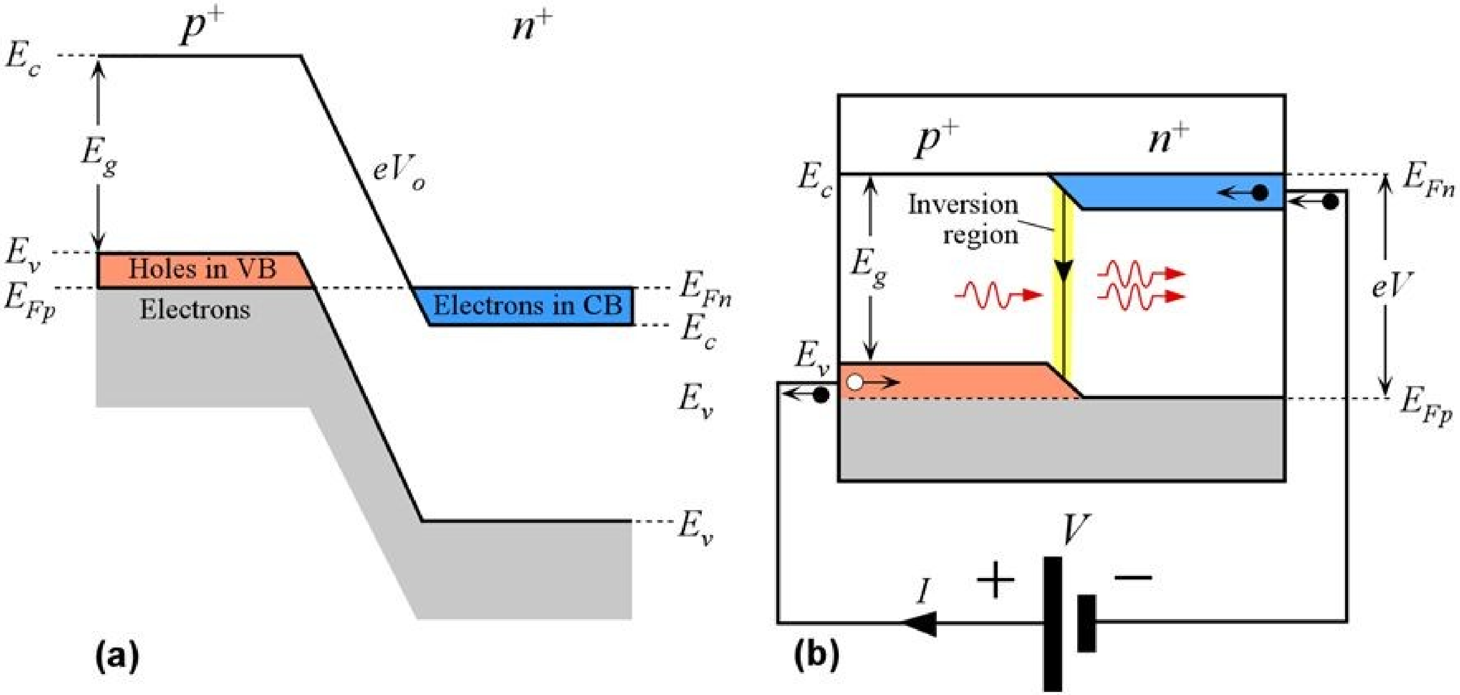


LASER Diode: Working Principle

• When the *applied voltage exceeds the threshold voltage*, *the current starts flowing* in the diode LASER.
• **The electron-hole recombination results in a photon generation: this is spontaneous emission.**
• This light travels between two reflecting surfaces in the active region hundreds of times.
• These radiations interact with other electron-hole pairs in active regions, and cause stimulated emission.
• Like this, the subsequent chain of stimulated emission results in lasing action.
Light traveling in other directions will not contribute to LASER output.



LASER Working Principle by Band diagram



$$E_g = h\nu = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

(a) The energy band diagram of a degenerately doped *pn* with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

Characteristics of LASER Diodes

Type: It is a solid state semiconductor laser.

Active medium: A PN junction diode made from single crystal of gallium arsenide is used as an active medium.

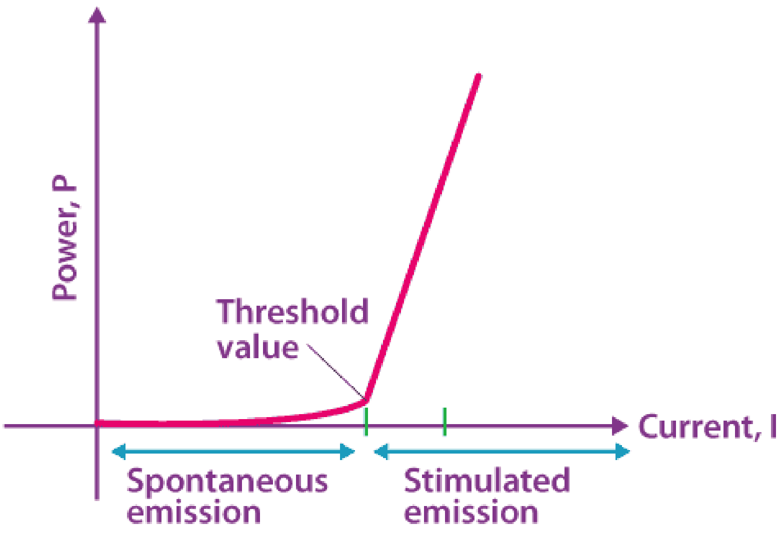
Pumping method: The direct conversion method is used for pumping action.

Power output: The power output from this laser is 1mW.

Nature of output: The nature of output is continuous wave or pulsed output.

Wavelength of Output: gallium arsenide laser gives infrared radiation in the wavelength 830 to 850 nm .

I-P characteristics of LASER Diodes



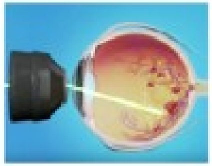
The **important characteristic of a laser diode** is its approach or the threshold. The laser diode ***doesn't operate until a minimum power is applied***. ***If the light is below its energy, then the emission is weaker than the threshold compared to the full energy.***

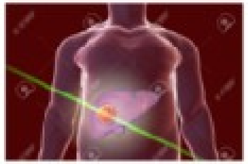
LASER Diodes and its Applications

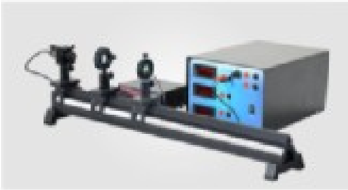
Semiconductor Material	Wavelength	Application
InGaN / GaN	3800, 4050, 4500, 4700 A^0	data storage
AlGaInP / GaAs	6350, 6500, 6700 A^0	laser pointers, DVD players
AlGaAs / GaAs	7200 – 8500 A^0	CD players, laser printers, For pumping solid-state lasers
InGaAs / GaAs	9000 –11000 A^0	pumping and other fiber amplifiers
InGaAsP / InP	1.2 – 2.0 µm	optical fiber communications, sensing, spectroscopy
AlGaAsSb / GaSb	1.8 – 3.4 µm	defense, sensing, spectroscopy


CD player


Barcode Scanner


Eye treatment

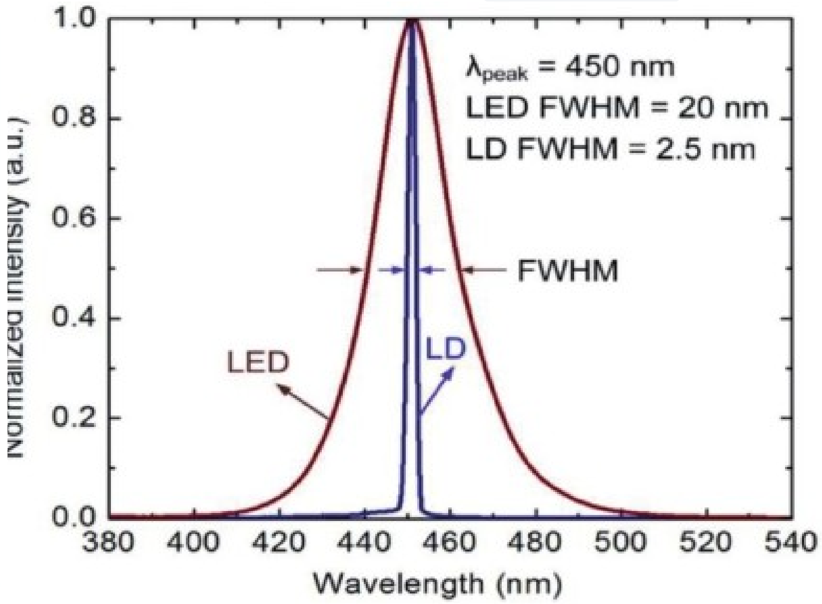

Killing cancer cell



Difference between LED and LASER diode

Difference between LED and LASER diode

LED	LASER diode
Radiation is generated by **spontaneous emission** resulted from electron-hole recombination: **Electroluminescence**	Radiation is generated by **stimulated emission.**
Efficiency: 10%	**Efficiency:** 70%
Bandwidth: 25 nm – 100nm (10THz – 50 THz)	**Bandwidth:** 5 nm – 10nm (< 2MHz)
Coherence: Less coherent	**Coherence:** Highly coherent
Directionality: High divergence angle	**Directionality:** Less divergence angle
Output power: Low output power	**Output power:** High output power

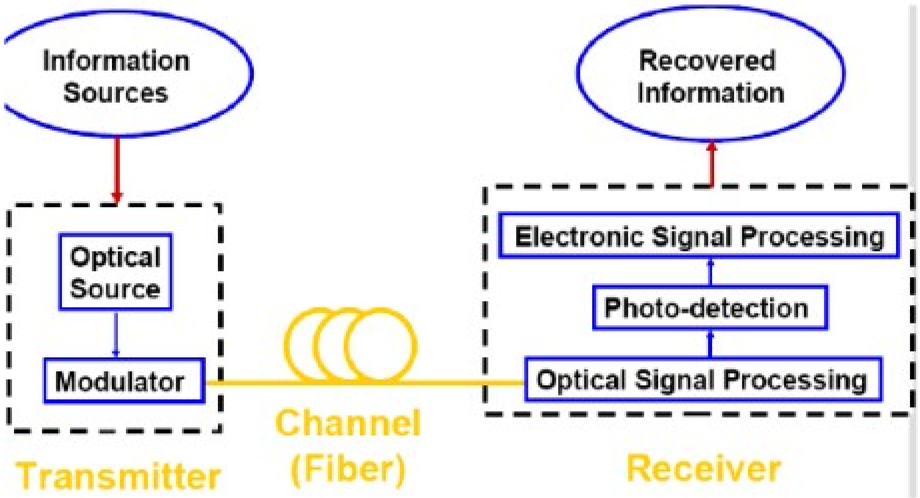


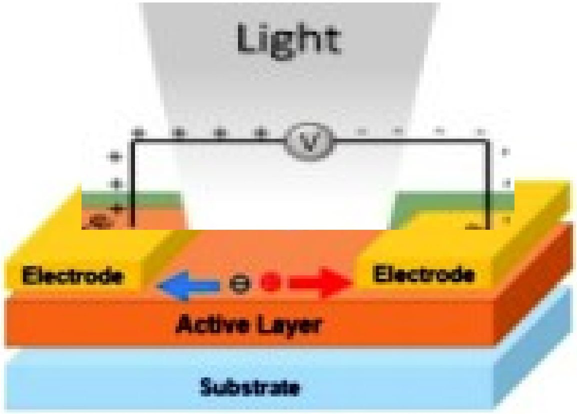
LASER is more monochromatic than LED, i.e. it **produces** a **narrower band of wavelengths**.

Photodetector

These are the semiconductor devices are used to detect light.
or
Semiconductor devices are implemented to detect the photon.

Why they are important ?



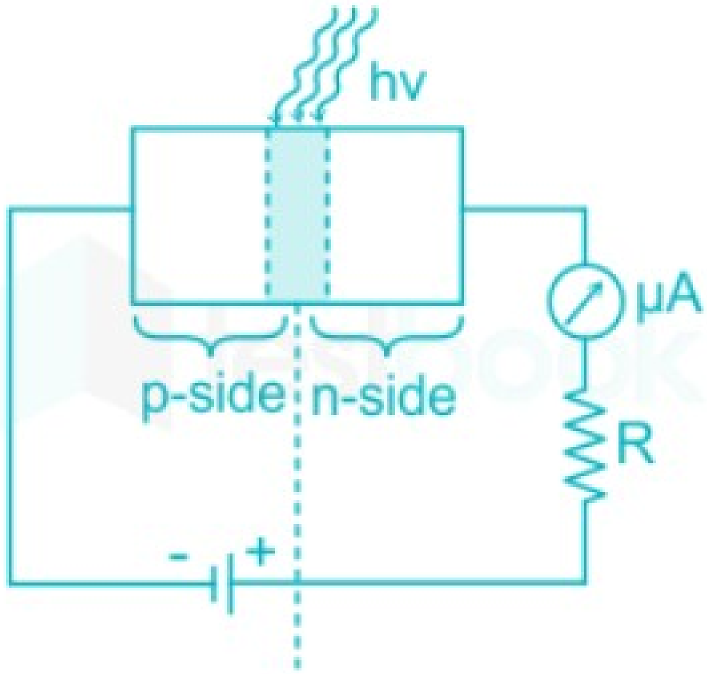


LED/LASER:
electrical signal====> light
Photodetector:
light====> Electrical signal

Photodetector: Construction

A ***photodiode*** is a **PN-junction diode** that consumes light energy to produce an electric current. Sometimes it is also called a photo-detector, a light detector, and a photo-sensor. These diodes are particularly designed to **work in reverse bias conditions**. This diode is very sensitive to light, so when light falls on the diode it easily changes light into an electric current

- It contains a p-n junction diode
- Generally p is heavily doped (p^+) compared to n
- Metal contact at both side to supply voltage
- Works in reverse bias
- Incident light generates e^- — h^+ pairs
- Carrier generate at depletion layer
- Carrier transport at external circuit
- Extraction of the carriers as current



Typical Design of a PN photodiode

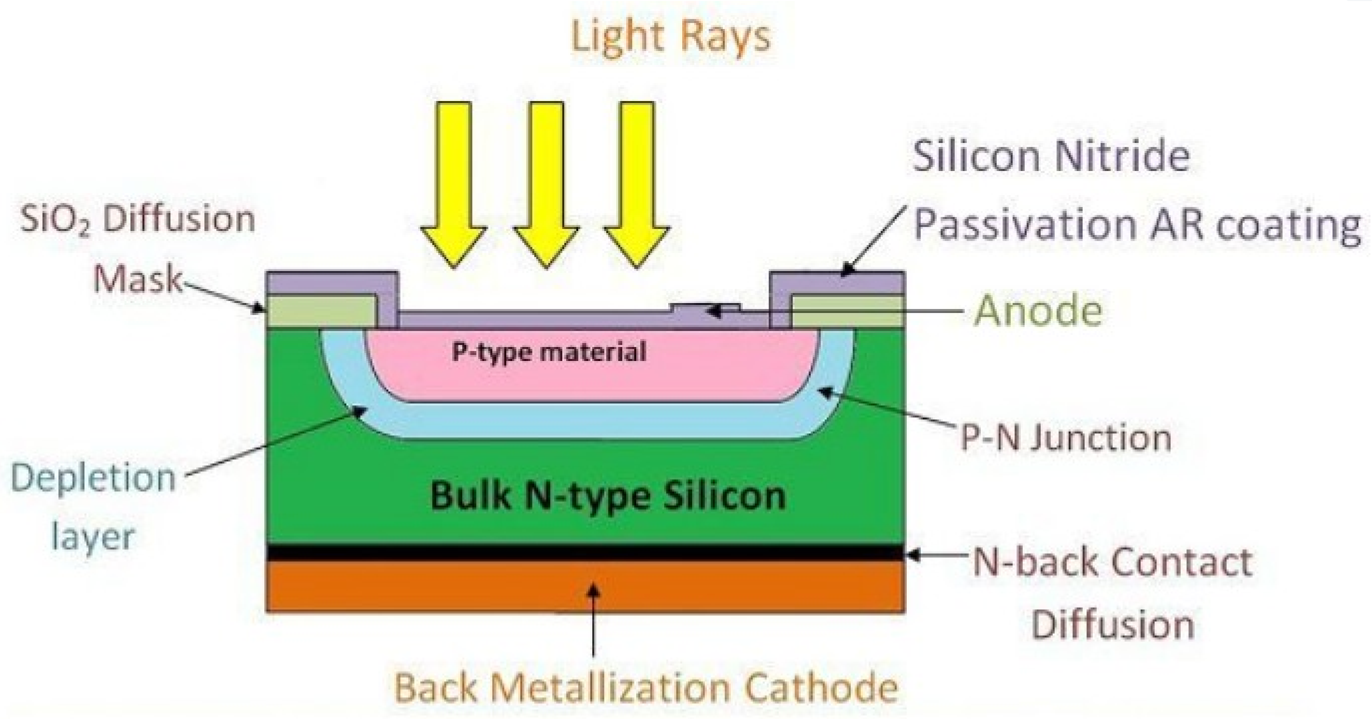
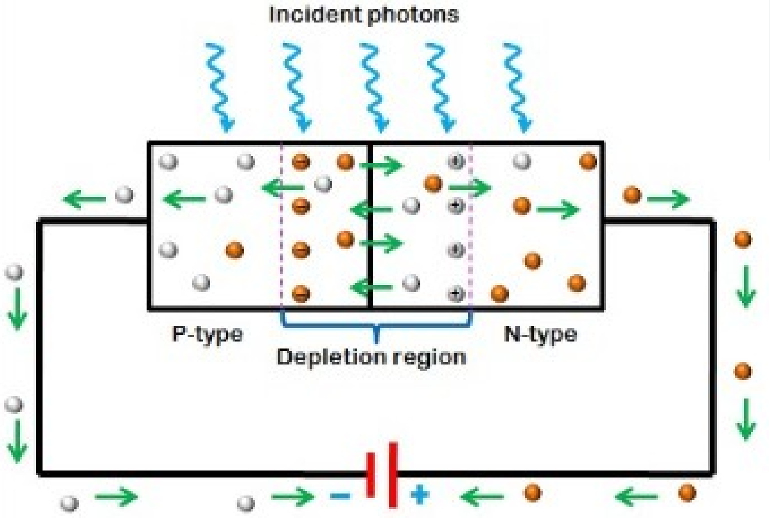
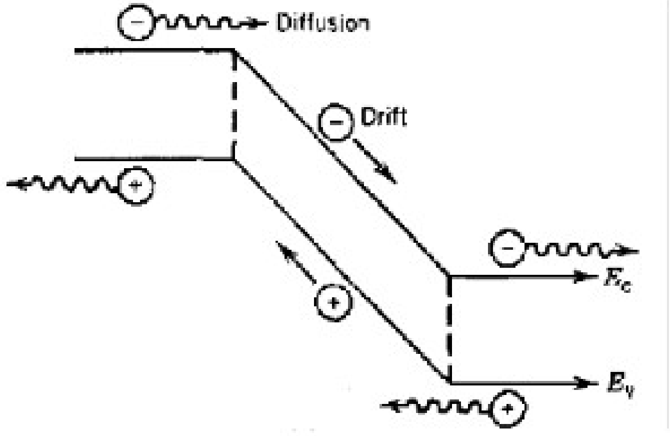


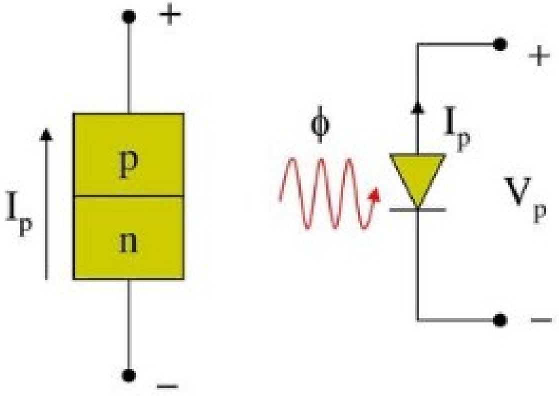
Photo Detector: Working Principle

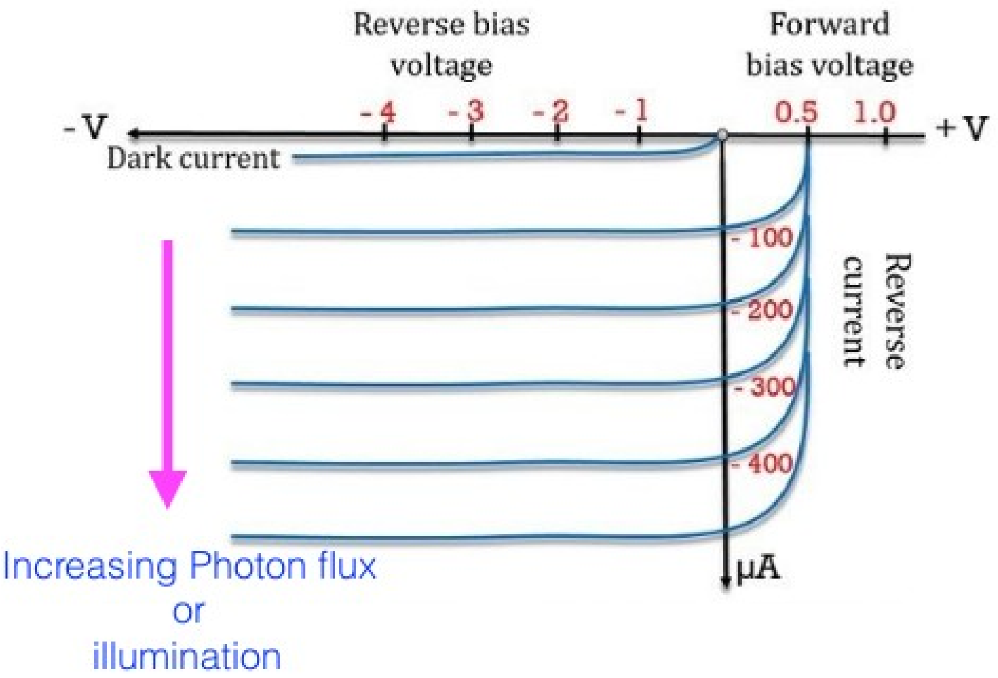
- When the photo diode is reversed biased the depletion layer near the PN junction increases. Only minority carriers conduct electricity.
- When the device is exposed to radiation or illuminated the photons are absorbed by the diode and electron- hole pair is generated.
- The minority carriers in the depletion region experience force due to the depletion region electric field and the external electric field.
- Holes in the region move toward the anode, and electrons move toward the cathode, and a photocurrent will be generated.
- The entire current through the diode is the sum of the absent current in the absence of light and the photocurrent. So the absent current must be reduced to maximize the sensitivity of the device.





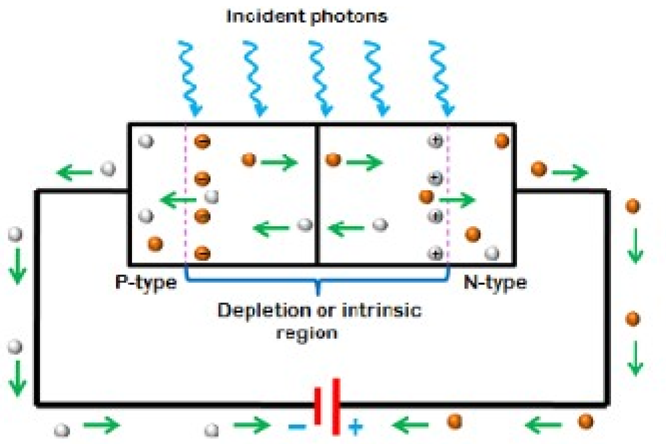
I-V Characteristics of Photodiode





The photo detection occurs within the depletion area of the diode. As this is relatively small, the sensitivity is not as great as that for some other forms of photo diode

Drawbacks of PN Photodiode



Narrow active area:

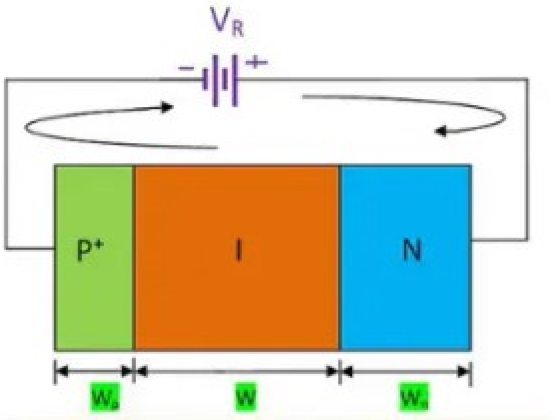
- The photodetection occurs within the depletion area of the diode, and this is os very small ~ 1µm.
- Photons are absorbed, and e-h are generated everywhere, but only e-h in presence of the E field is transported. A p-n junction supports an E field in the depletion layer.
- As this is relatively small, the quantum efficiency is low, and the sensitivity is not as great as that for some other forms of a photodiode

Junction capacitance:

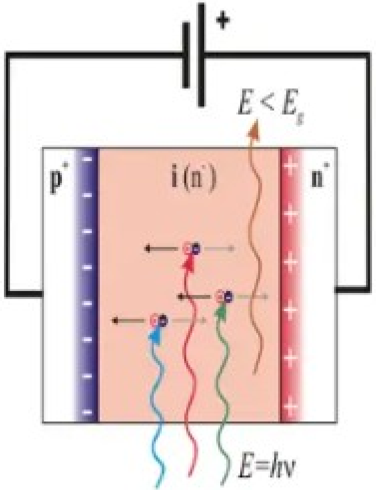
- As the junction capacitance due to the delation layer is large, so the modulation at high frequencies is limited due to the large time constant-RC. This limits the bandwidth

PIN Photodetector: Construction & working Principle

A **p–i–n photodiode**, also called PIN photodiode, is a **photodiode** with *an intrinsic (i) (i.e., undoped) region in between the n- and p-doped regions.* Most of the **photons are absorbed in the intrinsic region**, and carriers generated therein can efficiently contribute to the **photocurrent**.

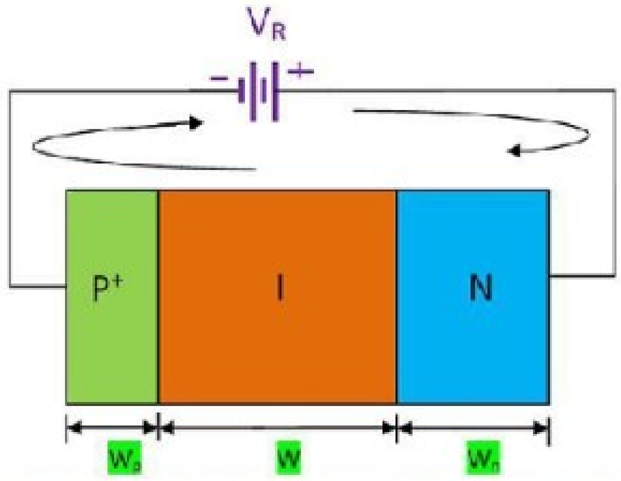


- It contains an Intrinsic layer (i) between the p-n junction diode
- Generally, p is heavily doped (p^+) compared to n
- Metal contact at both side to supply voltage
- Works in reverse bias
- Incident light generates e^- — h^+ pairs
- Large depletion layer
- Larger current extraction



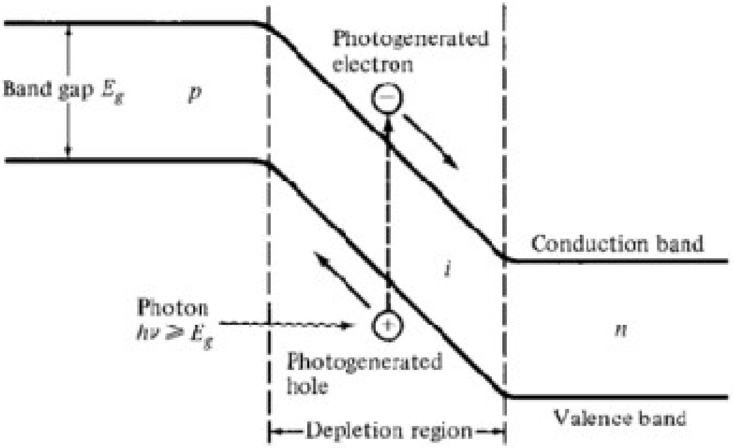
PIN Photodetector: Construction & working Principle

The high E-filed present in the depletion region causes photo-generated carriers to separate and be collected across the reverse bias junction. This leads to rise in the current flow in the external circuit.



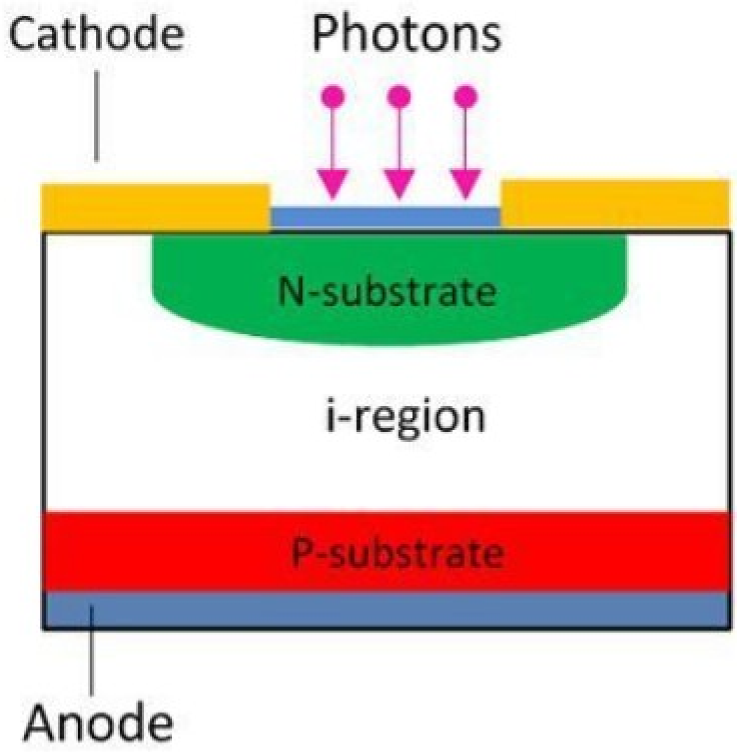
$$\lambda_c = \frac{hc}{E_g} = \frac{1.24\ (\mu m)}{E_g(eV)}$$

The cut-off wavelength is determined by the bandage of the materials



The wide intrinsic region makes the PIN diode suitable for attenuators, fast switches, photodetectors, and high-voltage power electronics applications.

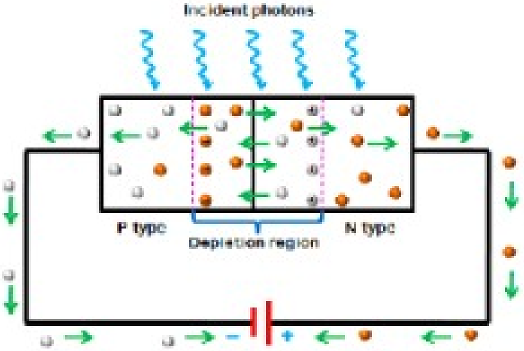
Typical Design of a PIN photodiode



PN vs PIN Photodiode

PN diode

- electron-hole pair generation in the depletion region of a pn junction
- unit gain, low noise (shot), low dark current
- bandwidth limited by RC, transit-time and lifetime
- slower than pin diodes due to diffusion currents
- poor responsivity due to small depleted region.



PIN diode

- electron hole pair generation in the intrinsic depleted region
- unit gain, low noise (shot), low dark current
- bandwidth limited by RC and transit time, diffusion region contribution usually negligible
- best device for speed (>40 Gbps)