Optoelectronic Devices and Applications of Optical Fibers

Dr. C. Krishnamoorthi PhD
krishnamoorthi.c@vit.ac.in

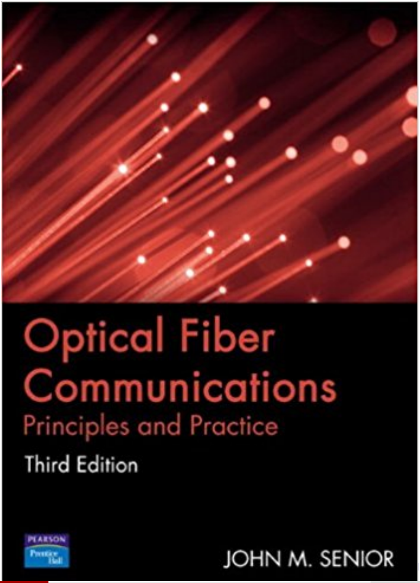
Ceter for Nanotechnology Research, Vellore Institute of Technology

8/10/2018

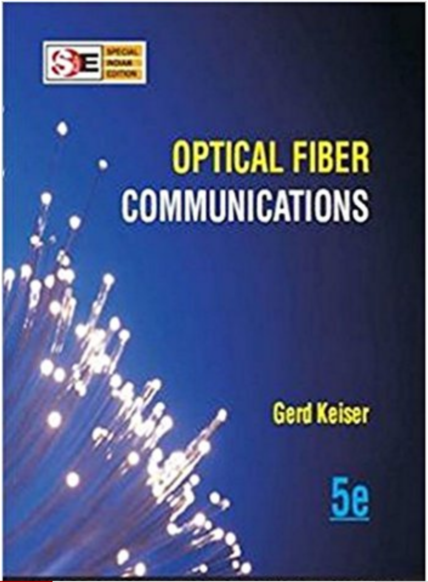
Outline I

1. Optical Transmitters
   - For efficient light absorption and emission
   - LED
   - Laser Diode or Diode laser
2. Fiber Optical Receivers
   - Classical photodetectors
   - Modern photodetectors
3. Applications
   - Endoscopy
   - In communication

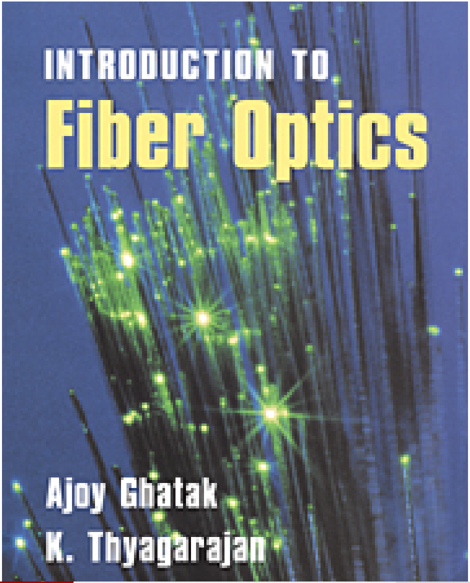
Textbook-1


Optical Fiber Communications
Principles and Practice
Third Edition
PEARSON
Prentice Hall
JOHN M. SENIOR

Textbook-2


SE SPECIAL INDIAN EDITION
OPTICAL FIBER
COMMUNICATIONS
Gerd Keiser
5e

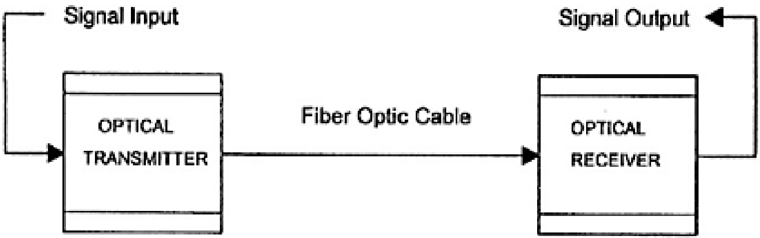
Textbook-3

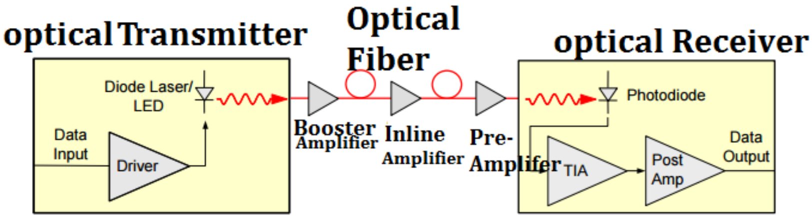


Syllabus of Module 7a

Module:7	**Optoelectronic Devices & Applications of Optical fibers**	**9 hours**	**SLO: 2,4**
Sources-LED & Laser Diode, Detectors-Photodetectors- PN & PIN - Applications of fiber optics in communication- Endoscopy.			

Components of fiber optic comm. networks





Fiber optic comm. components

- We know that in fiber-optic communication, three key components are required: **Optical transmitters, optical fiber cable and Optical receiver**.
- We are familiar with the “rules for light (binary data) propagation” and “impediments for light (data) propagation” in OF cables.
- In fiber-optic communication information is transmitted from one point to another by sending short pulses of light through an optical fiber cable.
- The light forms an electromagnetic carrier-wave that is modulated to carry info.
- “**Optical transmitters**” are used to convert an electrical pulse signal into an optical pulse signal to launch into an OF cable.

Fiber optic comm. components

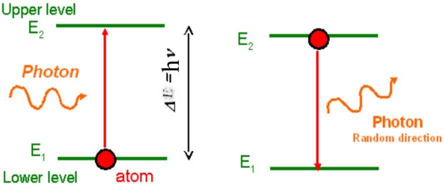
- "**Optical receivers**" are used to recover the signal as an electrical signal.

Optical Transmitters

- Optical transmitters are consists of optical source, electrical pulse generator and optical modulator.
- semiconductor devices such as LED and laser diode or diode laser are used as an optical sources.
- Semiconductor optical transmitters must be compact, efficient, and reliable while operating at optimal W/L or frequency.
- Ordinary electronic semiconductor diodes/transistors are activated by electrical potentials.
- Whereas optoelectronic devices (photodiodes and light emitting diodes) are designed to optimize light absorption and emission.

For efficient light absorption and emission

- It is known that incident photon with suitable energy generates e^- and h^+ pair in semiconductor. Similarly, e^- and h^+ pair recombination gives a photon emission.



- Light absorption and emission in semiconductor known to be heavily depend on detailed band structure of the semiconductor and charge carrier concentration in SC.
- Direct bandgap semiconductors: $E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$; $k = \frac{2\pi}{\lambda}$. Hence, **E-k** diagram is important for band representation.

Working principle of light emission

- **Electron-hole pair recombination**.
- **High radiative recombination probability**.
- Radiative electron-hole recombination probability is high in direct bandgap SC, degenerate SC at depletion region of p-n junction.
- FB potential give sufficient electrical energy (E = eV) to inject carriers into depletion region.

Types of bandgap in semiconductors

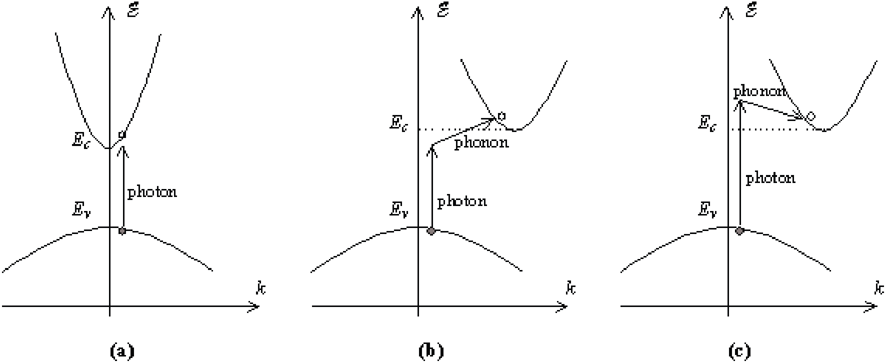


Figure: E-k diagram illustrating photon absorption in (a) direct bandgap (ii) indirect bandgap semiconductor assisted by phonon absorption and (c) indirect bandgap semiconductor assisted by phonon emission.

Direct bandgap semiconductor(DBSC)

- In electron-photon interaction, energy (E) and momentum ($p = \hbar k$) conservation is required.
- DBSC: the min. of CB and max. of VB are at the same k value. Whereas in indirect bandgap semiconductors (IBSC), the min. of CB is not at same k value of max. of VB.
- In SC, absorption of a photon occurs if an electron in the VB attains an energy and momentum of an empty state in CB.
- **Photons have little momentum relative their energy since they travel at the speed of light**. Therefore an electron makes almost a vertical transition on the E-k dia.
- Ref: Principles of Semiconductor devices by B Van Zeghbroeck [1].

[1] https://ecee.colorado.edu/~bart/book/book/chapter4/ch4_6.htm

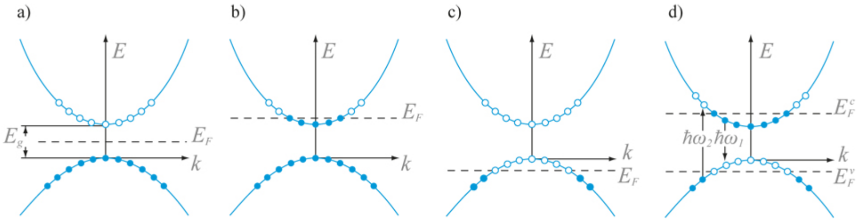
Indirect bandgap semiconductor (IBSC)

- If absorption of an incident photon directly provide an electron the correct energy and momentum equal to empty state in CB, it is DBSC. Ex.: GaAs, InP, and GaN. If does not provide, it is IBSC.Ex.: Si, Ge and SiC .
- Hence DBSC provide high e^{-} and h^{+} radiative recombination probability than IBSCs.
- Phonon associate with lattice vibrations and has low velocity close to the speed of sound in a material. It has small energy and large momentum compared to that of a photon.
- Conservation of energy and momentum can therefore be obtained in absorption processes if phonon is created or existing phonon participates, as shown in Fig.

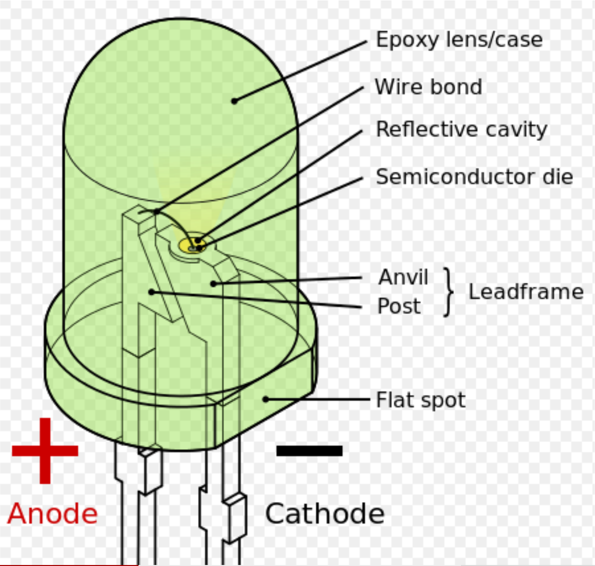
Degenerate SCs

- **High radiative recombination probability is achievable at high minority-carrier densities at a region in a semiconductor**.
- Degenerate semiconductors provide high minority carrier densities in a p-n junction region.
- A degenerate semiconductor p-n junction provide high minority carrier densities at a metallurgical junction (p- & n-) at low current densities.

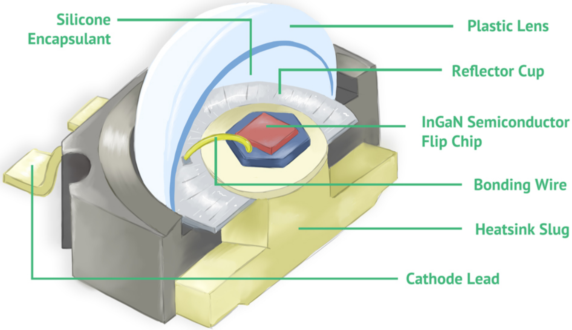
Degenerate SC



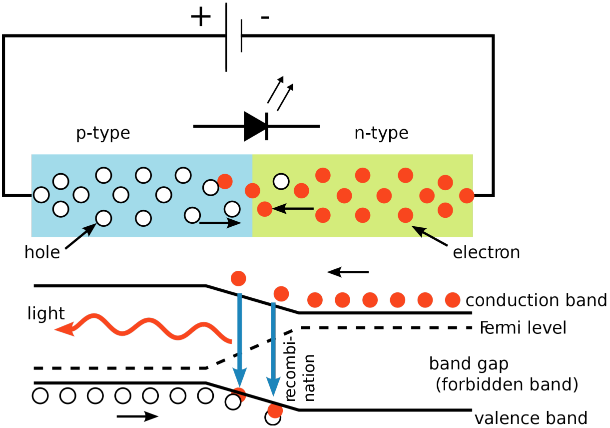
LED construction



LED construction-2



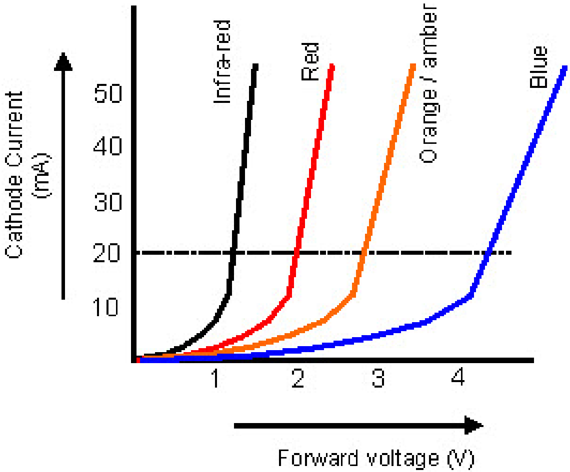
LED construction-3



Working Principle

- In FB, flow of free electrons in the opposite direction of current and flow of holes in the direction of the current.
- Hence there will be high radiative recombination of these carriers at metallurgical junction region where minority carrier densities are high in VB.
- In p-region and n-region there are no high minority carrier densities and hence no radiative recombination.
- External electrical bias provides sufficient carriers motion across the Jn. region or injection into jn. region resulting in recombination process.

LED I-V Characteristics



LED materials

WAVELENGTH RANGE (NM)	COLOUR	V_F @ 20MA	MATERIAL
< 400	Ultraviolet	3.1 - 4.4	Aluminium nitride (AlN) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN)
400 - 450	Violet	2.8 - 4.0	Indium gallium nitride (InGaN)
450 - 500	Blue	2.5 - 3.7	Indium gallium nitride (InGaN) Silicon carbide (SiC)
500 - 570	Green	1.9 - 4.0	Gallium phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
570 - 590	Yellow	2.1 - 2.2	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium phosphide (GaP)
590 - 610	Orange / amber	2.0 - 2.1	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaUInP) Gallium phosphide (GaP)
610 - 760	Red	1.6 - 2.0	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP)

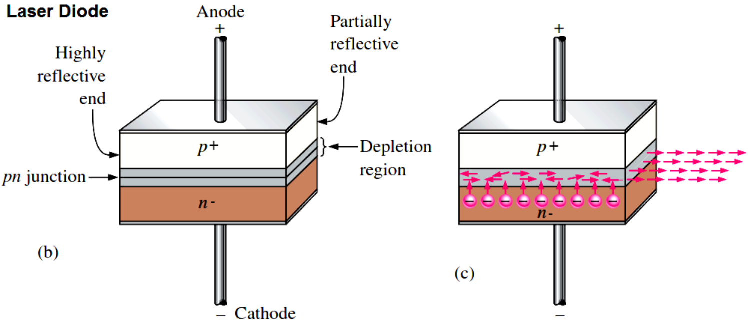
LED

- LED sources are cheap and reliable. They emit only incoherent light with relatively wide spectral width of 30-60 nm. In view of this the signal will be subjected to chromatic dispersion.
- LED produce light through spontaneous emission and electroluminescence phenomenon.
- LED light transmission is also inefficient with only about 1% of I/P power eventually converted into launch power. Chromatic dispersion limits the data transmission distance.
- However, due to their relatively simple design, LEDs are very useful for low-cost apps.

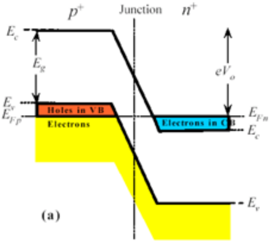
Laser Diode or Diode laser

- LEDs produce incoherent light while laser diodes produce coherent light.
- Laser active medium formed by a p-n junction similar to that formed in LED.
- p-n junction is formed by degenerate (p^+ or n^-) direct band gap semiconductor (Al-doped GaAs).

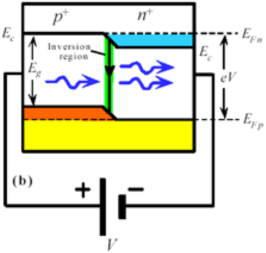
Construction



Diode Laser construction

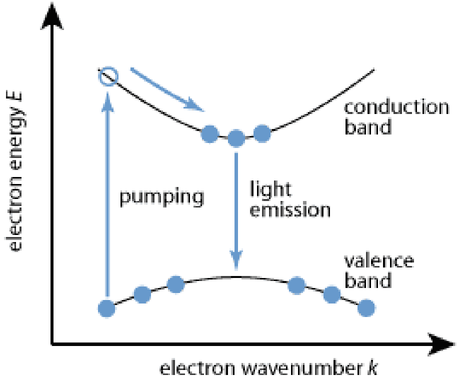


(a) p-n junction without bias

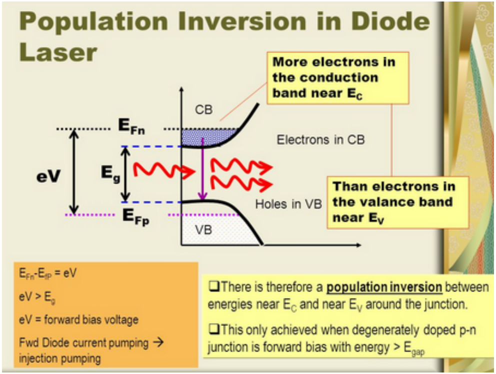


(b) p-n junction after forward bias

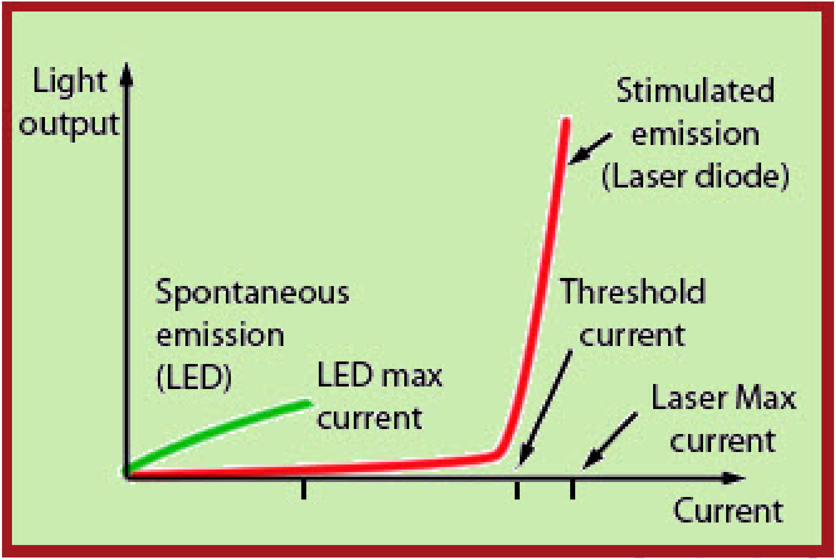
Diode Laser construction



Diode Laser construction



I-V characteristics



Working principle

- On applying FB connections, e^- and h^+ will inject into the opposite (minority) region through depletion (space charge) region.
- Radiative recombination occurs in the jn. region and emits suitable W/L radiation photons.
- The amount of recombination is determined by the current flowing across the junction.
- Emitted photons are oscillate to-and-pro between the mirrors, formed by smooth polishing,around the jn. region. Oscillating photons travel coherently in a particular, fixed direction.
- Laser O/P released through partially reflective mirror when energy is reached a threshold value.

Working principle

- Diode laser is 4-level laser. Hence efficiency is high.

LED vs Laser Diode

- LEDs are made from a very thin layer of fairly heavily doped SC material. Because of this thin layer a reasonable no. of photons leave the junction.
- Spontaneous emission predominates in LED. Hence it is incoherent. Whereas laser diode emits by stimulated emission and hence it is highly coherent.
-

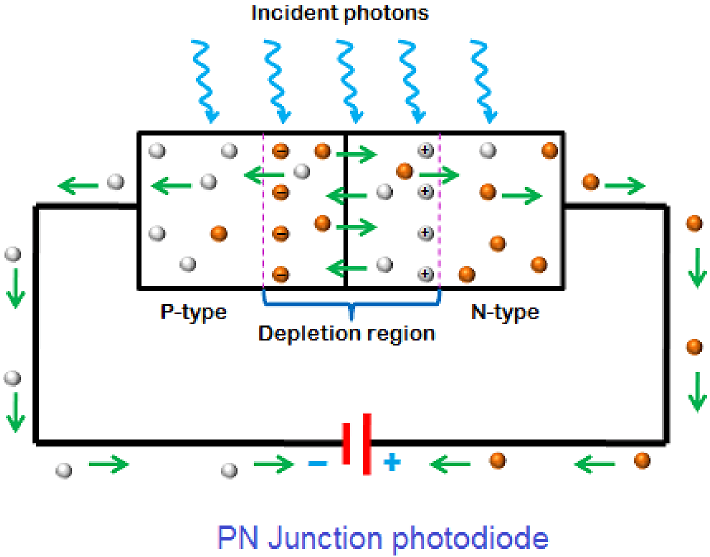
Fiber Optic Receiver

- They are used to receive the modulated light streams carrying data over fiber optic cables. The received light signals are converted into electrical pulses (square wave).
- Within the fiber optic receiver, photodetector is the key component. Major function of a photodetector is to convert an optical info signal back into an electrical signal (photocurrent) by photoelectric effect.
- Reliable photodetector is a semiconductor photo-diode. A variety of photodiodes such as **p-n photodiode, p-i-n photodiode, avalanche photodiodes, Schottky photodiodes**, etc., are used in fiber optic receivers.

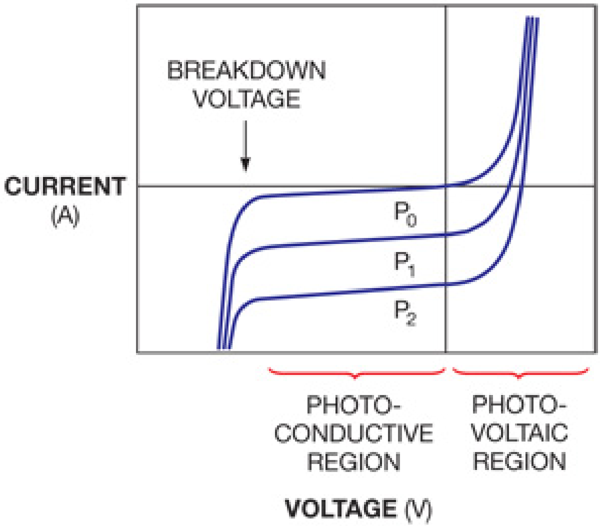
Working principles of photodiode

- Photodiode is basically a light detector semiconductor device, which converts light into electrical current or voltage.
- Separation and collection of electrical charge carriers (e^- and h^+) which are generated by absorbing a suitable energy (W/L) photon in SC.
- An e^--h^+ pair was generated in depletion region of p-n junction and was efficiently separated under reverse bias configuration.
- $h\nu + e^0 \rightarrow e^- + h^+$.
- Photocurrent is proportional to light intensity falling on the photodiode.

p-n photodiode



I-V characteristics



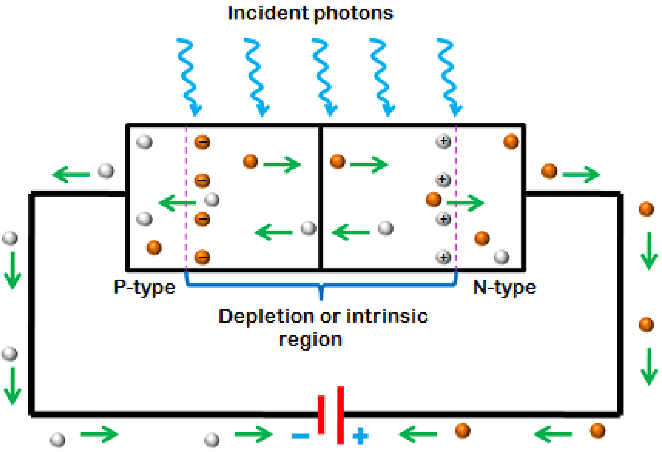
Drawback of PN photodiode

- The depletion region width in PN photodiode is limited. Hence the detection area is limited.
- High reverse bias voltage leads to p-n junction breakdown.
- Due to narrow depletion region, higher W/L radiation such as VIS and IR regions could not absorb completely.
- Higher W/L radiation travels deep into the device. Hence PN photodiode quantum efficiency is less.

p-intrinsic-n photodiode or PIN photodiode

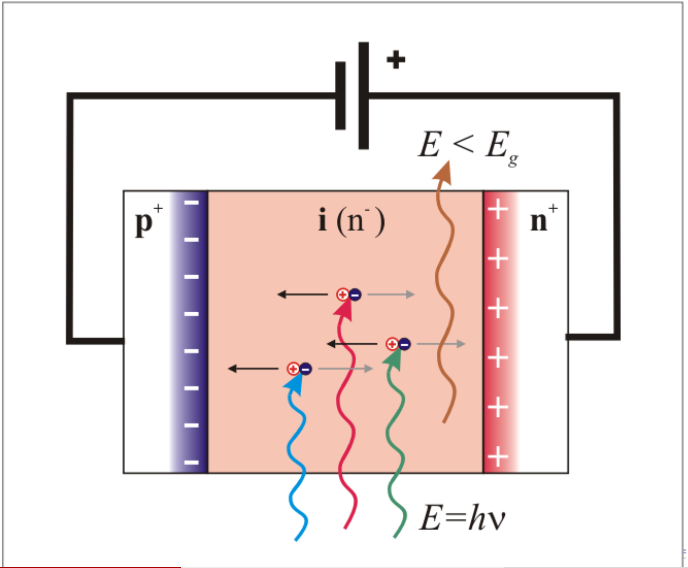
- PIN photodiode is formed by a wide, intrinsic semiconductor sandwiched between p- and n-region of a diode.
- The p- and n- regions are typically heavily doped because they are used for ohmic contacts.
- when the reverse bias is applied, the space charge region must cover the intrinsic region completely.
- The wide intrinsic layer makes the PIN diode an inferior rectifier but makes it suitable for photodetector.
- The wider depletion width enables e^{-}- h^{+} pair generation deep within the device. This increases the **quantum efficiency** of the photodiode.

PIN photodiode



PIN photodiode

PIN photodiode



Quantum Efficiency of PIN photodiode

- The electrical current produced by e^- and h^+ generated by incident photons are called as photocurrent (I_p). I_p is proportional to light power (P) (of suitable $h\nu$).
- $I_p \propto P$; $I_p = RP$. $\implies R = \frac{I_p}{P}$, here R-responsivity of photodiode.
- $I_p = \frac{Q}{t} = \frac{N_e e}{t}$; here $\frac{N_t}{t}$-no. of e^- generated per unit time.
- Light power $P = \frac{E}{t} = \frac{N_p E_p}{t}$; here $\frac{N_p}{t}$- no. of photons incident on depletion region per unit time. E_p- average energy of incident photon.
- $$R = \frac{I_p}{P} = \frac{\frac{N_e e}{t}}{\frac{N_p E_p}{t}} = \frac{N_e}{N_p}\frac{e}{E_p} = \frac{N_e}{N_p}\left(\frac{e\lambda_p}{hc}\right)$$

Endoscope

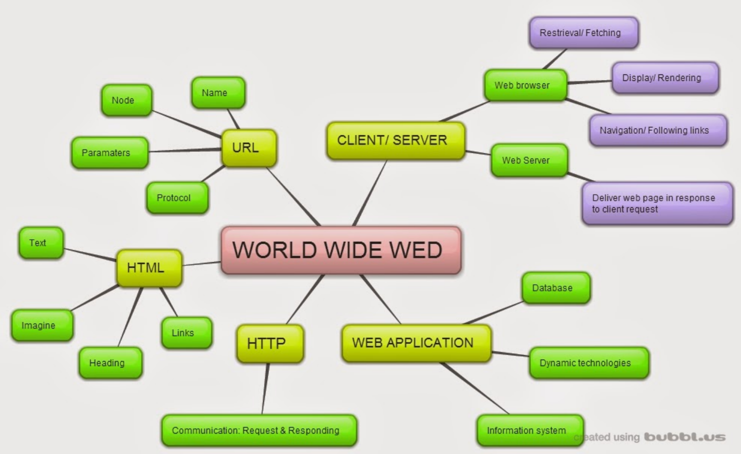
Self-study

In communication

Self-study

Assignment

Prepare Mind mapping of Module 7a (Optoelectronic devices and Applications of Optical fibers) content discussed in the class on a A4 size white paper.



THE END