Applied Physics

Unit 3: Optoelectronics

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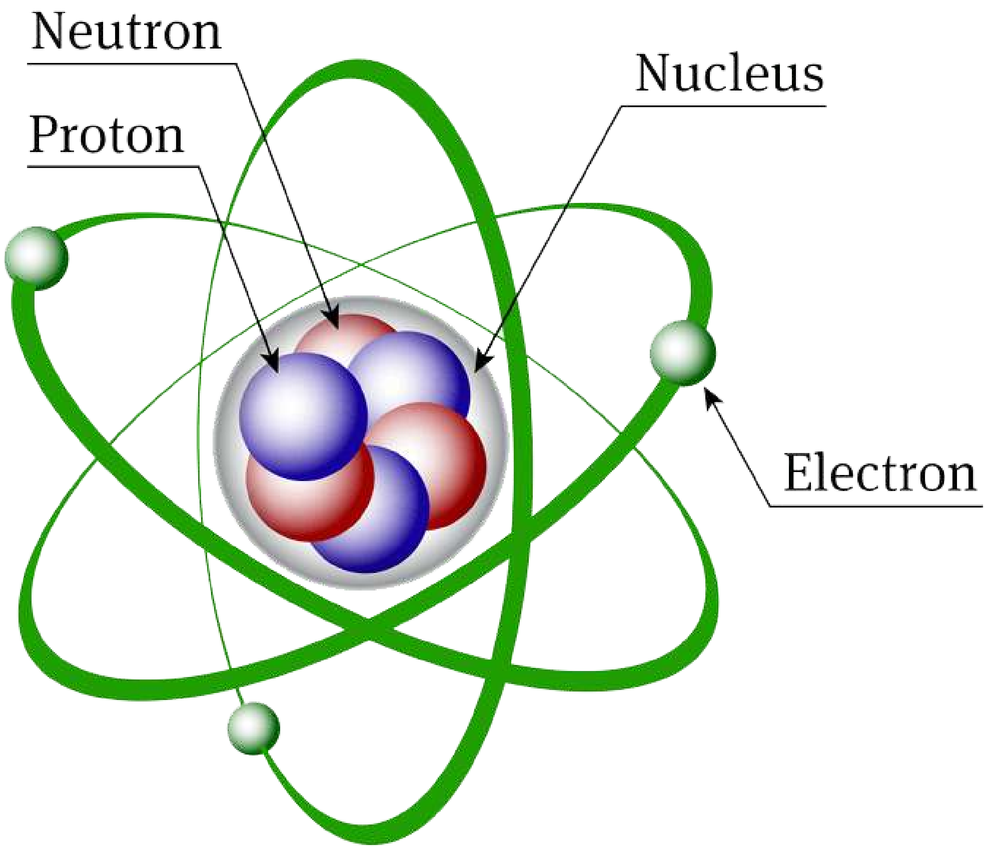
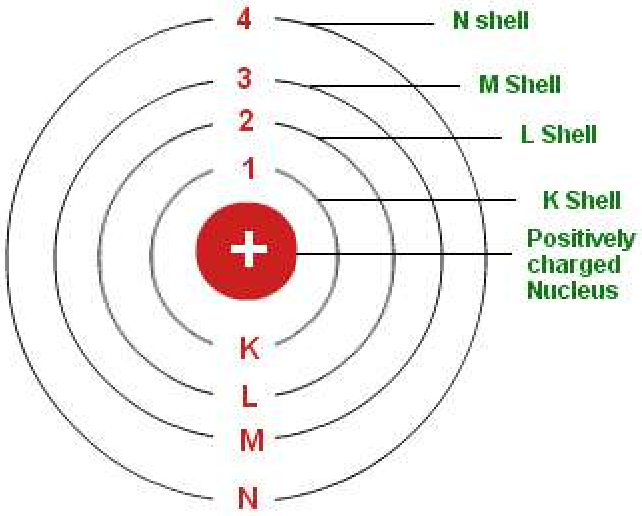
Unit 3: Optoelectronic Devices

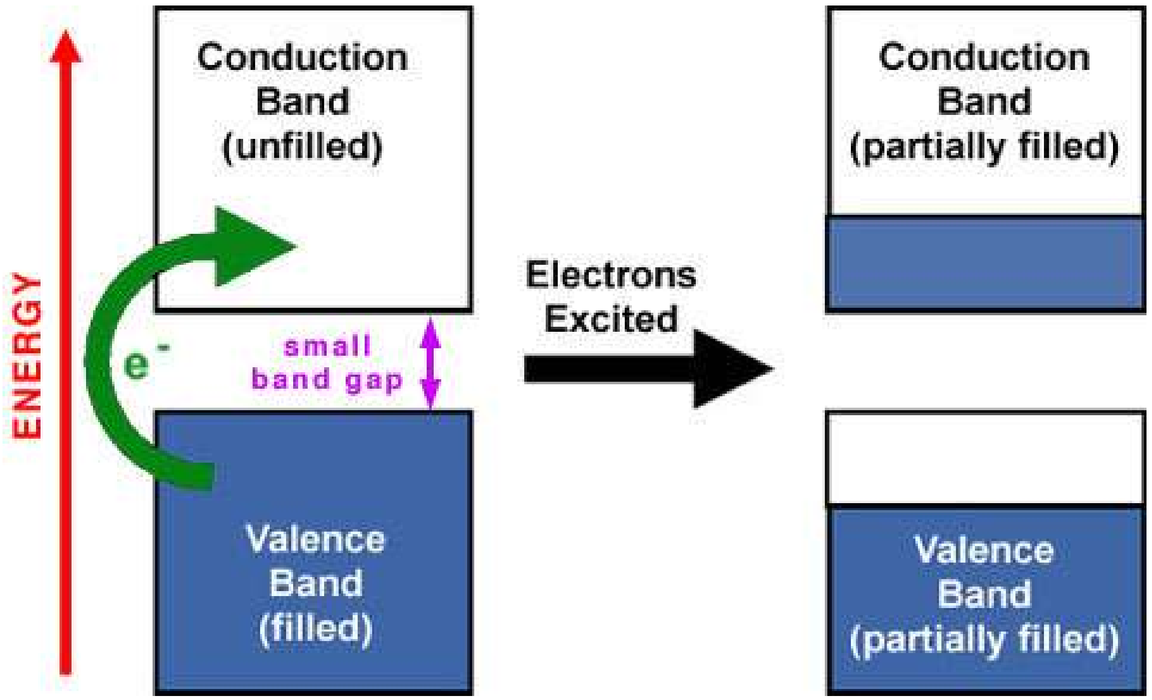
Radiative transitions: Absorption, Spontaneous and Stimulated emissions, Non-radiative transitions: Auger recombination, Surface recombination and recombination at defects, Generation and recombination mechanism in semiconductors, Principle, Construction, Working, Characteristics and Applications: LED, PIN photo detector, Avalanche photo detector and Solar cell.

Atomic Structure





Valence band and conduction band



Generation and Recombination

- When one electron leaving the energy level creates a hole, the process is called electron-hole pair generation. Similarly, when an electron from conduction band recombines with a hole in the valence band, the process is called recombination.
- Generation and recombination of electron - hole pair essentially require external energies such as optical, electrical or thermal energies. Such processes are mainly between the valence band and the conduction band.

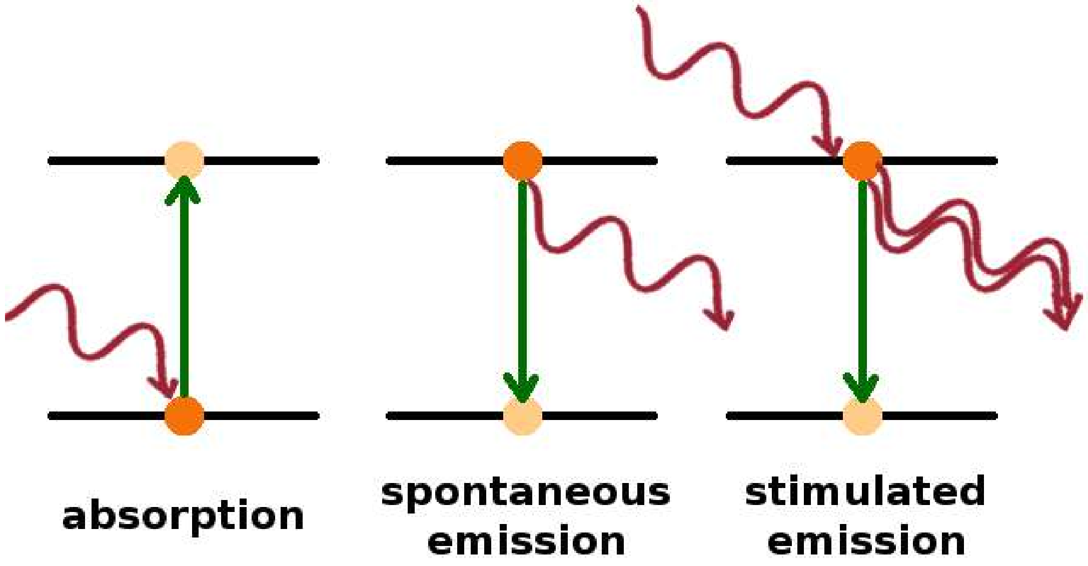
Radiative and Non radiative recombination

- **Radiative recombination** occurs when an electron in conduction band recombines with a hole in the valence band and the excess energy is given out as photon.
- Optical process associated with radiative recombination are: Absorption, Spontaneous emission and Stimulated emission.

- **Non - Radiative recombination** occurs when an electron in conduction band recombines with a hole in the valence band and the excess energy is given out as heat.
- Non-Radiative recombination process involves: Augur recombination, Surface recombination and recombination at defects.

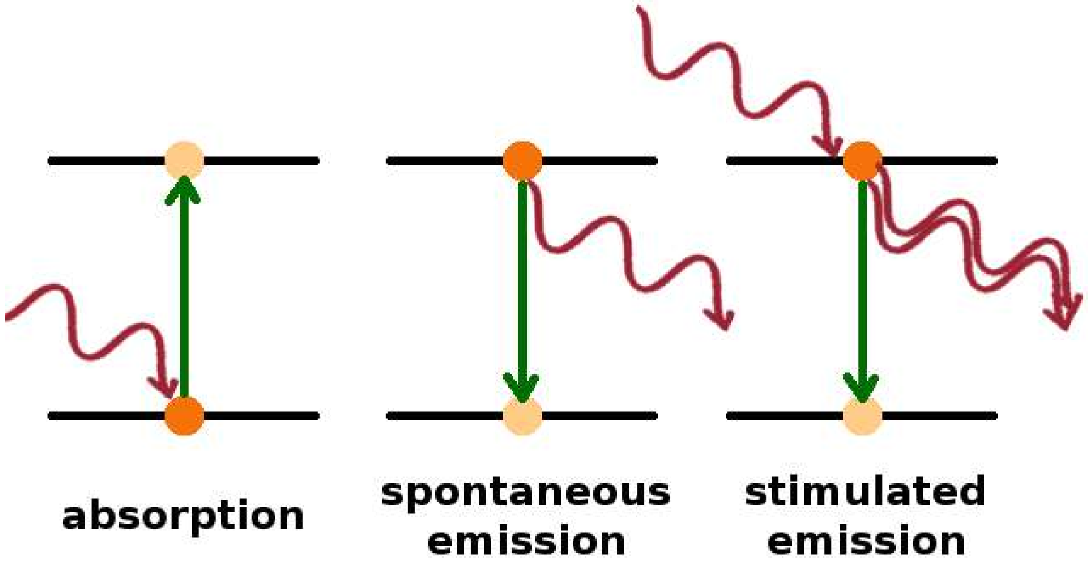
Radiative recombination

- **Absorption:** When an atom absorbs an amount of energy ‘hv’ in the form of photon from the external agency and is excited into the higher energy levels from ground state, then this process is known as absorption.
- **Spontaneous Emission:** When an atom in the excited state emits a photon of energy ‘hv’ coming down to ground state by itself without any external agency, such an emission is called spontaneous emission.
- Photons released in spontaneous emission are not coherent.



Radiative recombination

- **Stimulated Emission:** When an atom in the excited state, comes down to ground state with the influence of an external agency(energy), such an emission is called stimulated emission. Two photons of same energy 'hν' are emitted.
- In the two photons one photon induces the stimulated emission and the second one is released by the transition of atom from higher energy level to lower energy level.
- Both the photons are coherent.



Non Radiative transitions

- **Non - Radiative recombination** occurs when an electron in conduction band recombines with a hole in the valence band and the excess energy is given out as heat.
- Non-Radiative recombination process involves: Augur recombination, Surface recombination, recombination at defects.

Augur recombination

- Augur recombination is of 2 types:

1. One electron from conduction band recombines with a hole in valence band and releases energy. This energy may be taken by another electron in conduction band. The electron that gained energy jumps to higher state and then comes back to the valence band by giving out its energy.

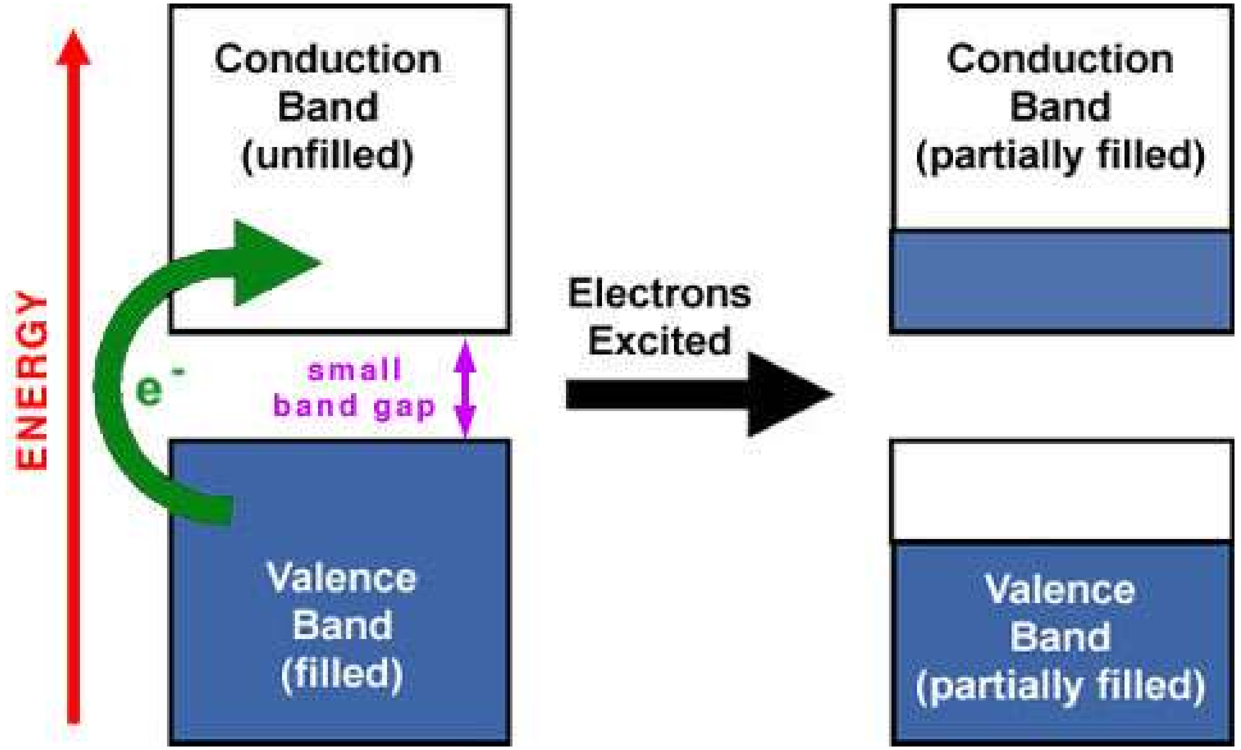
2. One electron from conduction band recombines with a hole in valence band and releases energy. This energy may knock out a electron and create a hole.

Both the processes are non-radiative.

Surface recombination

- Recombination at surfaces and interfaces can have a significant impact on the behavior of semiconductor devices. This is because surfaces and interfaces typically contain a large number of recombination centers because of the abrupt termination of the semiconductor crystal, which leaves a large number of electrically active states. In addition, the surfaces and interfaces are more likely to contain impurities since they are exposed during the device fabrication process.

Non Radiative transitions



Generation and Recombination

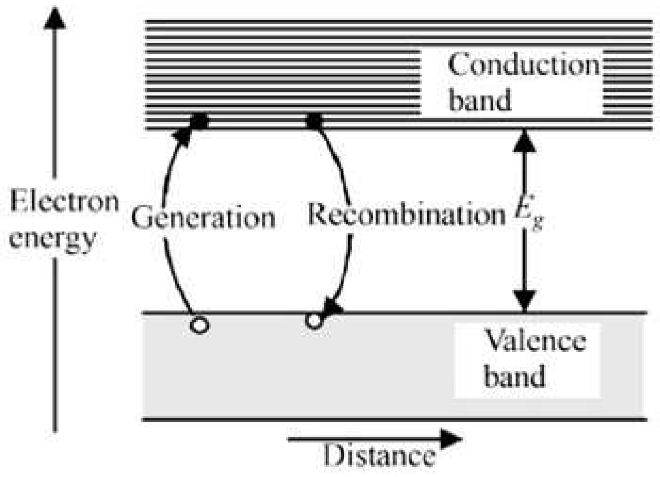
- When sufficient energy in the form of thermal energy or optical illumination is given to the semiconducting material, covalent bonds are broken and a pair of electron and hole is generated.
- The electrons are raised from valence band to conduction band. Holes remain in the valence band.
- The process of generation can occur only when the energy given to the semiconducting material is greater than its forbidden energy gap.
- The electrons move in the conduction band and holes in the valence band. Their motion is a random motion.
- The number of electrons is equal to the number of holes.

Generation and Recombination

- When an electron in the conduction band collides with other particles, it looses energy and falls to the valence band. In the valence band the electron combines with a hole and in the process energy is released.
- Recombination is the process where an electron from the conduction band recombines with a hole in the valence band. This is called band to band recombination and in the process a photon is released.

Generation and Recombination

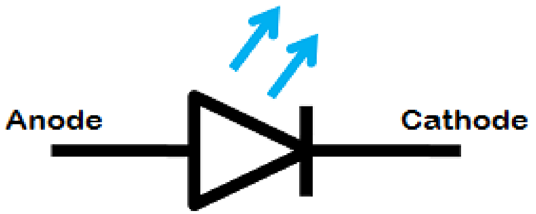
- At a steady temperature a dynamic equilibrium exists which balances the two processes of electron-hole pair generation and electron-hole recombination.



Generation and recombination of electron-hole pairs

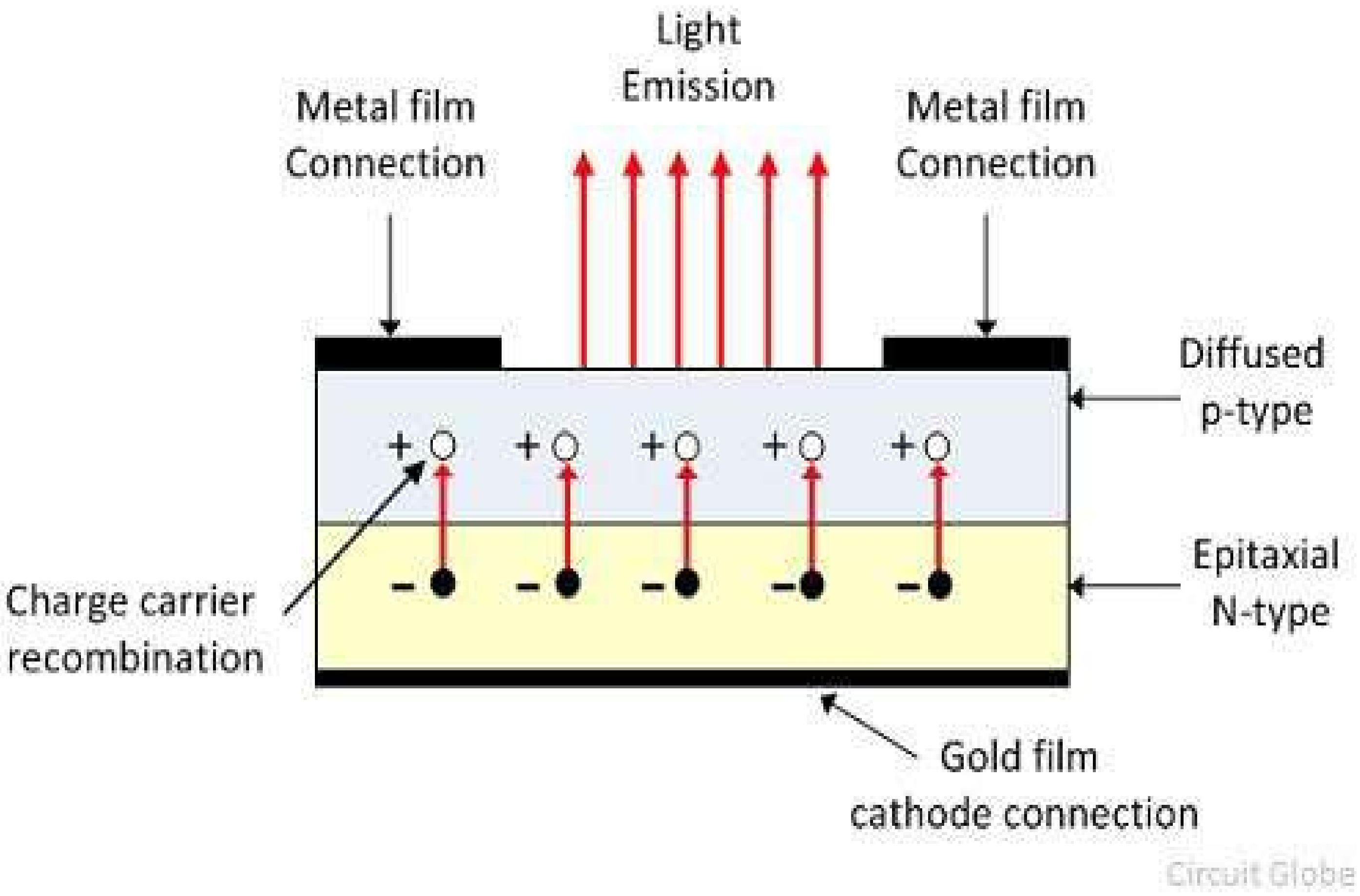
LED: Light emitting diode

- **Principle:** A Light emitting diode (LED) is essentially a p-n junction diode that gives off light when it is forward biased.
- The amount of light emitted is directly proportional to the forward current.
- The wavelength of the light emitted, and hence the color, depends on the band gap energy of the materials forming the p-n junction.
- $h\nu = E_g$
- $hc/\lambda = E_g$
- $\lambda = hc/ E_g$

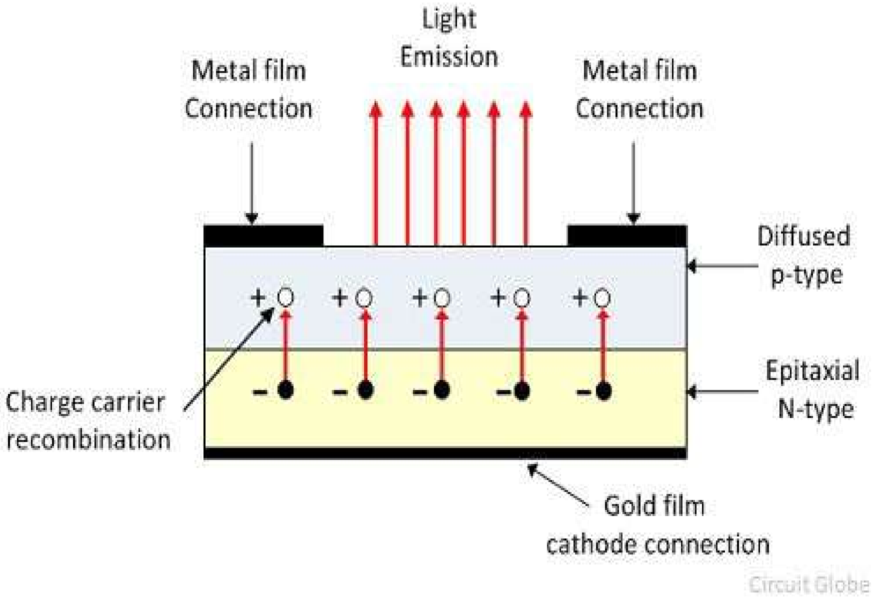


LED symbol

LED: Light emitting diode

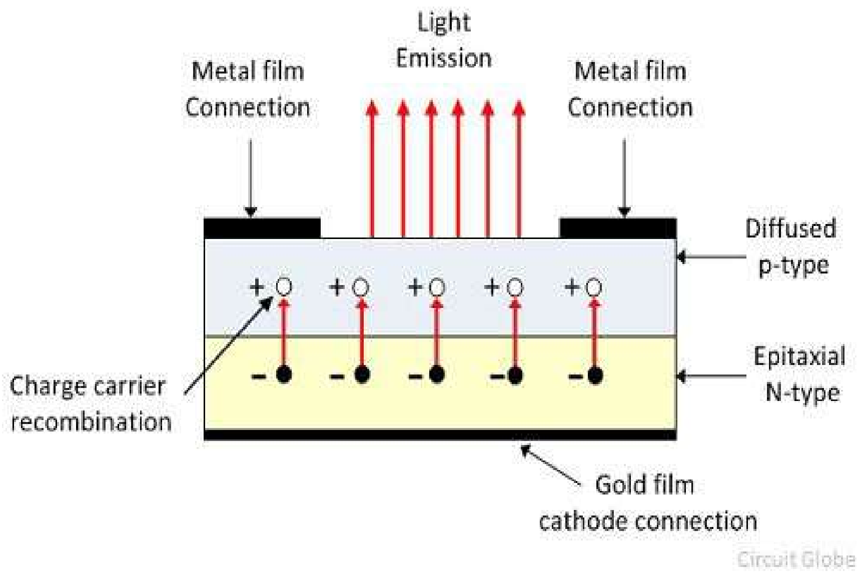


LED: Light emitting diode



- In a surface emitting LED light is emitted in a direction perpendicular to the p-n junction plane.
- An n-type layer is grown on a substrate and a p-type layer is grown on it by the process of diffusion.
- The p-layer is made very thin to prevent loss of photons due to absorption in the layer. Metal contact is present on the p-layer such that some part of p-layer will allow photons to escape.

LED: Light emitting diode



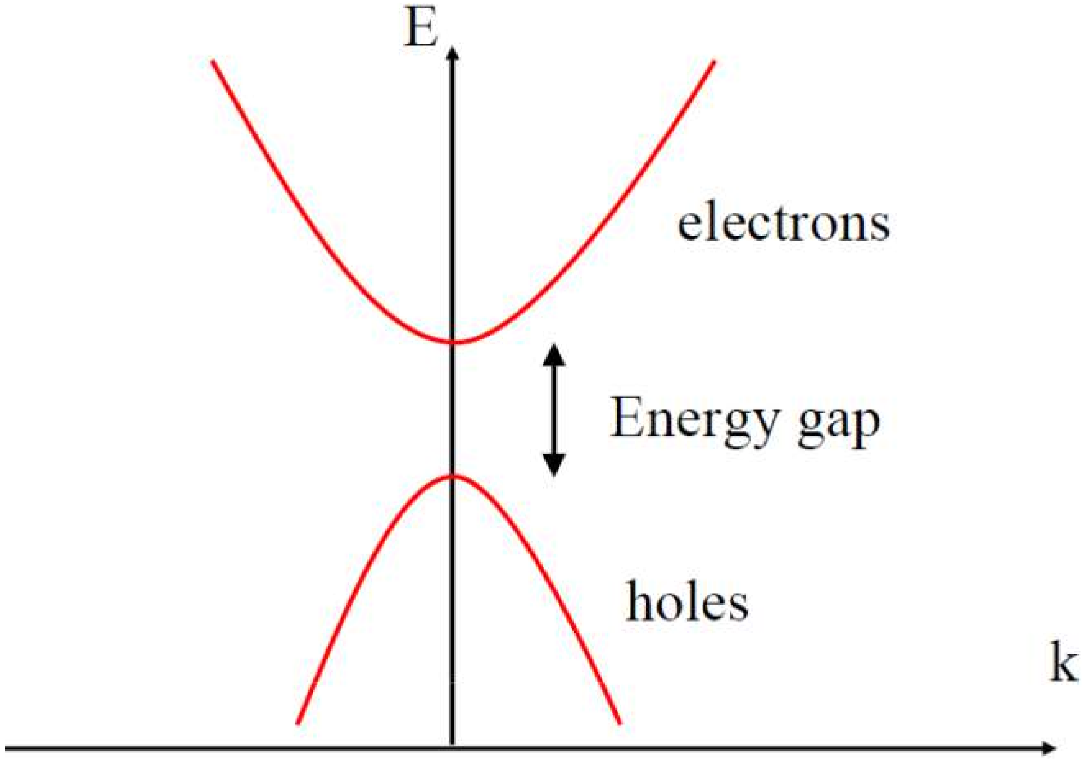
- Metal contact is present at the bottom for reflecting the photons into the material and to provide electrical contact.
- The generated light may suffer total internal reflection at the semiconductor-air interface and hence the device is enclosed in a epoxy resin of suitable refractive index so that the photons escape.

LED: Light emitting diode

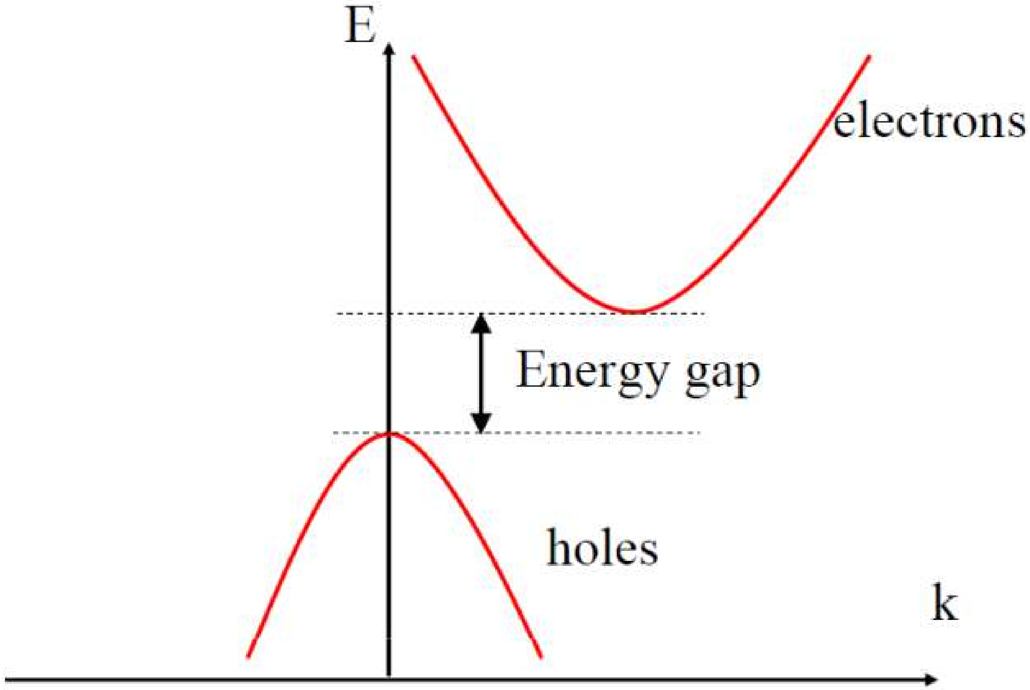
Working:

- The p-n junction is forward biased.
- Electrons from n side get injected to p side.
- Hole injection from p side to n side is very less(p side is thin)
- Electrons injected into the p-side recombine with the holes which results in spontaneous emission of photons (light). This effect is called injection electroluminescence. These photons should be allowed to escape from the device without being reabsorbed.
- The recombination can be classified into the following two kinds
- Direct recombination
- Indirect recombination

LED: Light emitting diode



Direct bandgap semiconductors



Indirect bandgap semiconductors

LED: Light emitting diode

Direct band gap semiconductor

- In direct band gap materials, the minimum energy of the conduction band occurs at the same value of momentum vector(K) as the maximum energy of the valence band.
- The efficiency of transition is good.
- GaAs is an example of a direct band-gap material

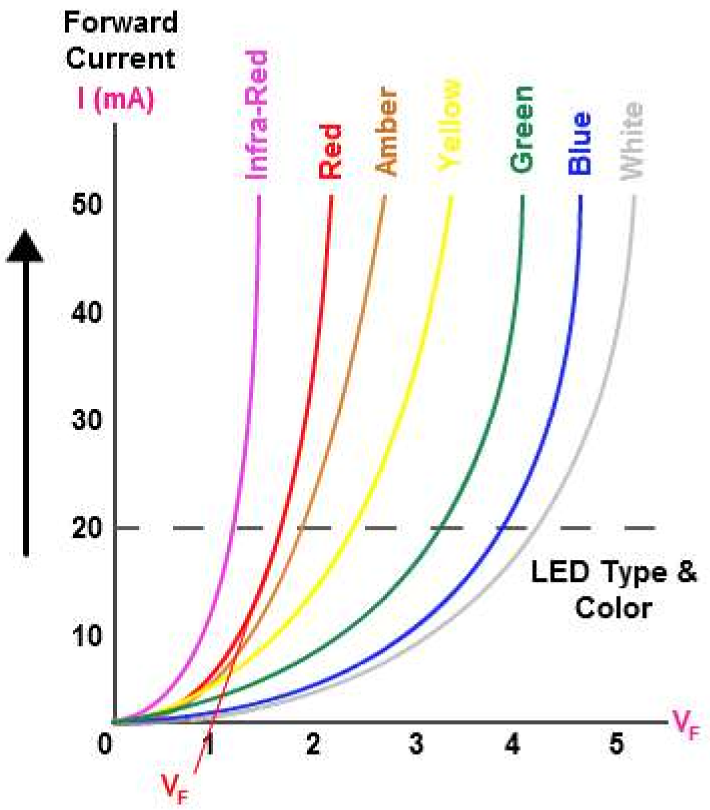
Indirect band gap semiconductor

- In in-direct band gap materials, the minimum energy of the conduction band and maximum energy of valence band occur at different values of momentum vector(K).
- Due to this difference in momentum, the probability of direct electron-hole recombination is less.
- GaP is an example of an indirect band-gap material

Characteristics of LED

One of the major characteristics of an LED is its colour.

- Gallium Arsenide, GaAs emits light in infrared region.
- Gallium Arsenide-Phosphide, GaAsP emits red or yellow colour.
- Gallium Phosphide, GaP emits red or green colour



LED: Light emitting diode - Applications

- As indicators and light source in fiber optics communication.
- A number of LED'S may be grouped together to form a display

Internal photoelectric effect

- When light is incident on an intrinsic semiconductor, electrons are excited from valence band to conduction band and this leads to generation of electron and hole. Thus an increase of charge carrier concentration occurs within the semiconductor and the effect is called internal photoelectric effect.

Photoconductive effect

- **Photoconductive effect:** An increase in free charge carriers leads to an increase in the conductivity of the semiconductor. The light induced increase in the electrical conductivity is called photoconductive effect or photoconductivity.

Photo detectors

- These are devices that absorb optical energy and convert it to electrical energy. The operation of photoelectric detectors is based on internal photoelectric effect.
- It is a p-n junction diode which is reverse biased.
- When a photon is incident on the junction, a electron - hole pair may be generated in the depletion region. The electric field due to the immobile ions in the depletion region will separate the electron and holes that are generated.

Photo detectors

- The charge separation in Photo detectors may be used in two ways:

1. Photoconductive mode and 2. Photovoltaic mode.

Photoconductive mode:

The device which is reversed biased is left on short circuit externally. The diode is reversed biased and dark currents flow(current due to minority charge carriers). The reverse voltage application will increase the depletion layer's width.

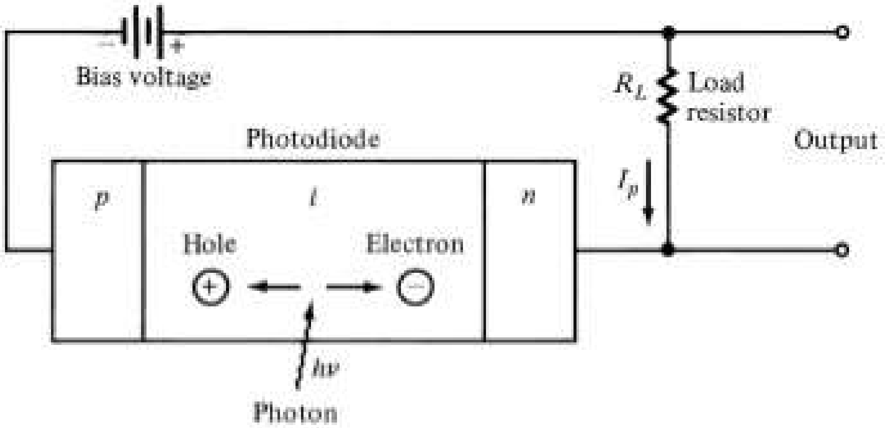
Photovoltaic mode:

If the diode is left on open-circuit, an externally measurable voltage appears between p and n regions. The diode is not biased and hence dark current does not flow. This mode of operation is used in solar cells.

Photo detectors are of two types: PIN and Avalanche detector.

PIN Photodetector

PIN PHOTODETECTOR



The high electric field present in the depletion region causes photo-generated carriers to separate and be collected across the reverse -biased junction. This give rise to a current flow in an external circuit, known as photocurrent.

PIN Photodetector

- It is a device that consists of p region and n region separated by a very lightly doped intrinsic region (i).
- The entire intrinsic region acts as depletion region.
- The p-i-n structure of the photodiode enables to increase the width of the depletion region to a value which is greater than a p-n junction.
- The p-i-n photodiode is reverse biased.
- When a photon having energy greater than or equal to band gap energy is incident on the depletion region, then electron-hole pairs are generated.

PIN Photodetector

- The high electric field present in the depletion region cause the electron-hole pair generated by the photon to separate and be collected across the reverse biased junction. This gives rise to a current flow in the external circuit.
- As the depletion region is wide, most of the incident photons are absorbed in this region and the efficiency of the device is high.
- Dark current is small. Dark currents are the current generated by minority charge carriers when no photons are incident on the material.

Characteristics of PIN Photodetector

- **V – I Characteristics:**
- Photodiode operates in reverse bias mode.
- The photocurrent is nearly independent of reverse bias voltage which is applied.
- For zero luminance, the photocurrent is almost zero but a small amount of dark current is present.
- As optical power rises the photo current also rises linearly.

Characteristics of PIN Photodetector

Characteristics of PIN Photodetector

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Internal photoelectric effect

- When light is incident on an intrinsic semiconductor, electrons are excited from valence band to conduction band and this leads to generation of electron and hole. Thus an increase of charge carrier concentration occurs within the semiconductor and the effect is called internal photoelectric effect.

Avalanche detector

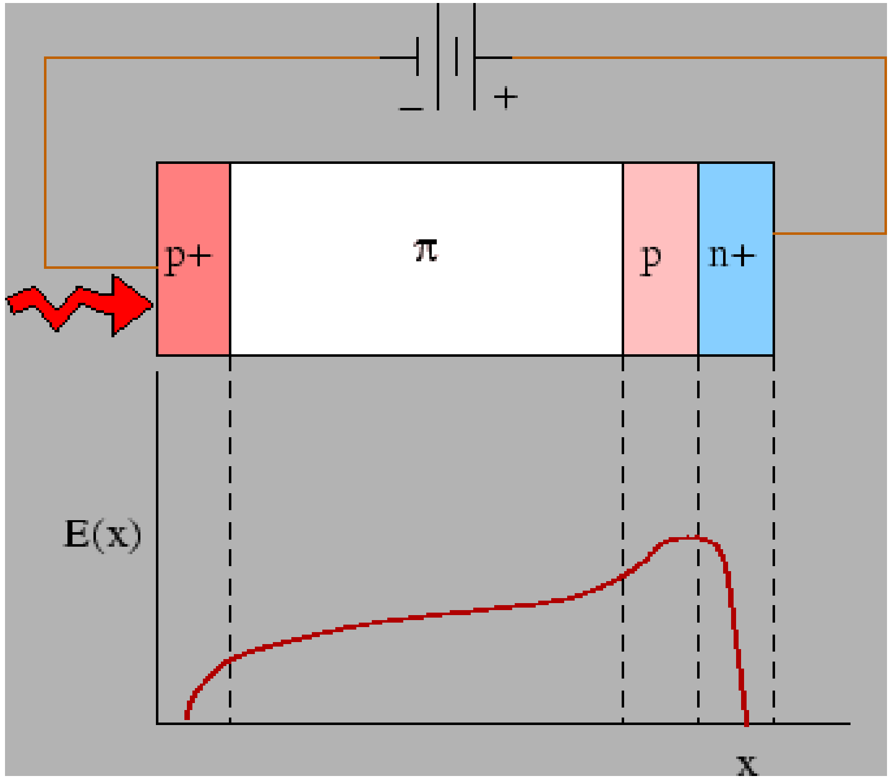
- Photoelectric current is amplified within the detector. It is very useful when low levels of light are to be detected.
- The structure is known as $p^+ \pi p n^+$ structure. The π region is the intrinsic region.
- The device is a reverse biased p-n junction. The p^+ and n^+ are heavily doped semiconductors and have a very low resistance.
- The π region is very lightly doped and is nearly intrinsic in nature.

Avalanche detector

- Under reverse biased condition a depletion region is present between p and n^+ region and it covers most of the π region.
- Under sufficient reverse bias, the junction approaches breakdown condition.
- A electric field is present in the junction region due to immobile charge carriers.

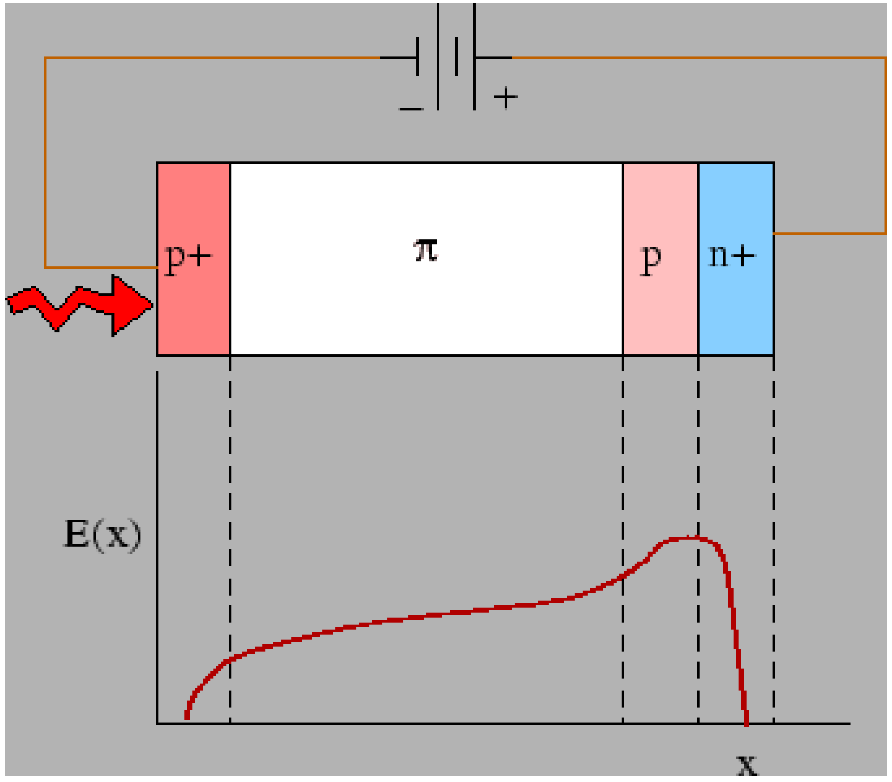
Avalanche detector

- A photon that enters through the p^+ region is absorbed in the intrinsic region and the resulting electron-hole pair that is generated is separated by the electric field in the π region.
- The hole drifts towards the p^+ region and do not take part in multiplication process. The electrons drift through the π region to the p n^+ junction.



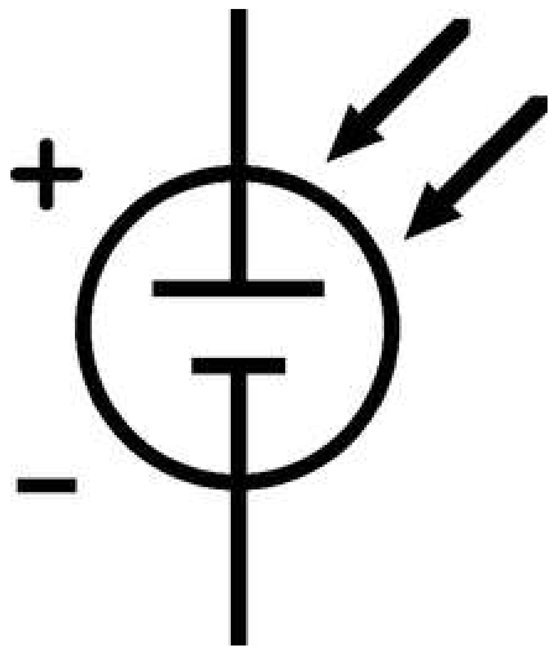
Avalanche detector

- The electric field present in the p n$^+$ region accelerates the electrons which in turn ionize neutral atoms in its path.
- The effect is cumulative and builds up into an avalanche. Thus there is carrier multiplication and internal amplification. This amplification process enhances the responsivity of the detector.

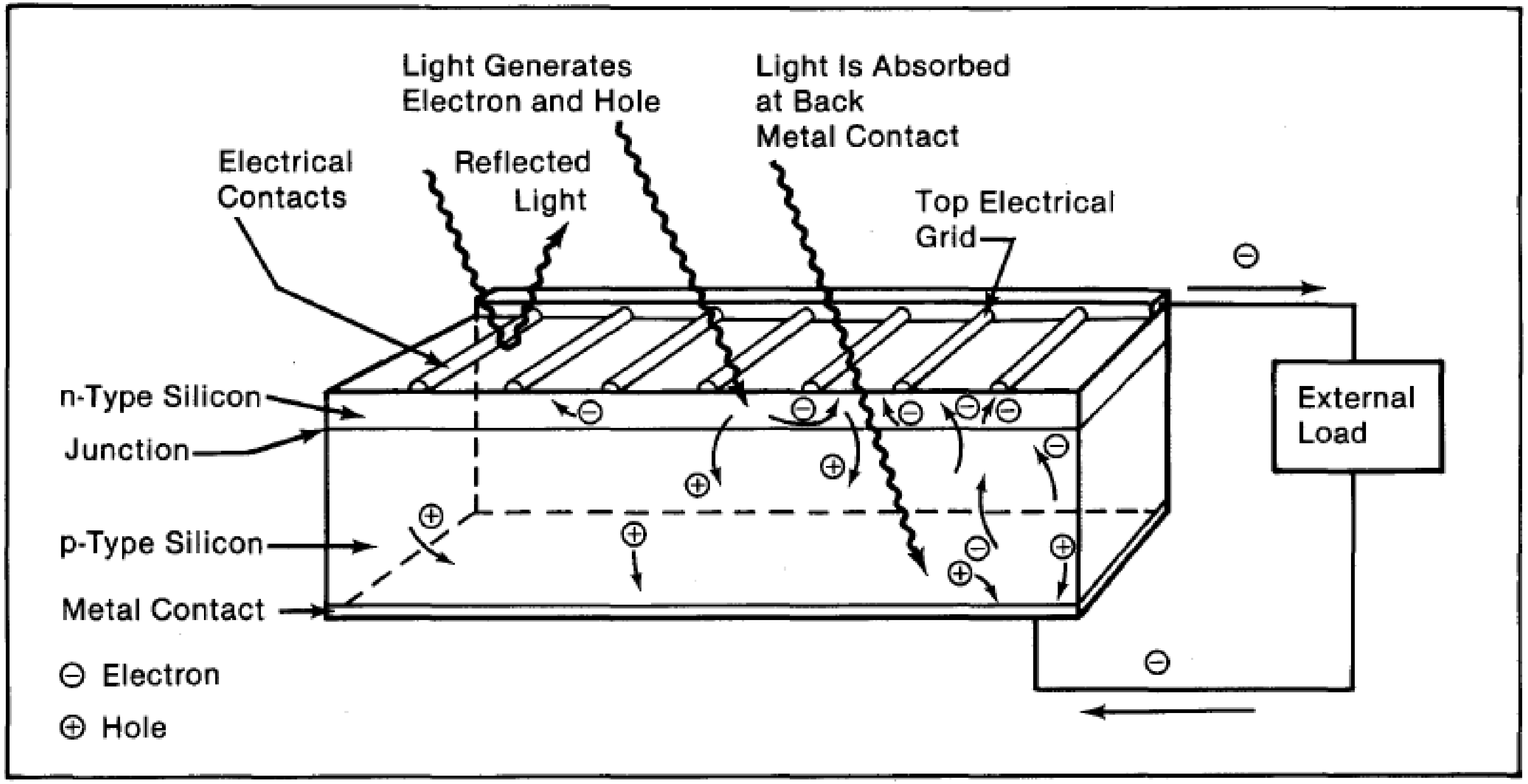


Solar cell

- A solar cell is a p-n junction that can generate electrical power when illuminated with sunlight.
- They operate under photovoltaic mode i.e. if the diode is left on open-circuit; an externally measurable voltage appears between p and n regions.

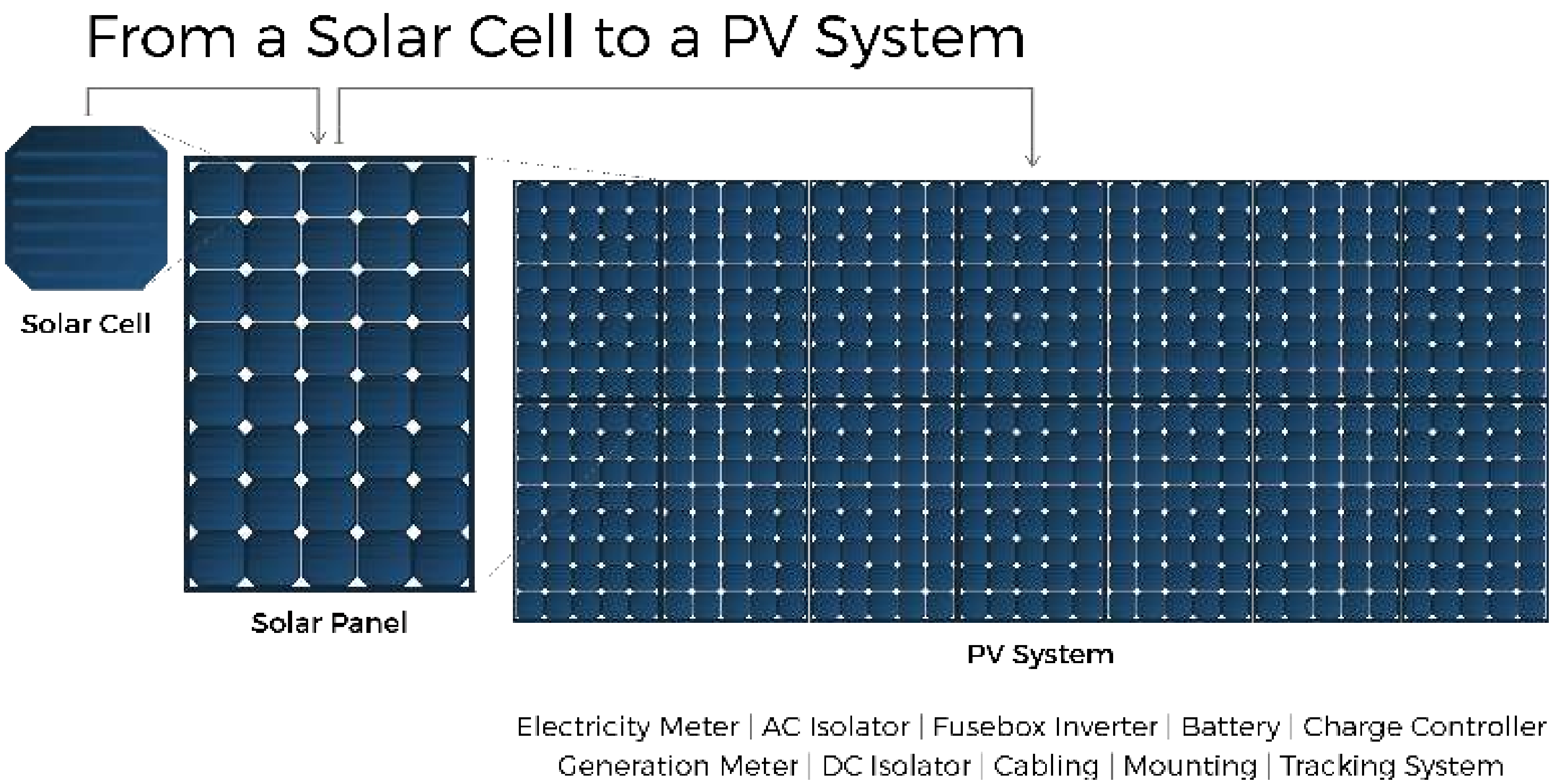


Solar cell



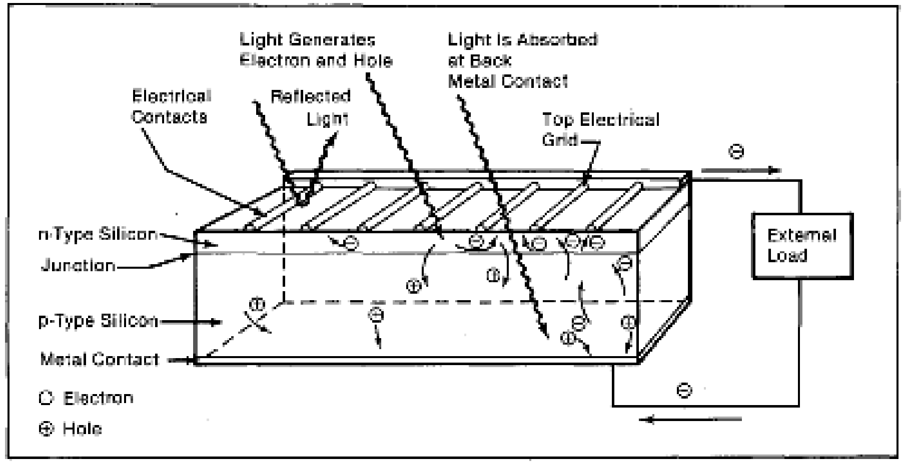
Light Generates
Electron and Hole
Light Is Absorbed
at Back
Metal Contact
Electrical
Contacts
Reflected
Light
Top Electrical
Grid
n-Type Silicon
Junction
p-Type Silicon
Metal Contact
External
Load
⊖ Electron
⊕ Hole

Solar cell – PV(Photovoltaic)system



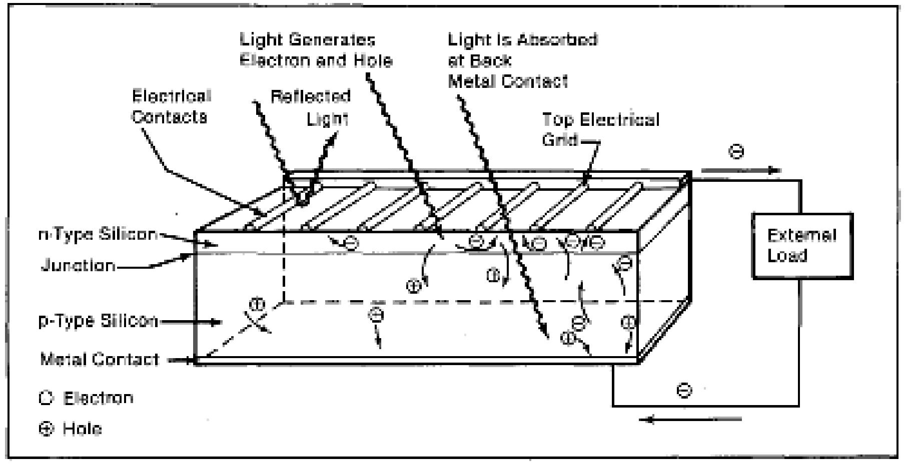
Solar Cell

- It consists of a p type chip on which a thin layer of n type material is grown.
- The n region is heavily doped and thin so that the light can penetrate through it easily.
- The p region is lightly doped so that most of the depletion region lies in the p side.



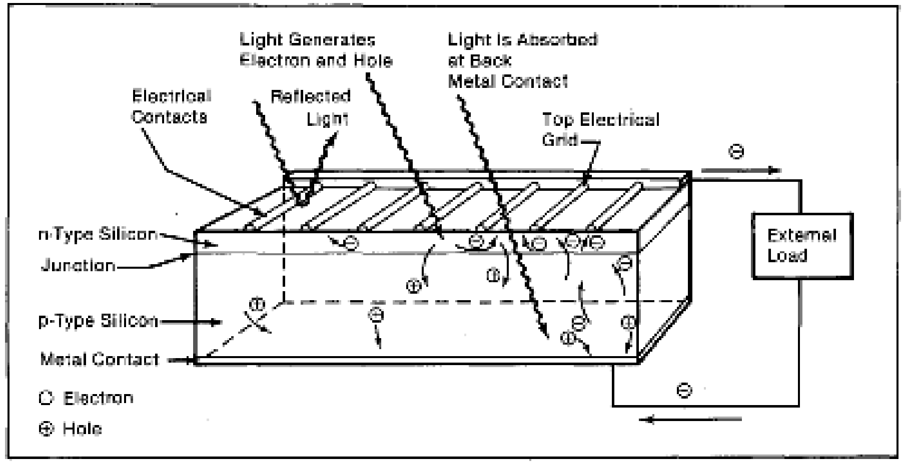
Solar Cell

- It also consists of a glass cover and antireflection coating.
- The front and back contacts are metallic contacts for the flow of electrons.
- Electron hole pairs are mainly created in the depletion region and due to the built-in potential and electric field, electrons move to the n region and the holes to the p region.



Solar Cell

- The movement of electrons and holes results in accumulation of charge on the two sides of the junction and produces a potential difference called photo emf.
- If a load (eg.-bulb) is connected across the cell a current flows through it.



Solar cell: I-V Characteristics

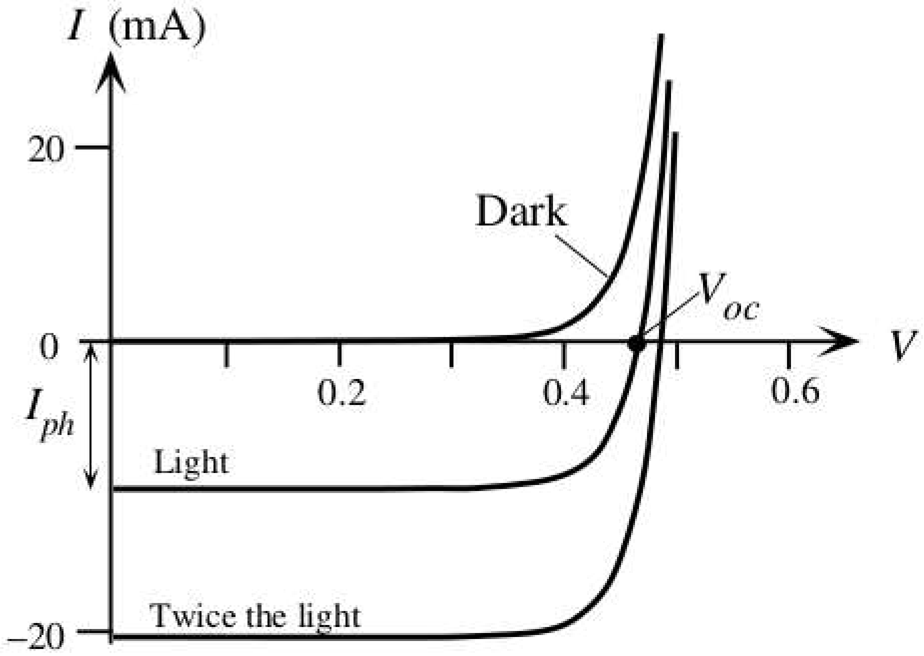
- The I-V characteristics depend on the intensity of the incident radiation and also the operating point (external load) of the cell.
- If the external circuit is a short circuit (external load resistance is zero) then the only current is due to the generated electron – hole pair by the incident light. This is called the photocurrent, denoted by I_{ph}. Another name for this is the short circuit current, I_{sc}.
- The photo current is related to the intensity of the incident radiation, I_{op}, by $I_{ph} = k \, I_{op}$ where k is equivalent to an efficiency metric that measures the conversion of light into electron-hole pairs.

Solar cell: I-V Characteristics

- When external load, R, is connected it develops a voltage. This voltage opposes the built in potential and reduces the barrier for carrier injection across the junction.
- This is similar to a pn junction in forward bias.
- This forward bias current opposes the photo current generated within the device due to the solar radiation.
- This is because I_{ph} is generated due to electrons going to the n side and holes to the p side due to the electric field within the device, i.e. drift current.
- The forward bias current(due to external load) is due to diffusion current (I_d) i.e. electrons going to the p side and holes to the n side.
- The net current can be written as $I = -I_{ph} + I_d$

Solar cell: I-V Characteristics

Dark current is the current due to minority charge carriers

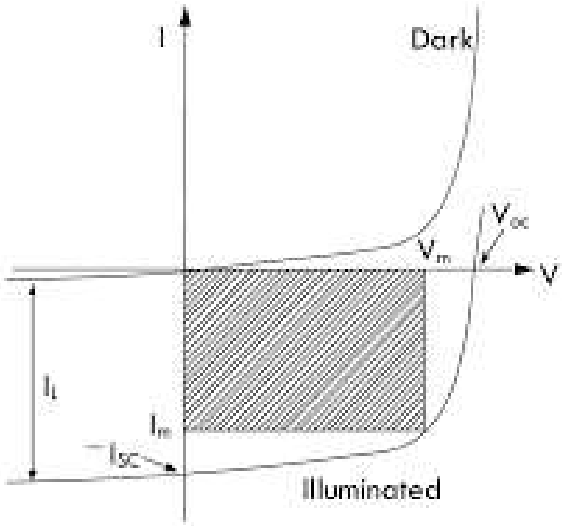


Useful Power(P_{max}) = V_m x I_m

Ideal power = V_{oc} x I_{sc}

Fill factor = useful power/ideal power

Fill factor is about 0.65 to 0.8 approx.



Solar cell: Efficiency

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