Optoelectronic Devices

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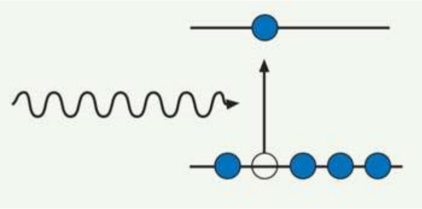
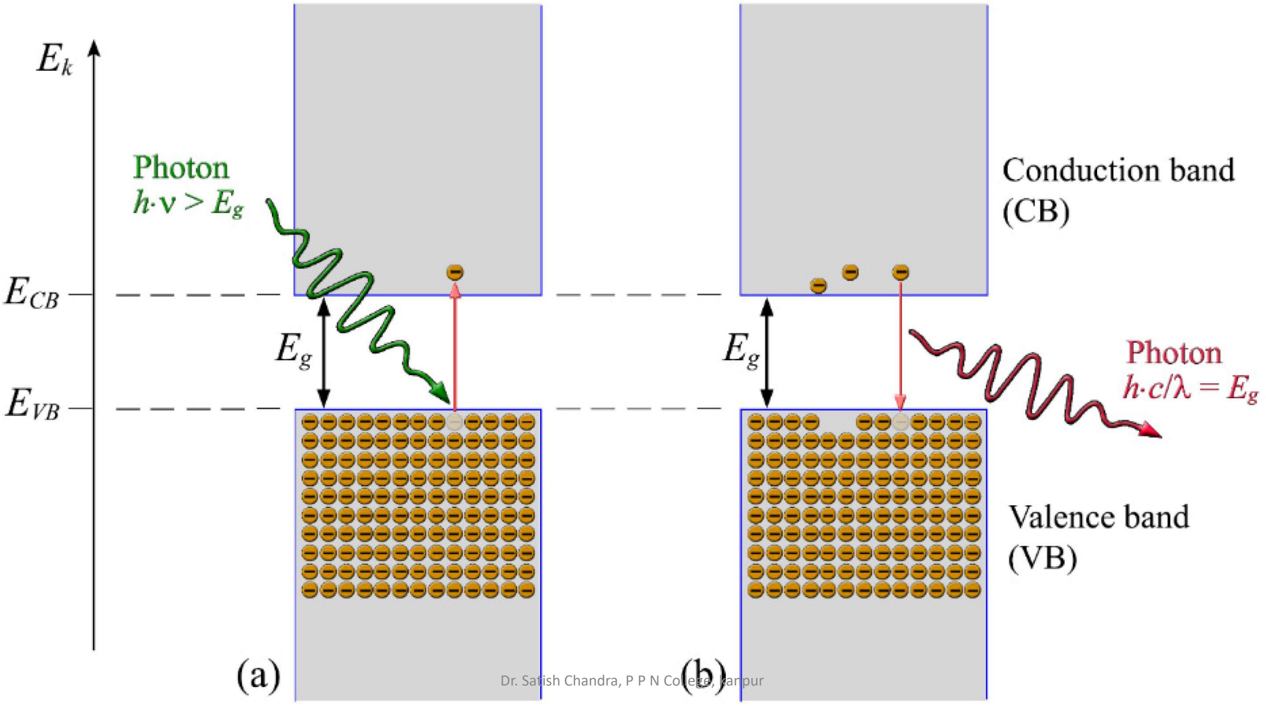
OPTOELECTRONIC DEVICES



- Two processes are fundamental to the operation of most of the semiconductor optical devices:
  - The absorption of a photon can create an electron–hole pair.
    - Photodetectors
  - The recombination of an electron and a hole can result in the emission of a photon.
    - light-emitting diode (LED) & laser diode (LD).



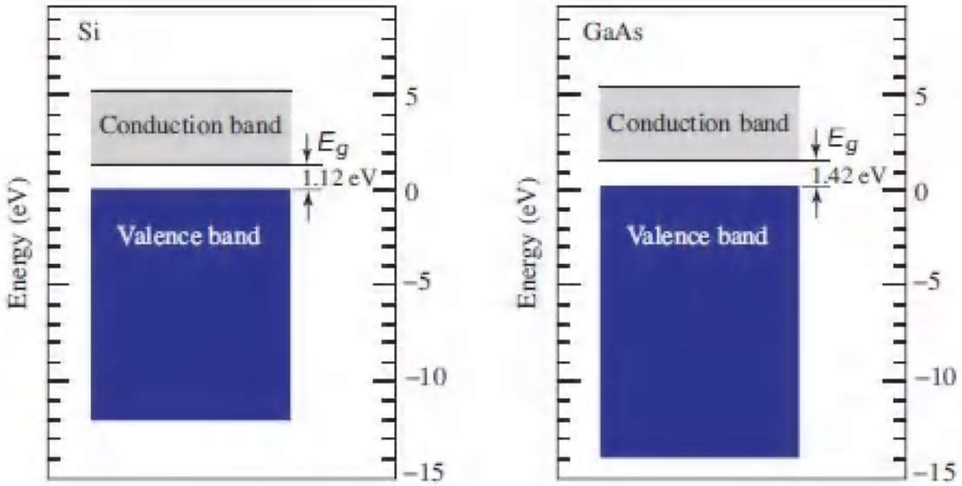
SEMICONDUCTORS

- A semiconductor is a crystalline or amorphous solid whose electrical conductivity is typically intermediate between that of a metal and that of an insulator.
- Its conductivity can be significantly altered by modifying the temperature or doping concentration of the material, or by illuminating it with light.
- The band structure of semiconductors, and the ability to form junctions, offer unique properties.

Energy Bands and Charge Carriers

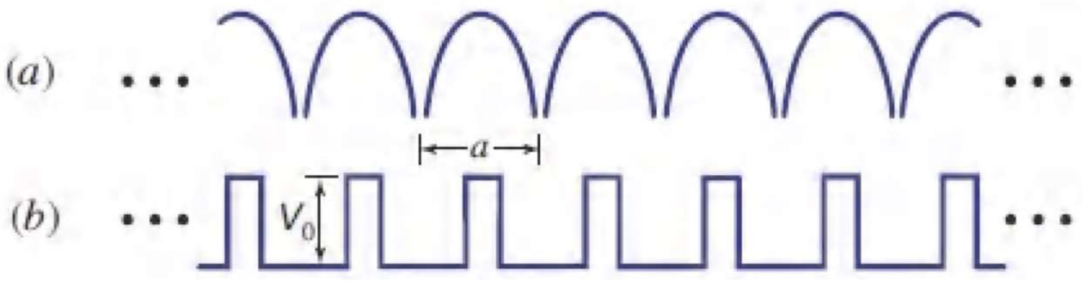
- The periodic potential created by the collection of atoms in the crystal lattice, results in a splitting of the atomic energy levels and the formation of energy bands.
- Each band contains a large number of densely packed discrete energy levels that is well approximated as a continuum.
- The *valence* and *conduction* bands are separated by a forbidden band or ***bandgap***.
- The bandgap energy, E_g plays an important role in determining the electrical and optical properties of the material.

Energy Bandgap



Kronig–Penney Model

- In this simple theory the crystal-lattice potential, a one-dimension (1D) version of which is approximated by a 1D periodic rectangular-barrier potential.
- The solution of the associated Schrödinger equation for this potential yields allowed energy bands with traveling-wave solutions, separated by forbidden bands with exponentially decaying solutions.
- It can be shown that the results are general and apply to three dimensions (3D).



a. Crystal-lattice potential associated with an infinite one-dimensional collection of atoms with lattice constant a.

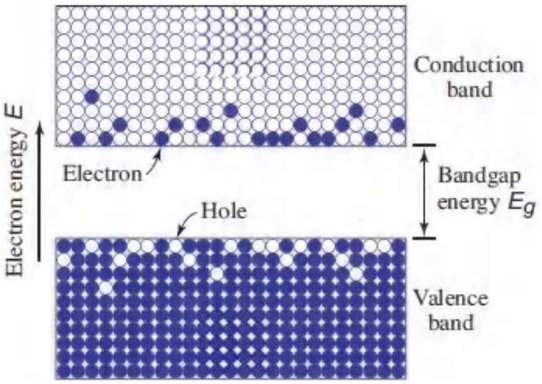
b. Idealized rectangular-barrier potential (height V_0) for the Kronig–Penney model.

Electrons and Holes

- Elemental semiconductors, such as Si and Ge, have four valence electrons per atom that form covalent bonds.
- At $T = 0° K$, the number of quantum states that can be accommodated in the valence band is such that it is completely filled while the conduction band is completely empty.
- The material cannot conduct electricity under these conditions and behaves like *insulator*.

Electrons and Holes

- As the temperature increases, however, some electrons can be thermally excited from the valence band into the empty conduction band, where unoccupied states are abundant.
- These electrons can then act as mobile carriers, drifting through the crystal lattice under the effect of an applied electric field, and thereby contributing to the electric current.

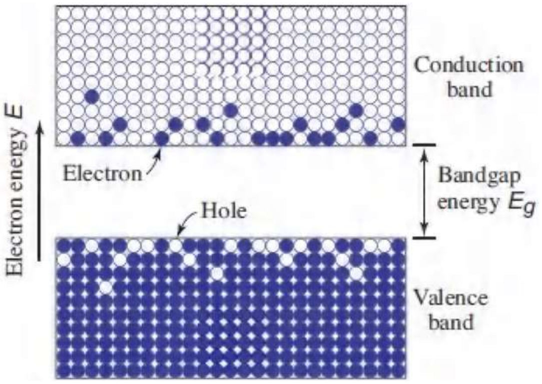


Electrons and Holes

- Moreover, an electron departing from the valence band leaves behind an unoccupied quantum state, which in turn allows the remaining electrons in the valence band to exchange places with each other under the influence of an external field.
- The collection of electrons remaining in the valence band thus undergoes motion.
- This can equivalently be regarded as motion, in the opposite direction, of the hole left behind by the departed electron.
- The hole therefore behaves as a particle with positive charge +e.

Electrons and Holes

- The net result is that each electron excitation creates a free electron in the conduction band and a free hole in the valence band.
- The two charge carriers are free to drift under the effect of the applied electric field and thereby to generate an electric current.
- The material behaves as a semiconductor whose conductivity increases sharply with increasing temperature, as an increasing number of mobile carriers are thermally generated.



Energy–Momentum Relations

- In accordance with Schrödinger wave mechanics, the energy E and momentum p of an electron in a region of constant potential, such as free electrons in metals, are related by,

$$E = \frac{p^2}{2m_0} = \frac{\hbar^2 k^2}{2m_0}$$

- where p is the magnitude of the momentum, k is the magnitude of the wavevector, and m_0 is the electron mass (9.1×10^{-31} kg).
- So that the electron energy is not quantized.
- The $E - k$ relation for a free electron is thus a simple parabola.

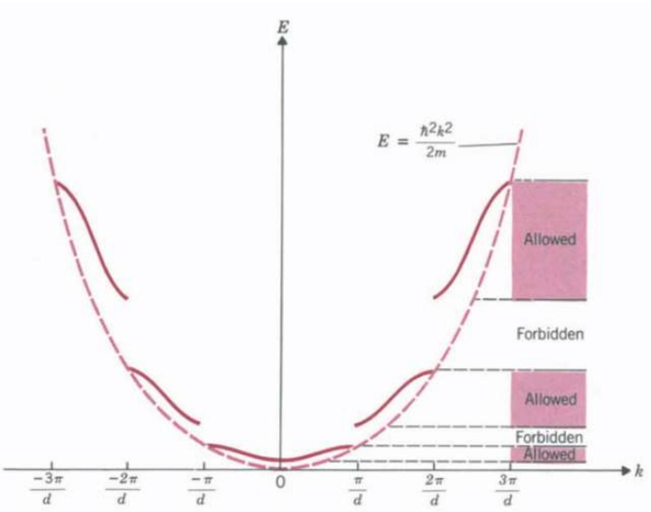
Energy–Momentum Relations

Dispersion Relation

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

$$P\frac{\sin \gamma d}{\gamma d} + \cos \gamma d = \cos kd$$

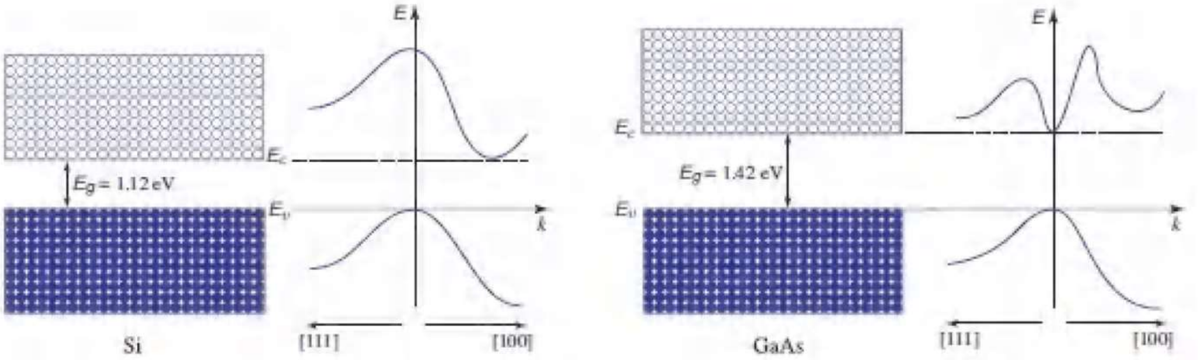
$$\gamma = \sqrt{\frac{2mE}{\hbar^2}}$$



Energy–Momentum Relations

- The motion of an electron in a semiconductor material is similarly governed by the Schrödinger equation, but with a potential generated by the charges in the periodic crystal lattice of the material.
- As this construct results in allowed energy bands separated by forbidden bands, as exemplified by the Kronig–Penney model.
- The ensuing $E-k$ relations for electrons and holes, in the conduction and valence bands respectively, are illustrated in next slide for Si and GaAs.

Energy–Momentum Relations



Cross sections of the $E-k$ relations for Si and GaAs along two crystal directions: [111] toward the left and [100] toward the right.

Energy–Momentum Relations

- The energy E is a periodic function of the components (k_1, k_2, k_3) of the wavevector k, with periodicities $(\pi/a_1, \pi/a_2, \pi/a_3)$, where a_1, a_2, a_3 are the crystal lattice constants.
- Figure displays cross sections of this relation along two particular directions of the wavevector k. The range of k values in the interval $[-\pi/a, \pi/a]$ defines the first Brillouin zone.
- The energy of an electron in the conduction band thus depends not only on the magnitude of its momentum, but also on the direction in which it is traveling in the crystal.

Energy–Momentum Relations

- It is apparent from last Figure that near the bottom of the conduction band, for both Si and GaAs, the $E - k$ relation may be approximated by a parabola

$$E = E_c + \frac{\hbar^2 k^2}{2mc}$$

- where E_c is the energy at the bottom of the conduction band and k is measured from the value of the wavevector where the minimum occurs.

Energy–Momentum Relations

- This parabolic relation suggests that a conduction-band electron behaves in a manner analogous to that of a free electron, but with a mass m_c, known as the conduction-band effective mass or the electron effective mass, in place of the free-electron mass m_0.
- The effective mass m_c embodies the influence of the ions of the lattice on the motion of a conduction-band electron.

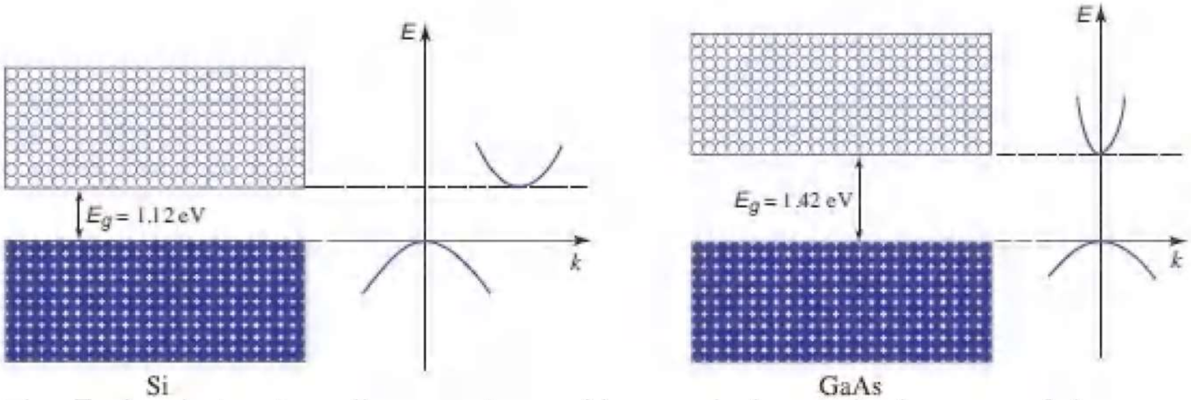
Energy–Momentum Relations

- Similarly, near the top of the valence band, we may write

$$E = E_v - \frac{\hbar^2 k^2}{2mv}$$

- where $E_v = E_c - E_g$ is the energy at the top of the valence band and m_v is the valence-band effective mass or the hole effective mass.
- The influence of the lattice ions on the motion of a valence-band hole is captured by its effective mass m_v.

Energy–Momentum Relations



The $E-k$ relation is well-approximated by parabolas at the bottom of the conduction band and at the top of the valence band, for both Si and GaAs.

Direct- and Indirect-Bandgap Semiconductors

- Semiconductors for which the conduction-band minimum energy and the valence-band maximum energy correspond to the same value of the wavenumber k (same momentum) are called direct-bandgap materials.
- Semiconductors for which this is not the case are known as indirect-bandgap materials.
- As is evident, GaAs is a direct-bandgap semiconductor, whereas Si is an indirect-bandgap semiconductor.

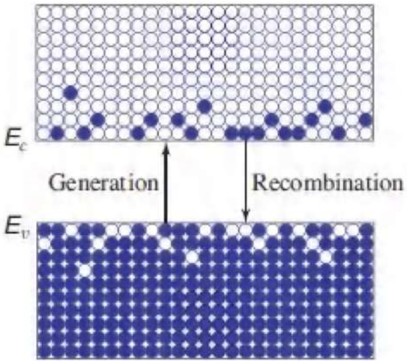
Direct- and Indirect-Bandgap Semiconductors

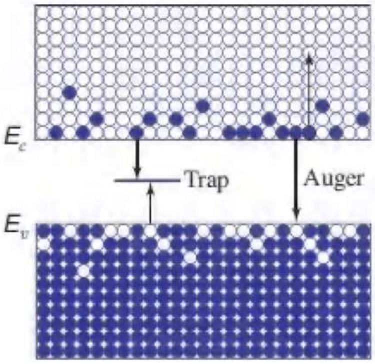
- The distinction is important because a transition between the bottom of the conduction band and the top of the valence band in an indirect-bandgap semiconductor must accommodate a substantial **change in the momentum** of the electron, requiring the participation of a third body such as a phonon.
- As a consequence, under ordinary circumstances indirect-bandgap semiconductors such as Si cannot serve as efficient light emitters whereas direct-bandgap semiconductors such as GaAs can serve.

Generation and Recombination in Thermal Equilibrium

- The thermal excitation of electrons from the valence band into the conduction band results in the electron–hole generation.
- Thermal equilibrium requires that this generation process be accompanied by a simultaneous reverse process of de-excitation. This process, called electron–hole recombination, occurs when an electron decays from the conduction band to fill a hole in the valence band.
- The energy released by the electron may take the form of an emitted photon, in which case the process is called radiative recombination.

Radiative and non-Radiative transition





Generation and Recombination in Thermal Equilibrium

- Nonradiative recombination can occur via a number of independent competing processes, including the transfer of energy to lattice vibrations (creating one or more phonons) or to another free electron via Auger recombination (which, as a three-particle interaction, can take place when the carrier density is very high).
- Recombination may also take place at surfaces and indirectly via traps or defect centers, which are energy levels associated with impurities or defects associated with grain boundaries, dislocations, or other lattice imperfections that *lie within the forbidden band*.

Generation and Recombination in Thermal Equilibrium

- An impurity or defect state can act as a recombination center if it is capable of trapping both an electron and a hole, thereby increasing their probability of recombining.
- Impurity-assisted recombination may be radiative or nonradiative.
- Auger recombination is a non-radiative process involving three carriers.
- Direct Auger recombination occurs when an electron and hole recombine, but instead of producing light, either an electron is raised higher into the conduction band or a hole is pushed deeper into the valence band

Generation Rate

- Because it takes both an electron and a hole for a recombination to occur, the rate of thermal electron–hole recombination, *R* is proportional to the product of the concentration of electrons and holes, i.e.,

$$R = rnp$$

- where the *recombination coefficient* r (cm^3/s) depends on the characteristics of the material, including its composition and defect density, and on temperature.
- It also depends relatively weakly on the doping level.

Generation Rate

- The equilibrium concentrations of electrons and holes n_0 and p_0 are established when the generation and recombination *rates are in balance*.
- In the steady state, the rate of recombination must equal the rate of generation. If G_0 is the rate of thermal electron–hole generation at a given temperature, then, in thermal equilibrium,

$$G_0 = rn_0p_0$$

- The product of the electron and hole concentrations $n_0p_0 = G_0/r$ is approximately the same whether the material is n-type, p-type, or intrinsic.

Internal Quantum Efficiency

- The internal quantum efficiency η_i of a semiconductor material is defined as the ratio of the radiative recombination coefficient (RRC) to the total (radiative and nonradiative) recombination coefficient (TRC).
- This parameter is important because it determines the **efficiency of light generation** in a semiconductor material.
- The total rate of recombination is given by, $R = rnp$.
- If the recombination coefficient r is split into a sum of radiative and nonradiative parts, $r = r_r + r_{nr}$, the internal quantum efficiency is

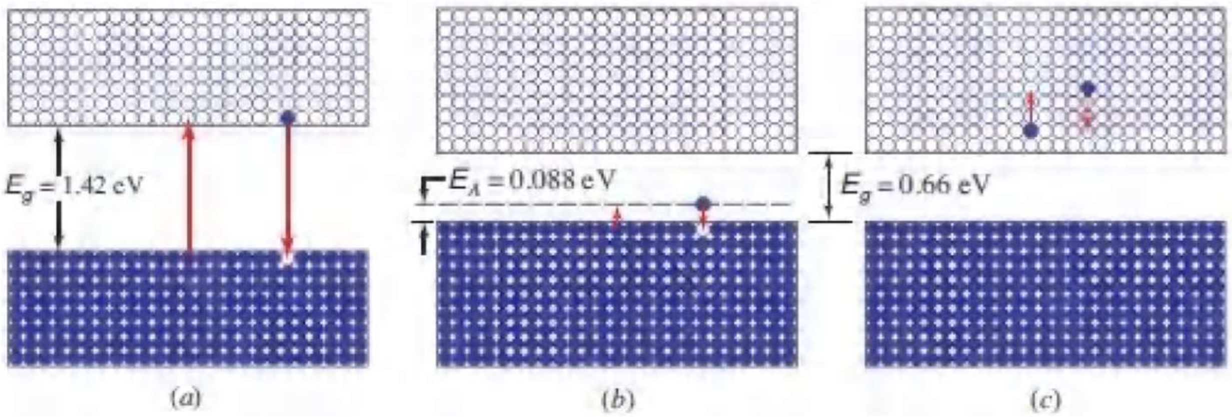
$$\eta_i = \frac{r_r}{r} = \frac{r_r}{r_r + r_{nr}}$$

Junctions

- Juxtapositions of differently doped regions of a single semiconductor material are called homojunctions.
- An important example is the p–n junction.
- Junctions between different semiconductor materials are called heterojunctions.

INTERACTIONS OF PHOTONS WITH CHARGE CARRIERS

- The processes of absorption and emission important in the operation of photonic devices.
- This domain of study is known as semiconductor optics.
- Photon interactions in bulk semiconductors is possible through;
  - Band-to-Band (Inter-band) Transitions.
  - Impurity-to-Band Transitions.
  - Free-Carrier (Intra-band) Transitions.
  - Phonon Transitions.
  - Excitonic Transitions.



Examples of absorption and emission of photons in bulk semiconductors.
(*a*) Band-to-band transitions in GaAs can result in the absorption or emission of photons of wavelength $\lambda_o < \lambda_g = hc/E_g = 0.87\ \mu$m.
(*b*) The absorption of a photon of wavelength $\lambda_A = hc/E_A = 14\ \mu$m results in a valence-band to acceptor - level transition in Hg-doped Ge (Ge:Hg).
(*c*) Free-carrier transitions within the conduction band of Ge.

Band-to-Band (Inter-band) Transitions

- An absorbed photon can result in an electron in the valence band making an upward transition to the conduction band, thereby creating an electron–hole pair.
- Electron–hole recombination can result in the emission of a photon.
- Band-to-band transitions may be assisted by one or more phonons.
- A phonon is a quantum of the **lattice vibrations** associated with molecular or **acoustic vibrations** of the atoms in a material.

Impurity-to-Band Transitions

- An absorbed photon can result in a transition between a donor (or acceptor) **level** and a **band** in a doped semiconductor.
- In a *p*-type material, for example, a low-energy photon can lift an electron from the valence band to the acceptor level, where it becomes trapped by an acceptor atom.
- A hole is created in the valence band and the acceptor atom is ionized, or a hole may be trapped by an ionized acceptor atom; the result is that the electron decays from its acceptor level to recombine with the hole.
- The energy may be released **radiatively** (in the form of an emitted **photon**) or **non-radiatively** (in the form of **phonons**).
- The transition may also be assisted by traps in defect states.

Free-Carrier (Intra-band) Transitions

- An absorbed photon can impart its energy to an electron in a given band, causing it to move higher **within** that **band**.
- An electron in the conduction band, for example, can absorb a photon and move to a higher energy level within the conduction band.
- This is followed by **thermalization**, a process whereby the electron relaxes down to the bottom of the conduction band while releasing its energy in the form of **phonons**.
- The strength of free-carrier absorption is proportional to the carrier density; it decreases with photon energy as a power-law function.

Phonon Transitions

- Long-wavelength photons can release their energy by directly exciting lattice vibrations, i.e., by creating **phonons**.

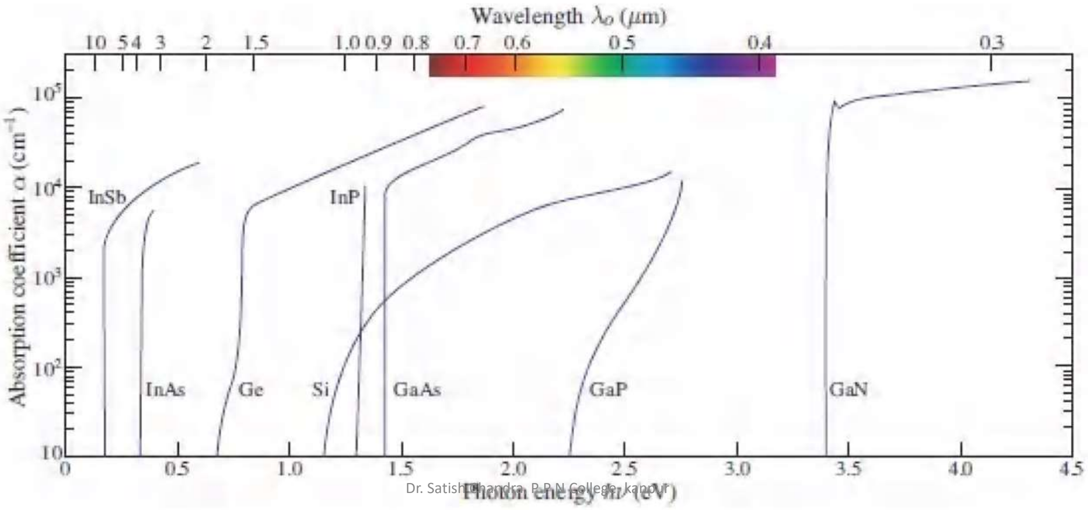
Excitonic Transitions

- The absorption of a photon in a semiconductor can result in the formation of a free electron in the conduction band and a hole that rises to the top of the valence band, where its energy is *minimized*.
- The hole and electron can be bound together by their mutual Coulomb attraction to form an exciton; the attractive potential results in a reduction of the total energy of the electron and hole.
- This entity is much like a hydrogen atom in which a hole plays the role of the proton.
- Excitons typically have lifetimes that range from hundreds of picoseconds to nanoseconds. A photon may be emitted as a result of the electron and hole recombining, thereby **annihilating the exciton**.

Photon Interactions in Bulk Semiconductors

- For photon energies greater than the bandgap energy E_g, the absorption is dominated by band-to-band transitions that form the basis of many photonic devices.
- The spectral region where the material changes from being relatively **transparent** ($h\nu < E_g$) to strongly **absorbing** ($h\nu > E_g$) is known as the absorption edge.
- Direct-bandgap semiconductors have a **more** abrupt absorption edge than indirect-bandgap materials

Photon Interactions in Bulk Semiconductors



Bandgap Wavelength

- Direct inter-band absorption and emission can take place only at frequencies for which the photon energy $h\nu > E_g$.
- The minimum frequency ν necessary for this to occur is $\nu_g = E_g/h$, so that the corresponding maximum wavelength is;

$$\lambda_g = \frac{c}{\nu_g} = \frac{hc}{E_g}$$

- If the bandgap energy is given in eV (rather than in J), the bandgap wavelength $\lambda_g = hc/eE_g$ in µm turns out to be;

$$\lambda_g \approx \frac{1.24}{E_g}$$

- The quantity λ_g is known as the bandgap wavelength.

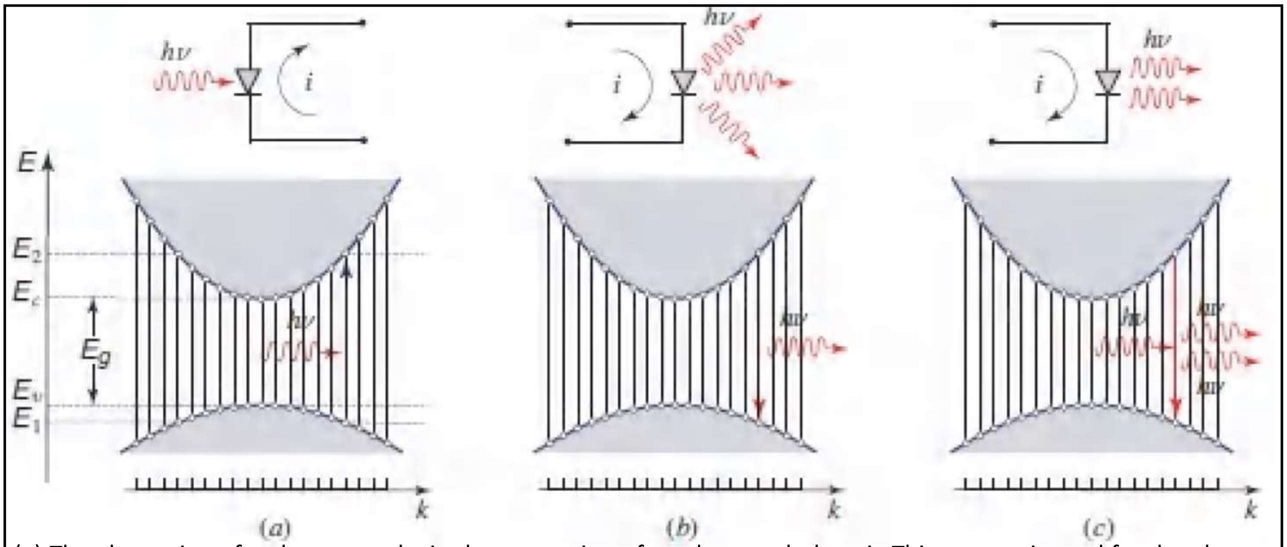
Material	Crystal Structure	Bandgap Type	Bandgap Energy (eV)	Bandgap Wavelength (µm)
Si	D	I	1.12	1.110
Ge	D	I	0.66	1.880
AlN	W	D	6.02	0.206
AlP	Z	I	2.45	0.506
AlAs	Z	I	2.16	0.574
AlSb	Z	I	1.58	0.785
GaN	W	D	3.39	0.366
GaP	Z	I	2.26	0.549
GaAs	Z	D	1.42	0.873
GaSb	Z	D	0.73	1.700
InN	W	D	0.65	1.910
InP	Z	D	1.35	0.919
InAs	Z	D	0.36	3.440
InSb	Z	D	0.17	7.290

Conditions for Photon Absorption

- Electron excitation from the valence to the conduction band may be induced by the absorption of a photon of appropriate energy ($h\nu > E_g$ or $\lambda < \lambda_g$).
- An electron–hole **pair is generated**.
- This adds to the concentration of mobile charge carriers and increases the **conductivity** of the material.
- The material behaves as a photoconductor with a conductivity proportional to the photon flux.
- This effect is used for the **photodetection of light**.

Conditions for Photon Emission

- Electron de-excitation from the conduction to the valence band (electron–hole recombination) may result in the spontaneous emission of a photon of energy $h\nu > E_g$, or in the stimulated emission of a photon when a photon of energy $h\nu > E_g$ is initially present.
- Spontaneous emission is the underlying phenomenon on which the light-emitting diodes (LEDs) are based.
- Stimulated emission is responsible for the operation of semiconductor optical amplifiers (SOAs) and laser diodes (LDs).



(a) The absorption of a photon results in the generation of an electron–hole pair. This process is used for the photo-detection of light.

(b) The recombination of an electron–hole pair results in the **spontaneous emission** of a photon. Light-emitting diodes (LEDs) operate on this basis.

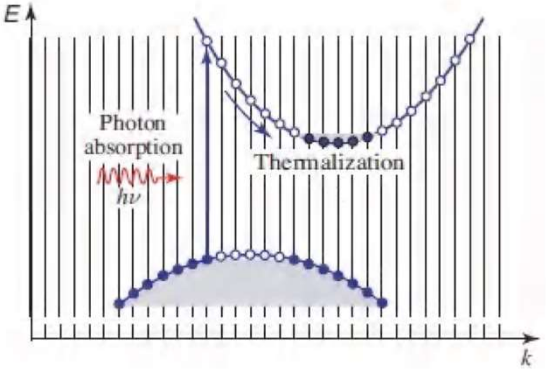
(c) Electron–hole recombination can be induced by a photon. The result is the **stimulated emission** of an identical photon. This is the underlying process responsible for the operation of semiconductor laser diodes (LDs).

Photon Absorption in an Indirect-Bandgap Semiconductor

- The energy and momentum **conservation** required for photon absorption in an indirect bandgap semiconductor is readily accommodated by means of a two-step process.
- The electron is first excited to a high energy level within the conduction band by a **k-conserving vertical transition**.
- It then quickly relaxes to the bottom of the conduction band by a process called **thermalization**, in which its momentum is transferred to phonons.
- The generated hole behaves similarly.

Photon Absorption in an Indirect-Bandgap Semiconductor

- Since the process occurs **sequentially**, it does not require the simultaneous presence of three bodies and is thus not unlikely in indirect-bandgap semiconductors.
- Indeed, Si and Ge are widely used as **photodetector** materials, as are direct bandgap semiconductors such as AlGaAs and InGaAs.



Photon Emission in an Indirect-Bandgap Semiconductor

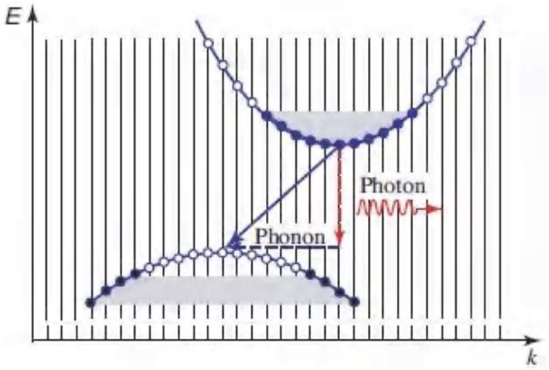
- Radiative electron–hole recombination is unlikely in an indirect-bandgap semiconductor.
- This is because a transition from near the bottom of the conduction band to near the top of the valence band requires an **exchange of momentum** that cannot be accommodated by the emitted photon.
- Momentum may be conserved, however, by the participation of phonons in the interaction.

Photon Emission in an Indirect-Bandgap Semiconductor

- Phonons can carry relatively large momenta but typically have small energies (≈ 0.01–0.1 eV), so that their transitions appear **horizontal** on the E–k diagram.
- However, because phonon-assisted emission involves the **simultaneous** participation of three bodies (electron, photon, and phonon), the probability of its occurrence is substantially reduced.
- Thus, Si, which is an indirect bandgap semiconductor, has a substantially lower radiative recombination coefficient than does GaAs, which is a direct-bandgap semiconductor.

Photon Emission in an Indirect-Bandgap Semiconductor

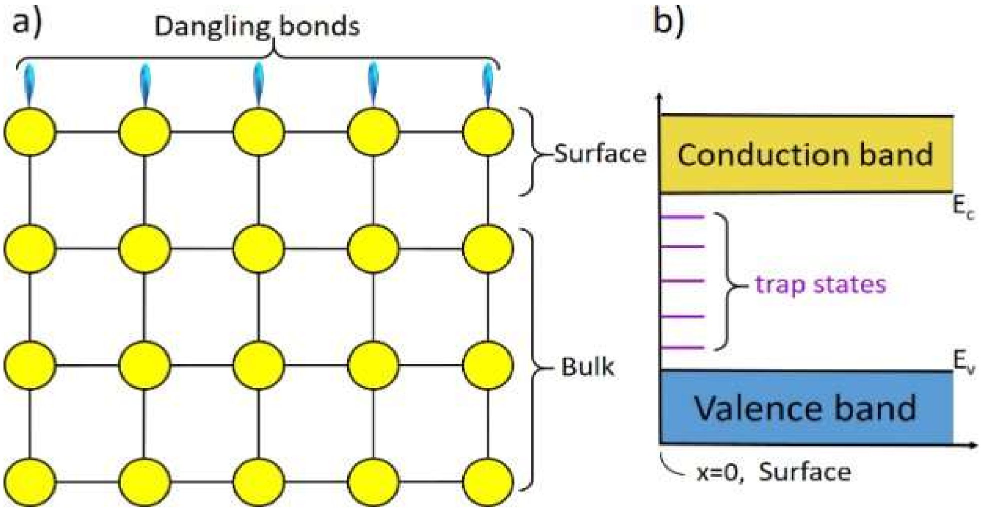
- Silicon therefore does not emit light efficiently via interband transitions, whereas GaAs does.
- However, under special circumstances it is sometimes possible to elicit photon emission from an indirect bandgap semiconductor.



Surface Recombination

- A strong perturbation of crystal lattice can be called a **surface**.
- The surfaces in semiconductor crystal lattices create **dangling bonds** that are exposed to the ambient.
- Such exposed surfaces absorb impurities from the ambient and become localized centers of defects.
- The high concentration of defects in surfaces increases the probability of non-radiative surface recombination.

Surface & Indirect Recombination



Indirect Recombination

- There are special locations within the semiconductor which are lattice defects or special impurity atoms that introduce allowed electronic levels near the center of the band gap. These levels are not be mistaken for donor or acceptor levels. They are called **trap states**.
- Recombination involves a two step process.
- A carrier and electron, for example, an electronic level near mid-gap, and is trapped.
- Later comes a hole and the electron is attracted to the hole and loses more energy so it goes into the valence band annihilating the hole along with itself, this is called indirect recombination.
- This method releases non-radiative thermal energy or produces lattice vibrations.

Injection Electroluminescence

- Light can be emitted from a semiconductor material as a result of **electron–hole recombination**.
- An external source of energy can be used to produce electron–hole pairs in sufficient numbers that they generate large amounts of **spontaneous recombination radiation**, causing the material to luminesce.
- A convenient way of achieving this is to **forward bias** a p–n junction, which promotes the injection of electrons and holes in the vicinity of the junction.
- The subsequent recombination radiation is called injection electroluminescence.

Light Emitting Diodes

- Electroluminescence is a phenomenon in which light is emitted by a material that is subjected to an electric field.
- **Injection electroluminescence**, first observed in 1907, underlies the operation of light-emitting diodes, which are highly efficient devices capable of emitting light of just about any color.
- A light-emitting diode (LED) is a forward-biased p–n junction, usually fabricated from a direct-bandgap semiconductor material, that emits light via injection electroluminescence
- LEDs are highly important in a number of areas of photonics.

Quantum Efficiency of LED

- LED is an active illumination photo-device which has the reverse process of solar cell.
- The quantum efficiency of LEDs describes that how many injected electrons converted to photons, which is call the electroluminescence phenomena.
- There are two types of quantum efficiencies of LEDs.
- One is the external quantum efficiency (EQE) and the other is internal quantum efficiency (IQE).

Quantum Efficiency of LED

- IQE of LEDs is defined as the number of injected electrons per unit time became the number of photons per unit time (inside the LED device). The IQE formula of LED’s is:

$$IQE\ of\ LEDs = \frac{emitted\ photons\ inside\ LED/sec}{injected\ electrons/sec}$$

- EQE of LEDs is defined as the number of injected electrons per unit time converted to the number of illuminated photons per unit time (outside the LED device). The EQE of LED’s formula is:

$$EQE\ of\ LEDs = \frac{emitted\ photons\ outside\ LED/sec}{injected\ electrons/sec}$$

Quantum Efficiency of LED

- The ratio between EQE and IQE of LEDs is the Light Extraction Efficiency (LEE). The relationship is:

$$EQE = IQE * LEE$$

- Therefore, the formula of LEE is

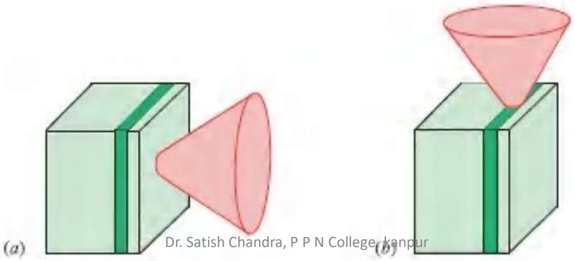
$$LEE = \frac{EQE}{IQE} = \frac{emitted\ photons\ outside\ LED}{emitted\ photons\ inside\ LED}$$

Quantum Efficiency of LED

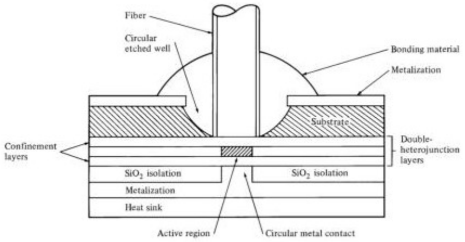
- The IQE characterizes the ability of LED's active layer to convert the injected electrons into photons.
- The EQE is the ability of LED electrical energy into light energy outside the whole device.
- The LEE represents the light extraction capability of LED's device structure design, which includes the layer structure and layer refractive index n matching.

Structure

- LEDs may be constructed either in surface-emitting or edge emitting geometries.
- The surface-emitting LED emits light from a face of the device that is parallel to the plane of the active region.
- The edge-emitting LED, in contrast, emits light from the edge of the active region.

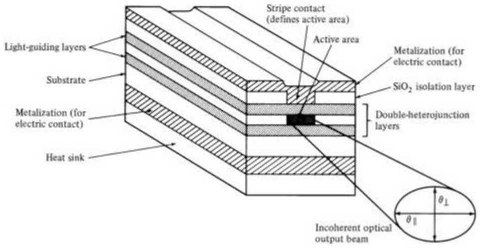


Surface-Emitting LED



- Active region is etched circular well.
- The circular active area have diameter 50μm and up to 2.5 μm thick.
- The emission pattern is almost isotropic with a 120^{o} half-power beam width.
- This pattern is called **Lambertian Pattern** i.e., the source is equally bright when viewed from any direction but the power diminishes as $\cos\theta$ where θ is the angle between the viewing direction and the normal to the surface
- The power is half when $\theta = 60^{o}$ so half power beam width is 120^{o}.

Edge-Emitting LED



- Consists of an active junction region (source of incoherent light and two guiding layers).
- To match the core diameter, the contact strip is 50-70 μm.
- Length of active region range from 100 to 150μm.
- The emission pattern is more directional.
- In the plane parallel to the junction, emitted beam is Lambertian with half power width 120^{o}.
- In the perpendicular plane half power width decrease to $25 – 35^{o}$.

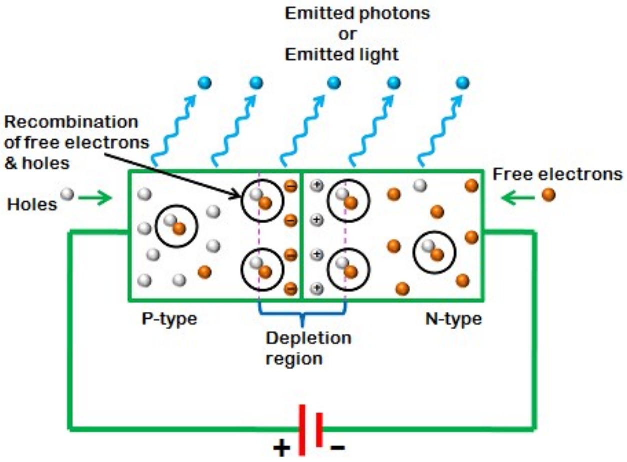
LED

- The construction of LED is similar to the normal p-n junction diode except that gallium, phosphorus and arsenic materials are used for construction instead of Si or Ge materials.
- Because, Si or Ge diodes do not emit energy in the form of light. Instead, they emit energy in the form of heat. Thus, Si or Ge is not used for constructing LEDs.
- LEDs emit either visible light or invisible infrared light when forward biased. The efficiency of generation of light in LED increases with increase in injected current and with a decrease in temperature.

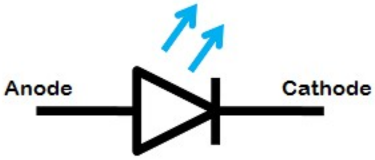
LED - Working

- When LED is forward biased, the free electrons from n-side and the holes from p-side are pushed towards the junction.
- When free electrons reach the junction or depletion region, some of the free electrons recombine with the holes in the positive ions. Thus, free electrons recombine with holes in the depletion region.
- In the similar way, holes from p-side recombine with electrons in the depletion region.

LED - Working



Light Emitting Diode (LED)



LED symbol

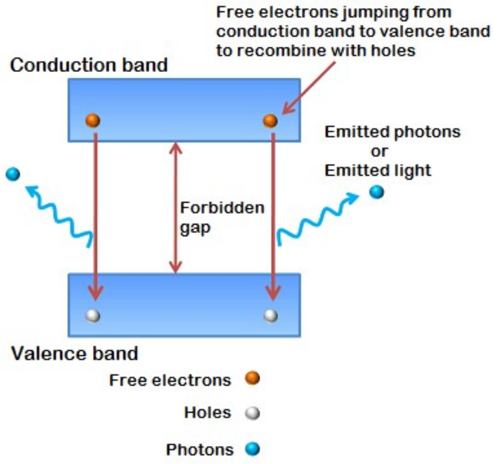
LED - Working

- Because of the recombination of free electrons and holes in the depletion region, the width of depletion region decreases. As a result, more charge carriers will cross the p-n junction.
- Some of the charge carriers from p-side and n-side will cross the p-n junction before they recombine in the depletion region. Thus, recombination takes place in depletion region as well as in p-type and n-type semiconductor.
- The free electrons in the conduction band releases energy in the form of light before they recombine with holes in the valence band.

LED - Working

- The free electrons in the conduction band do not stay for long period.
- After a short period, the free electrons lose energy in the form of light and recombine with the holes in the valence band.
- Each recombination of charge carrier will emit some light energy.
- The energy lose of free electrons or the energy/frequency of emitted light is depends on the forbidden gap or energy gap between conduction band and valence band.

LED - Working



Process of light emission in LED

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

$$\lambda = \frac{1.24}{E_g}$$ In micro-meter

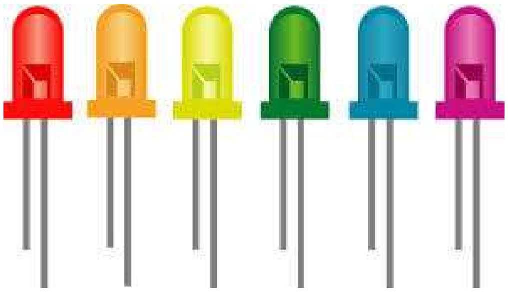
LED - Material

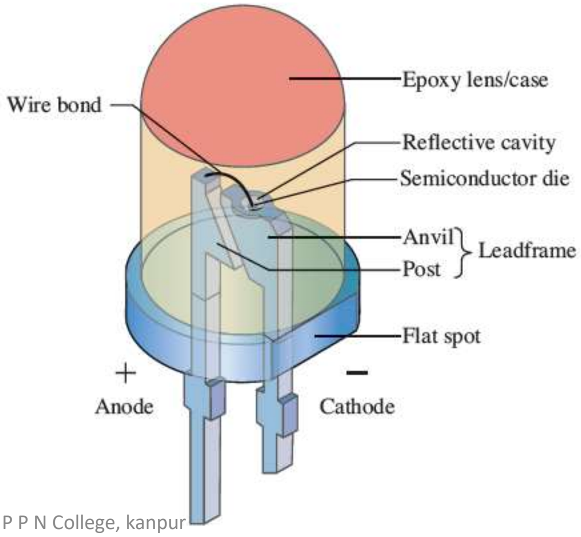
- In Si and Ge diodes, most of the energy is released in the form of heat and emitted light is too small.
- However, in materials like gallium arsenide (GaAs) and gallium phosphide (GaP) the emitted photons have sufficient energy to produce intense visible light.
- Now a days, Aluminum indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN) are two of the most commonly used semiconductors for LED technologies. They have replaced the older LED technologies which used gallium arsenide (GaAs), gallium phosphide (GaP), and aluminum gallium arsenide (AlGaAs).

LED - Colours

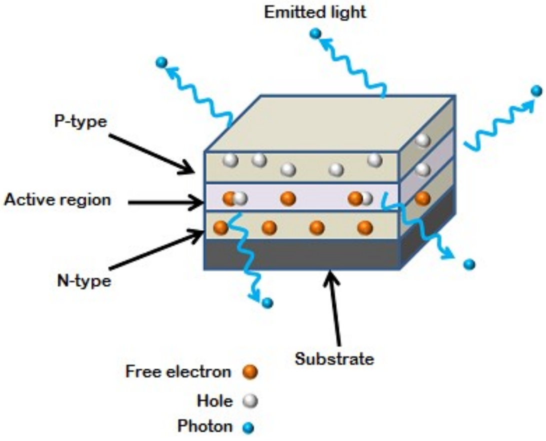
- Different materials emit different colors of light.
  - Gallium Arsenide LEDs emit red and infrared light.
  - Gallium Nitride LEDs emit bright blue light.
  - Yttrium Aluminium Garnet LEDs emit white light.
  - Gallium Phosphide LEDs emit red, yellow and green light.
  - Aluminium Gallium Nitride LEDs emit ultraviolet light.
  - Aluminum Gallium Phosphide LEDs emit green light.

LED - Construction





LED - Construction



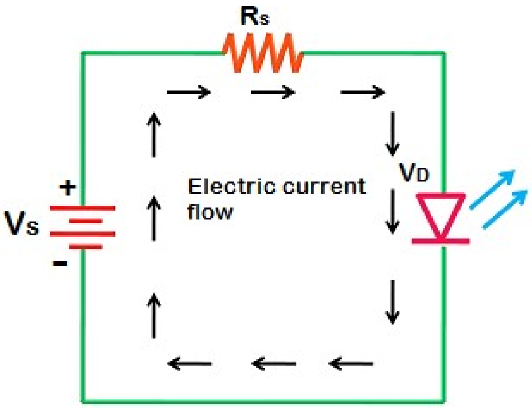
Construction of LED

LED - Construction

- Deposit three semiconductor layers on the substrate. The three semiconductor layers deposited on the substrate are n-type semiconductor, p-type semiconductor and active region.
- Active region is present in between the n-type and p-type semiconductor layers and is also called as depletion region.
- When LED is forward biased, free electrons from n-side and holes from p-side are pushed towards the active region.
- When they recombine with the opposite charge carriers (free electrons with holes or holes with free electrons) in active region, an invisible or visible light is emitted.

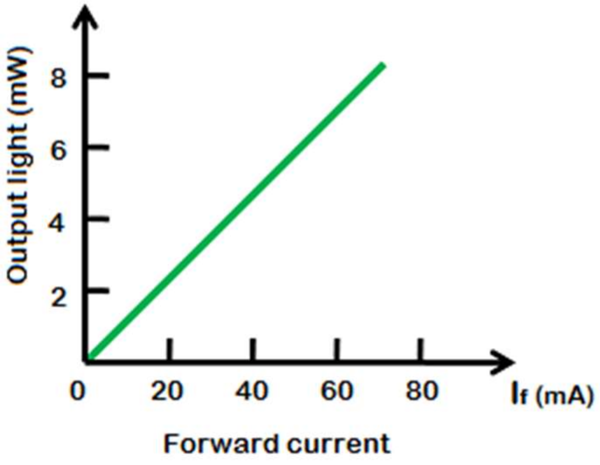
Biasing of LED

- The safe forward voltage ratings of most LEDs is from 1V to 3 V and forward current ratings is from 200 mA to 100 mA.
- The resistor placed between LED and voltage source is called current limiting resistor.
- This resistor restricts extra current which may destroy the LED. Thus, current limiting resistor protects LED from damage.



LED - Characteristics

- The amount of output light emitted by the LED is directly proportional to the amount of forward current flowing through the LED.
- More the forward current, the greater is the emitted output light.



Advantages of LED

- Light emitting diodes consume low energy.
- LEDs are very cheap and readily available.
- LEDs are light in weight and smaller in size.
- LEDs have longer lifetime.
- LEDs operates very fast. They can be turned on and off in very less time.
- LEDs do not contain toxic material like mercury which is used in fluorescent lamps.
- LEDs can emit different colors of light.

Applications of LED

- Burglar alarms systems
- Calculators
- Picture phones
- Traffic signals
- Digital computers
- Multimeters
- Microprocessors
- Digital watches
- Automotive heat lamps
- Camera flashes
- Aviation lighting

Photodiode

- A photodiode is a PN junction or PIN semiconductor device that consumes light energy to generate electric current.
- It is also sometimes referred as photo-detector, photo-sensor, or light detector.
- Photodiode is very sensitive to light so when light or photons falls on the photodiode it easily converts light into electric current.

Photodiode

- The **photodiode** is a kind of diode which operates in reverse biased mode. In this diode the reverse saturation current increase with the increase of incident light on it.
- If we can increase the number of minority carriers in the diode the reverse saturation current also increases.
- In the **photodiode**, we just increase the number of minority carriers by applying light energy at the junction.
- In photodiode the light needs to fall at the junction, to create higher reverse saturation current.

Photodiode

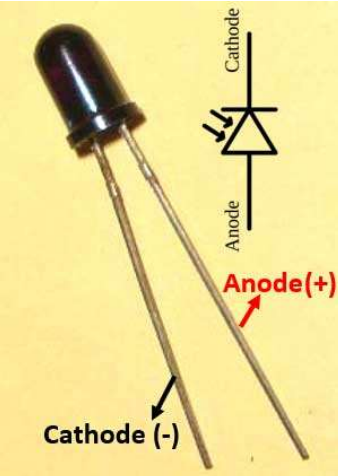
- The light photons transfer their energy to the electrons due to which some of the valence electrons in the crystal jump to the conduction band and create corresponding holes and free electrons.
- If the light falls on the semiconductor away from the junction, there will be electrons-hole pairs generated also get vanished due to recombination.
- The light falls on the junction and nearby the junction increase the reverse saturation current.

Photodiode

- The construction and working of photodiode is almost similar to the normal p-n junction diode.
- PIN (p-type, intrinsic and n-type) structure is mostly used for constructing the photodiode instead of PN (p-type and n-type) junction structure because PIN structure provide fast response time.
- PIN photodiodes are mostly used in high-speed applications.

Photodiode

- The different types of photodiodes are
  - PN junction photodiode
  - PIN photodiode
  - Avalanche photodiode
- Among all the three photodiodes, PN junction and PIN photodiodes are most widely used.

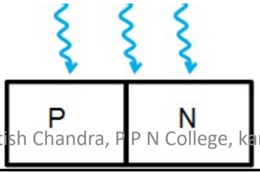


PN Junction Photodiode

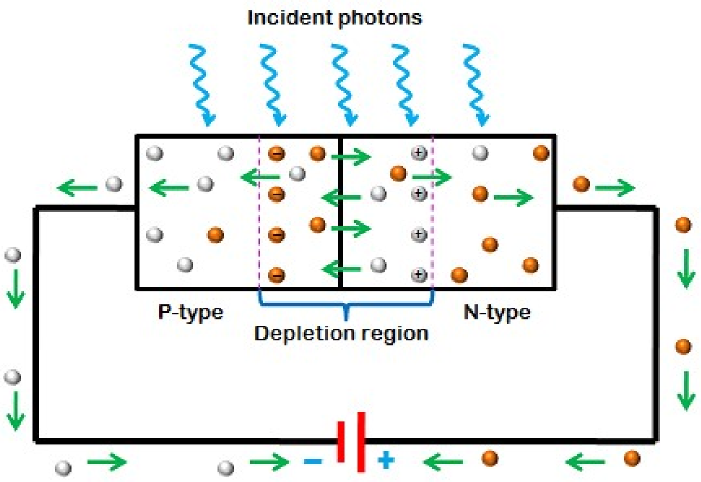
- When external light energy is supplied to the p-n junction photodiode, the valence electrons in the depletion region gains energy.
- If the light energy applied is greater then the band-gap of semiconductor material, the valence electrons break bonding with the parent atom and will become free electron.
- When the electron leave the valence shell, a hole is created in the shell. Thus, both free electrons and holes are generated as pairs.
- The mechanism of generating electron-hole pair by using light energy is known as the *inner photoelectric effect*.

PN Junction Photodiode

- The minority carriers in the depletion region experience force due to the depletion region electric field and the external electric field. As a result, free electrons move towards the *n*-region.
- When the free electrons reaches *n*-region, they are attracted towards the positive terminals of the battery.
- In the similar way, holes move in opposite direction.



PN Junction Photodiode



PN Junction photodiode

PN Junction Photodiode

- When no light is applied to the reverse bias photodiode, it carries a small reverse current due to external voltage.
- This small electric current under the absence of light is called dark current. It is denoted by I_d.
- The reverse current is independent of reverse bias voltage. Reverse current is mostly depends on the light intensity.
- The electric current generated in the photodiode due to the application of light is called photo-current, I_p.

PN Junction Photodiode

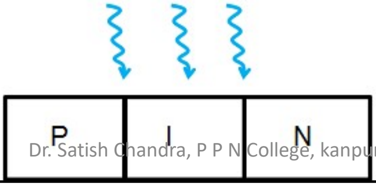
- The total current through the photodiode is the sum of the dark current and the photo-current. The dark current must be reduced to increase the sensitivity of the device.
- The electric current flowing through a photodiode is directly proportional to the incident number of photons.

$$I = I_p + I_d$$

$$I = I_p + I_0\left(1 - e^{\frac{eV}{\eta kT}}\right)$$

PIN Photodiode

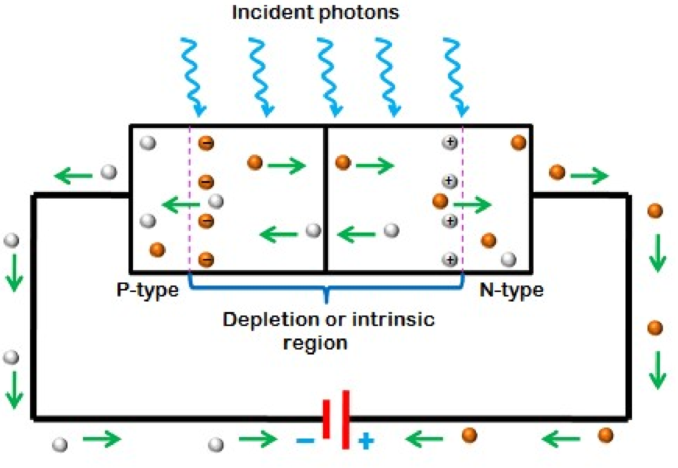
- A PN junction photodiode is made of two layers namely *p*-type and *n*-type semiconductor whereas PIN photodiode is made of three layers namely *p*-type, *n*-type and intrinsic semiconductor.
- In PIN photodiode, an addition layer called intrinsic semiconductor is placed between the *p*-type and *n*-type semiconductor to increase the minority carrier current.



PIN Photodiode

- When light or photon energy is applied to the PIN diode, most part of the energy is observed by the intrinsic or depletion region because of the wide depletion width. As a result, a large number of electron-hole pairs are generated.
- Free electrons generated in the intrinsic region move towards *n*-side whereas holes move towards *p*-side. The free electrons and holes moved from one to another region carry electric current.
- When electrons and holes reach *n* region and *p* region, they are attracted towards the positive and negative terminal of the battery.

PIN Photodiode



PIN photodiode

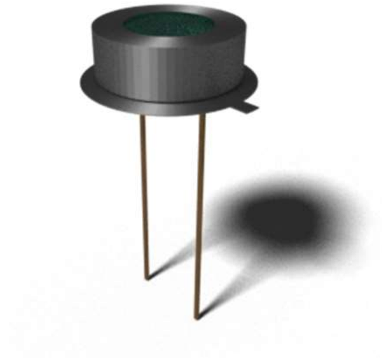
PIN Photodiode

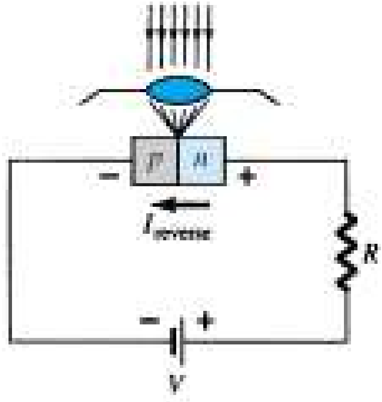
- The population of minority carriers in PIN photodiode is very large compared to the PN junction photodiode. Therefore, PIN photodiode carry large minority carrier current than PN junction photodiode.
- When forward bias voltage is applied to the PIN photodiode, it behaves like a resistor.
- The separation distance between p region and n region in PIN photodiode is very large because of the wide depletion width. Therefore, PIN photodiode has low capacitance compared to the PN junction photodiode.

Construction of Photodiode

- The photodiodes are available in a metallic package. The diode is a *pn* junction, mounted in an insulated plastic substrate. The plastic substrate is then seal in the metal case.
- On the top of the metal case, there is a transparent window, which allows light to entire up to the PN Junction.
- Two leads, anode and cathode of the diode come out from the bottom of the metal case.
- A tab extending from the side of the bottom portion of the metal case identifies the cathode lead.

Construction of Photodiode

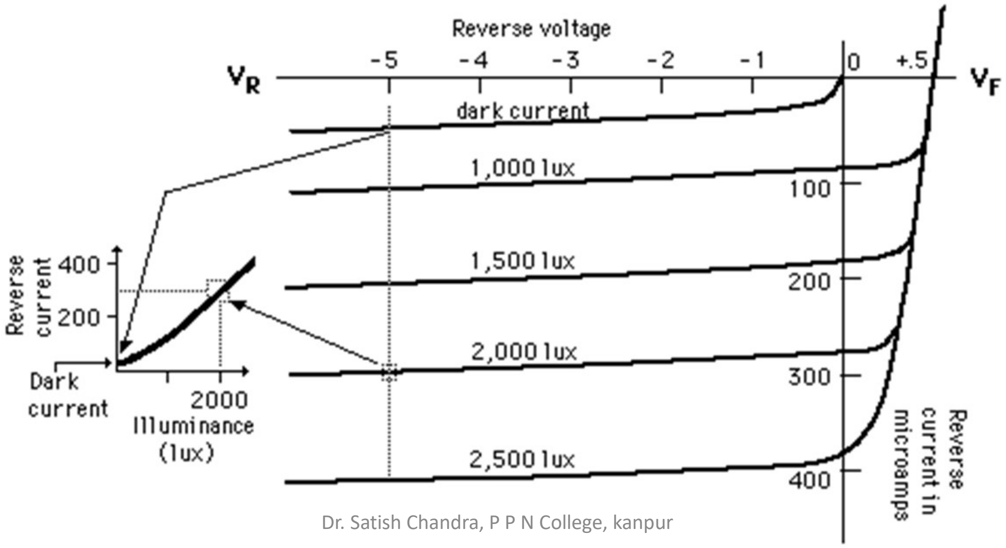




Construction of Photodiode

- The different materials used to construct photodiodes are Silicon (Si), Germanium, (Ge), Gallium Phosphide (GaP), Indium Gallium Arsenide (InGaAs), Indium Arsenide Antimonide (InAsSb), Mercury Cadmium Telluride (MCT, HgCdTe).
- Germanium, Indium Arsenide Antimonide, Indium Gallium Arsenide and Mercury Cadmium Telluride generates large dark current because they are very sensitive to temperature.
- The response speed of Silicon, Gallium Phosphide, Indium Gallium Arsenide and Indium Gallium Arsenide is very high.

Characteristic of Photodiode



Characteristic of Photodiode

- A photo diode is always operated in reverse bias mode.
- From the photo diode characteristics it is seen clearly that the photo current is almost independent of applied reverse bias voltage.
- For zero luminance the photo current is almost zero except for small dark current. It is of the order of nano amperes.
- As optical power increases the photo current also increases linearly. The maximum photo current is limited by the power dissipation of the photo diode.

Applications of Photodiode

- Photo diodes are used as photo detectors.
- Photo diodes are used in providing electric isolation using a special circuitry called as Opto-couplers.
- They are used in consumer electronics.
- They are used in cameras as photo sensors, Slotted optical switch, in scintillators *etc.*

Solar Cell

- A solar 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.
- Solar cells operate on the principle of **photovoltaic effect**.
- The photovoltaic effect refers to their voltage-generating capability.
- Since these cells generate a voltage proportional to sunlight intensity, the solar cells are also called **photovoltaic cells** or PV cell.

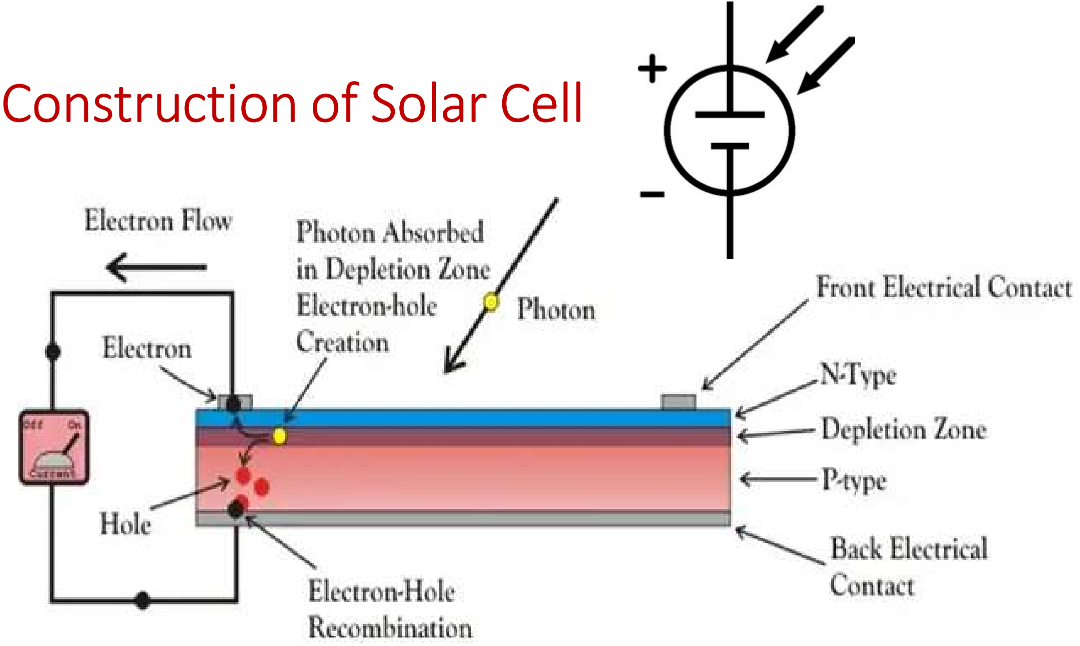
Solar Cell

- The solar cell is essentially a large **photodiode** to operate as a photovoltaic device and to give as much output power as possible.
- Semiconductor materials like silicon, gallium arsenide (GaAs), indium arsenide (InAs), and cadmium arsenide (CdAs) are used for manufacturing solar cells.
- Silicon and selenium are the most widely used materials.
- The solar cell can convert energy directly into electrical energy with high conversion efficiency and can provide nearly permanent power at a low operating cost and also free of pollution.
- The maximum theoretical efficiency of a solar cell depends on the bandgap of the semiconductor material.

Construction of Solar Cell

- A solar cell is basically a junction diode. 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.

Construction of Solar Cell



Working Principal 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.

Working Principal of Solar Cell

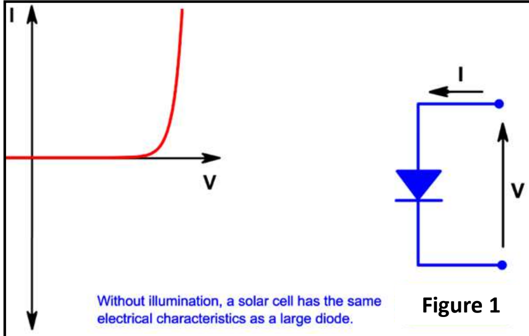
- Once, the newly created free electrons come to the n-type side, cannot further cross the junction because of barrier potential of the junction.
- Similarly, the newly created holes once come to the p-type side cannot further cross the junction became of same barrier potential of the junction.
- As 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 Solar Cell

- The V-I curve of a solar cell is the superposition of the V-I curve of the solar cell diode in the dark with the light-generated current.
- The light has the effect of shifting the V-I curve down into the fourth quadrant where power can be extracted from the diode.
- Illuminating a cell adds to the normal **dark** currents in the diode so that the diode law becomes:

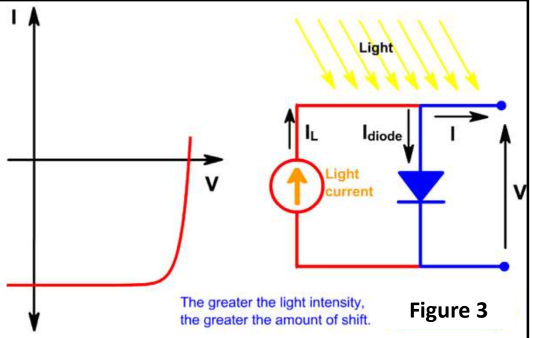
$$I = I_0\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right] - I_L$$

- where I_L = light generated current.



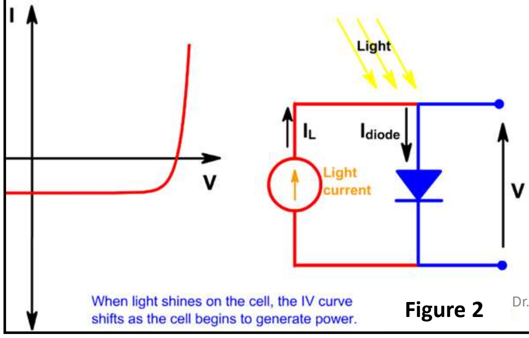
Without illumination, a solar cell has the same electrical characteristics as a large diode.

Figure 1



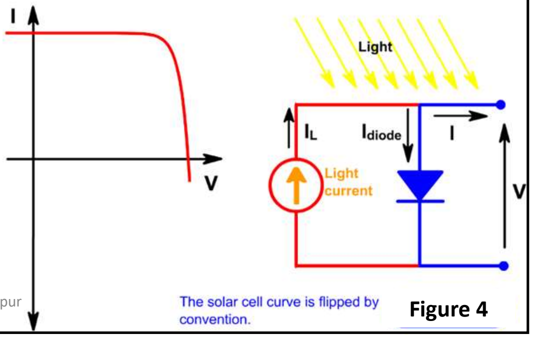
The greater the light intensity, the greater the amount of shift.

Figure 3



When light shines on the cell, the IV curve shifts as the cell begins to generate power.

Figure 2



The solar cell curve is flipped by convention.

Figure 4

V-I Characteristics of a Solar Cell

- The equation for the V-I curve in the first quadrant is:

$$I = I_L - I_0\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$$

- The -1 term in the above equation can usually be neglected. The exponential term is usually >> 1 except for voltages below 100 mV.
- Further, at low voltages, the light generated current I_L dominates the $I_0\left[\exp\left(\frac{eV}{\eta kT}\right) - 1\right]$ term so the -1 term is not needed under illumination.

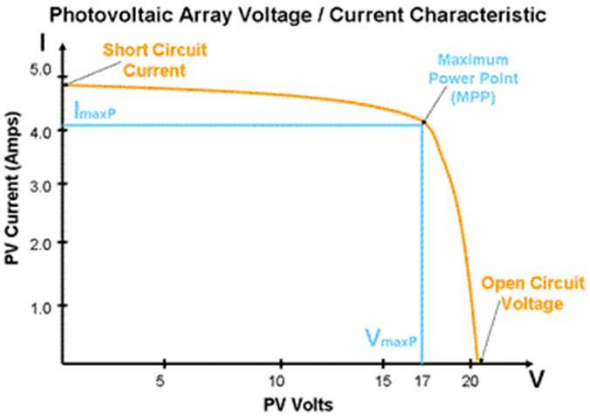
$$I = I_L - I_0\exp\left(\frac{eV}{\eta kT}\right)$$

V-I Characteristics of a Solar Cell

- Plotting the above equation gives the V-I curve.
- Rearranging the equation gives the voltage in terms of current.

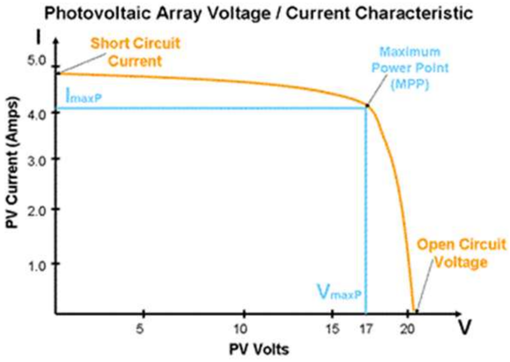
$$V = \frac{\eta k T}{e} \ln\left(\frac{I_L - I}{I_0}\right)$$

- The short-circuit current, open-circuit voltage, fill factor and the efficiency are the parameters that can be determined from the V-I curve.



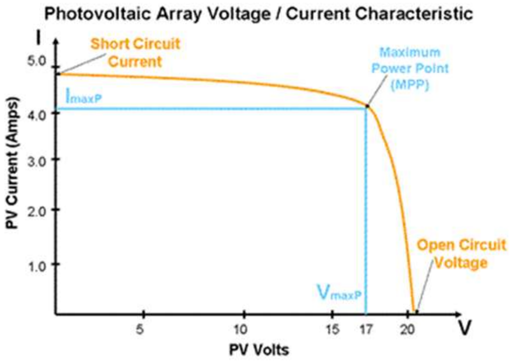
Open-Circuit Voltage - V_{OC}

- This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition).
- This value is much higher than V_{maxP} which relates to the operation of the PV array which is fixed by the load.
- This value depends upon the number of PV panels connected together in series.



Short-Circuit Current - I_{SC}

- The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition).
- This value is much higher than I_{maxP} which relates to the normal operating circuit current.

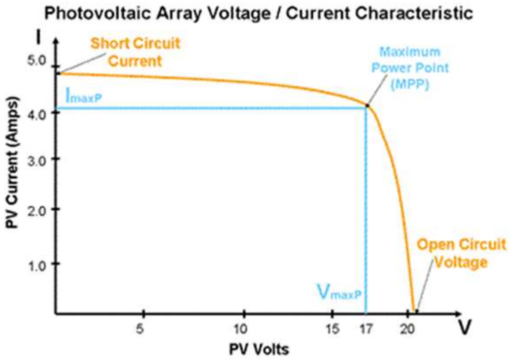


Maximum Power Point - MPP

- This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where

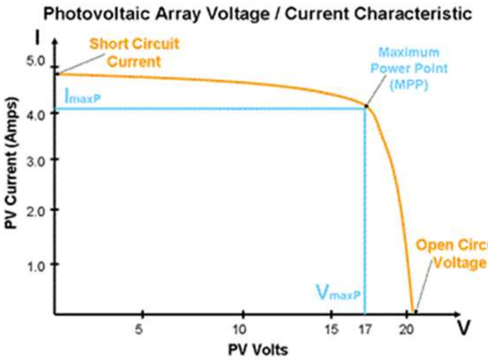
$$MPP = I_{maxP} \times V_{maxP}$$

- The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (W_p).



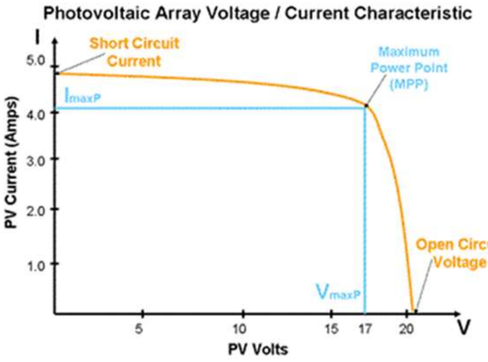
Fill Factor - FF

- The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions.
- It is the product of the open-circuit voltage multiplied by the short-circuit current, ($V_{OC} \times I_{SC}$).
- This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide.
- Typical values are between 0.7 to 0.8.



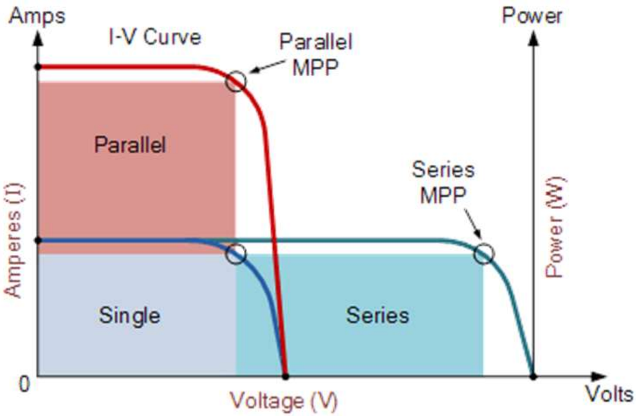
Percent Efficiency - %Eff

- The efficiency of a photovoltaic array is the ratio between the maximum electrical power that the array can produce compared to the amount of solar irradiance hitting the array.
- The efficiency of a typical solar array is normally low at around 10 - 12%, depending on the photovoltaic type (monocrystalline, polycrystalline, amorphous or thin film) of cell being used.



Solar Cell Array

- Photovoltaic panels can be wired or connected together in either series or parallel combinations, or both to increase the voltage or current capacity of the solar array.
- If the array panels are connected together in a series combination, then the voltage increases and if connected together in parallel then the current increases.

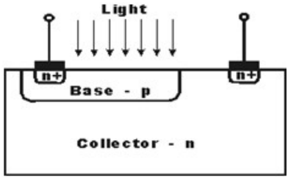


Phototransistor

- A **Phototransistor** is an electronic switching and current amplification component which relies on exposure to light to operate.
- When light falls on the junction, reverse current flows which is proportional to the luminance.
- Phototransistors are used extensively to detect light pulses and convert them into digital electrical signals.
- These are operated by light rather than electric current.
- Providing large amount of gain, low cost and these phototransistors might be used in numerous applications.

Phototransistor

- **Phototransistors** are transistors with the base terminal exposed to light. Instead of sending current into the base, the photons from striking light activate the transistor.
- This is because a phototransistor is made of a bipolar semiconductor and focuses the energy that is passed through it.
- The structure of the **phototransistor** is specifically optimized for photo applications. These devices can be either homojunction structured or heterojunction structured
- Compared to a normal transistor, a photo transistor has a larger base and collector width and is made using diffusion



Phototransistor

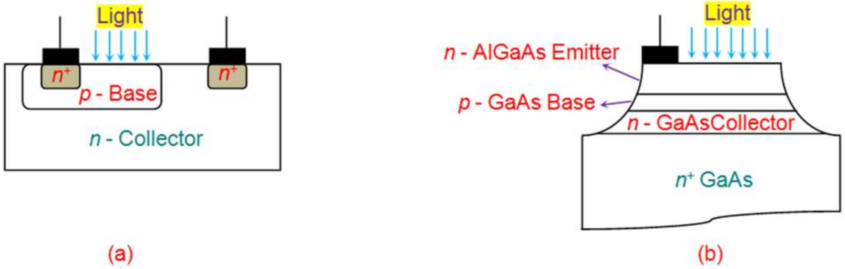


Figure 1 Phototransistor (a) Homojunction Structure (b) Heterojunction Structure

(a) (b)

Figure 1 *npn* Phototransistor Symbol with (a) Three Leads (b) Two Leads

Phototransistor

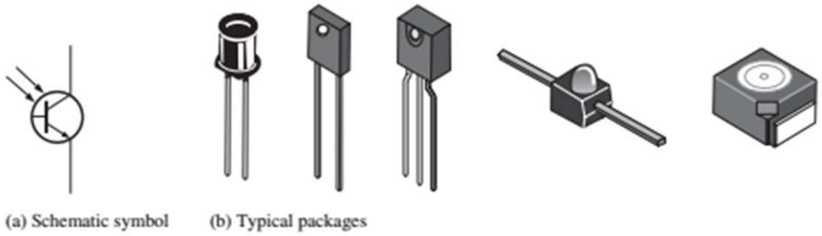
- In a Photo-transistor the base current is produced when light strikes the photosensitive semiconductor base region.
- The collector-base *pn* junction is exposed to incident light through a lens opening in the transistor package.
- When there is no incident light, there is only a small thermally generated collector-to-emitter leakage current, I_{CEO} .
- This **dark current**, I_λ, is produced that is directly proportional to the light intensity.
- This action produces a collector current that increases with I_λ.
- Except for the way base current is generated, the phototransistor behaves as a conventional BJT. In many cases, there is no electrical connection to the base.

Phototransistor

- The relationship between the collector current and the light-generated base current in a phototransistor is:

$$I_C = \beta_{DC} I_\lambda$$

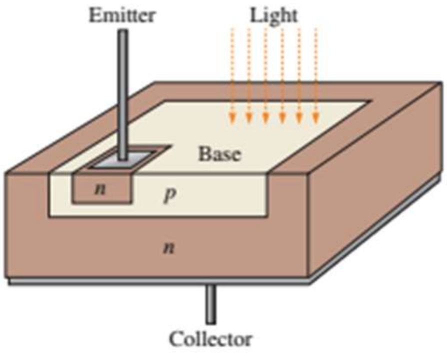
- The schematic symbol and some typical photo-transistors are shown.



(a) Schematic symbol (b) Typical packages

Phototransistor

- Since the actual photo-generation of base current occurs in the collector-base region, the larger the physical area of this region, the more base current is generated.
- Thus, a typical photo-transistor is designed to offer a large area to the incident light



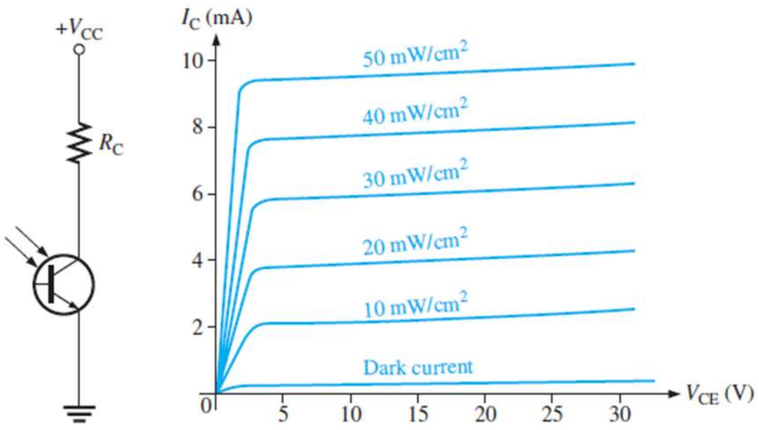
Phototransistor

- Phototransistors are either tri-terminal (emitter, base and collector) or bi-terminal (emitter and collector) semiconductor devices which have a light-sensitive base region.
- In the three-lead configuration, the base lead is brought out so that the device can be used as a conventional BJT with or without the additional light-sensitivity feature.
- In the two-lead configuration, the base is not electrically available, and the device can be used only with light as the input.
- In many applications, the phototransistor is used in the two-lead version.

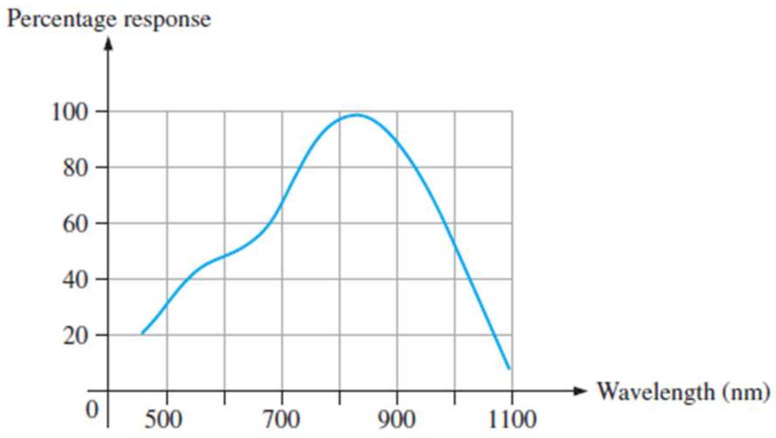
Phototransistor

- A phototransistor with a biasing circuit and typical **collector characteristic** curves.
- Each curve on the graph corresponds to a certain value of light intensity and that the collector current increases with light intensity.
- Phototransistors are not sensitive to all light but only to light within a certain range of wavelengths.
- They are most sensitive to particular wavelengths in the red and infrared part of the spectrum, as shown by the peak of the infrared **spectral response curve**.

Collector Characteristic



Spectral Response Curve



Applications of Phototransistor

- Object detection
- Encoder sensing
- Automatic electric control systems such as in light detectors
- Security systems
- Punch-card readers
- Relays
- Computer logic circuitry
- Counting systems
- Smoke detectors
- Laser-ranging finding devices

Applications of Phototransistor

- Optical remote controls
- CD players
- Astronomy
- Night vision systems
- Infrared receivers
- Printers and copiers
- Cameras as shutter controllers
- Level comparators

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END