UNIT 1

* Schrodinger time Independent eqn :-

napla

let wave function

$$\psi = e^{i(kx-\omega t)} \quad \text{--- (1)}$$

take 1st derivative wr to x

$$\frac{\partial \psi}{\partial x} = ik e^{i(kx-\omega t)}$$

take 2nd derivative wr to x.

$$\frac{\partial^2 \psi}{\partial x^2} = i^2 k^2 \psi$$

$$\therefore \left[\begin{array}{l} p = \frac{h}{\lambda} \times \frac{2\pi}{2\pi} \\ p = \hbar k \\ k^2 = p^2/\hbar^2 \end{array} \right]$$

Now $p = \hbar k$

$$\frac{\partial^2 \psi}{\partial x^2} = \frac{-p^2}{\hbar^2} \cdot \psi \quad \text{--- (2)}$$

Total Energy

$$E = KE + PE$$

$$= \frac{1}{2} m v^2 \frac{m}{m} + U$$

$$E = \frac{p^2}{2m} + U$$

multiply by ψ

$$E\psi = \frac{p^2}{2m}\psi + U\psi$$

$$E\psi - U\psi = \frac{p^2}{2m}\psi$$

$$(E-U)(\psi) = \frac{p^2}{2m}\psi \quad \text{--- (3)}$$

from eqn (2)

$$\frac{p^2}{2m}\psi = \frac{-\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2} \quad \text{--- (4)}$$

from eqn (3) & (4)

$$(E-U)\psi = \frac{-\hbar^2}{2m}\frac{\partial^2 \psi}{\partial m^2}.$$

$$\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2} + (E-U)\psi = 0 \quad \text{--- (5)}$$

eqn 5 is called Schrodinger time Independent eqn for x-dimension.

For 3D eqn.

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right]\psi + \frac{2m}{\hbar^2}(E-U)\psi = 0$$

$$\nabla^2 \psi + \frac{2m}{\hbar^2}(E-U)\psi = 0$$

$\Rightarrow \nabla^2$ is called laplacian operator.

* Schrodinger time dependent eqn :-

Let wave function

$$\psi = e^{i(kx-\omega t)} \quad \text{—} (1)$$

take 1st derivative wr to 't'

$$\frac{\partial \psi}{\partial t} = -i\omega e^{i(kx-\omega t)} \quad \text{—} (2)$$

$$E = h\nu \times \frac{2\pi}{2\pi}.$$

$$E = \hbar\omega$$

$$\omega = E/\hbar$$

Substitute in eqn (2)

$$\frac{\partial \psi}{\partial t} = -i\frac{E}{\hbar}\psi$$

$$E\psi = -\frac{\hbar}{i}\cdot\frac{\partial \psi}{\partial t}.$$

$$E\psi = -\frac{\hbar i}{i i}\frac{\partial \psi}{\partial t}$$

$$E\psi = \hbar i\frac{\partial \psi}{\partial t} \quad \text{—} (3)$$

From time Independent eqn

$$\nabla^2\psi + \frac{2m}{\hbar^2}(E-V)\psi = 0$$

$$\nabla^2\psi - \frac{2m}{\hbar^2}V\psi = -\frac{2m}{\hbar^2}E\psi$$

take commom $\left(-\frac{2m}{\hbar^2}\right)$

$$\cancel{-\frac{2m}{\hbar^2}}\left[\frac{-\hbar^2}{2m}\nabla^2 - V\right]\psi = \cancel{-\frac{2m}{\hbar^2}}E\psi$$

$$\left[\frac{-\hbar^2}{2m}\nabla^2 + V\right]\psi = E\psi$$

Here $-\frac{\hbar^2}{2m}\cdot\nabla^2 + V = H$ — (4)

$$H\psi = E\psi$$

H is called Helmiltonian operator.

$$H\psi = \hbar i\frac{\partial \psi}{\partial t}$$

(or)

$$\left[\frac{-\hbar^2}{2m}\nabla^2 - V\right]\psi = \hbar i\frac{\partial \psi}{\partial t} \quad \text{—} (5)$$

eqn (5) is called Schrodinger time dependent eqn.

3. Explain the physical significance of wave function

The wave function in quantum mechanism describes in probability amplitude of finding a particles in a particular state. Its physical significance lies in it's square modulus which gives the probability densisty of finding a particle in a certain region of space at a given time. This probability density helps predict where a particle might be located or its properties upon measurement. The wave function is fundamental in ~~us~~ understanding the probabilistic nature of quantum particles, forming the basics for predicting their behaviour and interactions.

UNIT 2

1) * Concentration of carriers on conduction Band.

→ occupency probability

$$f(\epsilon) = \frac{N(\epsilon)}{g(\epsilon)} \quad \text{—} (1)$$

$$N(\epsilon) = g(\epsilon) \cdot f(\epsilon) \quad \text{—} (A)$$

density of state in conduction Band.

$$g_c(\epsilon) = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}(\epsilon - \epsilon_c)^{1/2} \quad \text{—} (2).$$

from eqn (A)

$$\left[\because f(\epsilon) = e^{\left(\frac{\epsilon - \epsilon_f}{KT}\right)}\right]$$

$$n_0 = \int_{\epsilon_c}^{\infty} g_c(\epsilon) \cdot f(\epsilon)\, d\epsilon.$$

$$= \int_{\epsilon_c}^{\infty} \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}(\epsilon - \epsilon_c)^{1/2} \cdot e^{\left(\frac{\epsilon - \epsilon_f}{KT}\right)} d\epsilon$$

$$= \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{\epsilon_c}^{\infty}(\epsilon - \epsilon_c)^{1/2} \cdot e^{\left(\frac{\epsilon - \epsilon_f}{KT}\right)} d\epsilon.$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{\epsilon_c}^{\infty}(\epsilon - \epsilon_c)^{1/2} e^{\left[\frac{\epsilon - \epsilon_c + \epsilon_c - \epsilon_f}{-KT}\right]} d\epsilon$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{\epsilon_c}^{\infty}(\epsilon - \epsilon_c)^{1/2} e^{\frac{[\epsilon - \epsilon_c]}{KT}} \cdot e^{\frac{[\epsilon_c - \epsilon_F]}{-KT}} d\epsilon$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} e^{\left(\frac{\epsilon - \epsilon_c}{KT}\right)}\int_{\epsilon_c}^{\infty}(\epsilon - \epsilon_c)^{1/2} \cdot e^{\left(\frac{\epsilon_c - \epsilon_F}{-KT}\right)} d\epsilon$$

$$\eta = \left(\frac{\epsilon - \epsilon_c}{KT}\right) \quad \Bigg| \quad d\eta = \frac{1}{KT} d\epsilon \Rightarrow d\epsilon = d\eta \cdot KT.$$

$$\& \ \epsilon - \epsilon_c = \eta \cdot KT$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} e^{\left(\frac{\epsilon_c - \epsilon_F}{-KT}\right)} \int \eta^{1/2}(KT)^{1/2} \cdot e^{-\eta} KT \cdot d\eta$$

$$= \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} e^{\left(\frac{\epsilon_c - \epsilon_F}{-KT}\right)} (KT)^{3/2} \int \eta^{1/2} \cdot e^{-\eta} d\eta.$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2mKT}{\hbar^2}\right)^{3/2} e^{\frac{(\epsilon_C-\epsilon_F)}{KT}} \cdot \frac{\sqrt{\pi}}{2}$$

$$\boxed{\therefore n_0 = \frac{1}{4}\left(\frac{2mKT}{\hbar^2\cdot\pi}\right)^{3/2} e^{\left[\frac{\epsilon_C-\epsilon_F}{-KT}\right]}}$$

Concentration of carriers on valence Band

occupency probability.

$$f(\epsilon) = \frac{N(\epsilon)}{g(\epsilon)} \quad \text{--- (1)}$$

$$N(\epsilon) = g(\epsilon)\cdot f(\epsilon) \quad \text{--- A}$$

density of state in valence Band.

$$g_v(\epsilon) = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}(\epsilon_v-\epsilon)^{1/2} \quad \text{--- (2)}$$

from eqn (A)

$$f(\epsilon) = e^{\left(\frac{\epsilon_F-\epsilon_v}{KT}\right)}$$

$$n_0 = \int_{\epsilon_v}^{\infty} g_c(\epsilon)\cdot f(\epsilon)\, d\epsilon.$$

$$= \int_{\epsilon_c}^{\infty} \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}(\epsilon_v-\epsilon)^{1/2}\cdot e^{\left(\frac{\epsilon_F-\epsilon_v}{-KT}\right)} d\epsilon$$

$$= \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{\epsilon_v}^{\infty}(\epsilon_v-\epsilon)^{1/2}\cdot e^{\left(\frac{\epsilon_F-\epsilon_v}{-KT}\right)} d\epsilon.$$

$$= \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{\epsilon_v}^{\infty}(\epsilon_v-\epsilon)^{1/2}\cdot e^{\frac{(\epsilon_v-\epsilon+\epsilon_F-\epsilon_v)}{-KT}} d\epsilon$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{\epsilon_v}^{\infty}(\epsilon_v-\epsilon)^{1/2}\, e^{\frac{(\epsilon_v-\epsilon)}{KT}}\, e^{\left(\frac{\epsilon_F-\epsilon_v}{-KT}\right)} d\epsilon$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} e^{\left(\frac{\epsilon_v-\epsilon}{KT}\right)}\int_{\epsilon_v}^{\infty}(\epsilon_v-\epsilon)^{1/2}\cdot e^{\left(\frac{\epsilon_F-\epsilon_v}{-KT}\right)} d\epsilon.$$

$$n = \left(\frac{\epsilon_v-\epsilon}{KT}\right) \quad dn = \frac{1}{KT}d\epsilon \Rightarrow d\epsilon = dn\cdot KT$$

$$\& \quad \epsilon_v - c = n\cdot KT$$

$$n_0 = \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\left(\frac{\epsilon_F-\epsilon_v}{-KT}\right)\int n^{1/2}(KT)^{1/2}\cdot e^{-n} KT\, dn$$

$$= \frac{1}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} e^{\left(\frac{\epsilon_F-\epsilon_v}{-KT}\right)}(KT)^{3/2}\int n^{1/2}\cdot e^{-n}\, dn$$

② Define schottky junction and its application.

A schottky is a type of junction formed between a ~~material~~ metal and a semiconductor. It's chara-cterized by a better created due to the difference in work function between the metal and the semiconductor, leading to the formation of a depletion region.

Application of schottky junctions include:-

1) It is used in Diodes for their fast switching speed and low forward voltage drop.

2) It is used in RF Devices.

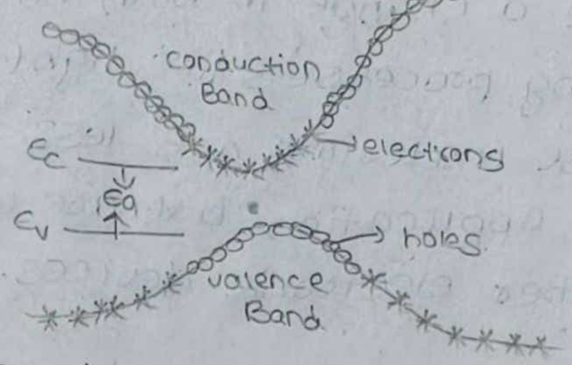
3) It is used in Power Rectifiers for their low power losses and high efficiency.

4) It is used in solar cells

their unique properties makes schottky junctions valuable in various electronic and energy conversion devices

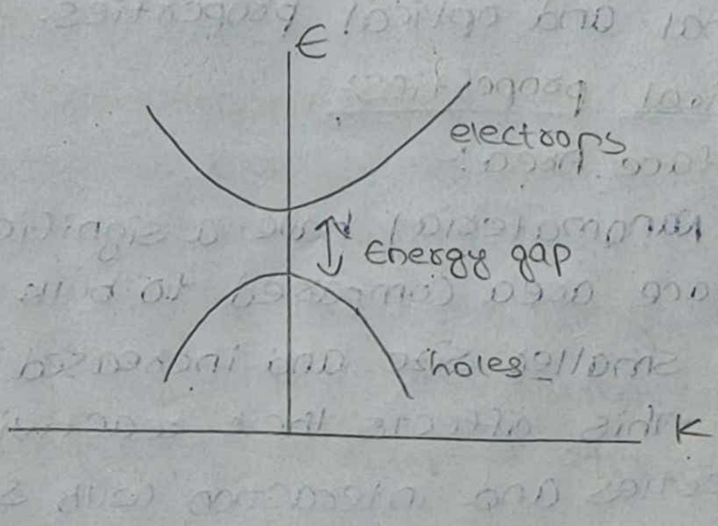
3) Explain E-K diagram with Direct and indirect Band gap.

A) A E-K diagram, or Energy - momentum diagram illustrate the relationship between the energy (E) and momentum (K) of electrons in a crystalline materials.



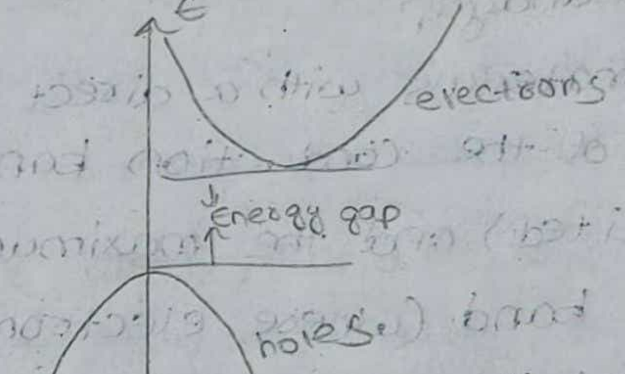
Direct Bandgap:-

In materials with a direct bandgap, the minimum energy of the conduction band (where electrons are excited) and the maximum energy of the valence band (where electrons normally reside) occur at the same momentum in the Brillouin zone. Electrons can easily transition between the bands with the absorption or emission of photons, allowing for efficient emission of light. This property is vital optoelectronic devices like LEDs and lasers.



Indirect Bandgap:-

In materials with an indirect bandgap, the minimum energy of the conduction band and the maximum energy of the valence band occur at different momentum value in the Brillouin zone. As a result, electron transistion between the bands involve a change in both energy and momentum, making processes like light emission less efficient. these materials are less effective in optoelectronic application but are used in transistors and other electronic devices.



unit 3

1. Discuss in brief regarding the changes observed in physical properties, thermal properties when a bulk material is transformed

A) when a bulk material is tranformed into a nanomaterial, several changes occurs in its physical thermal and optical properties.

Physical properties:-

1) surface Area:-

Nanomaterial have a significantly higher surface area compared to bulk materials due to their smaller size and increased surface to volume ratio. This affects their reactivity, adsorption properties and interaction with surrounding environments.

2) mechanical properties :

Nanometerials have a significant often exhibit enhanced mechanical properties sch as, increased strength, hardness and flexibility compared to their bulk counterparts due to the presence of grain boundaries and quantum effect at the nanoscale

3) melting point and phase transitions:-

Nanomaterials might have altered melting points and phase transition temperature compared to bulk materials. due to the dominance of surface and interface effects.

Thermal properties:-

1) Thermal conductivity:-

Nanomaterials can display altered thermal conductivity compared to bulk material. for instance, some nanomaterials exhibit enhanced thermal conductivity due to conductivity due to phonon confinement effects.

2) melting and Boiling points:-

These properties can also change in nanomaterial due to the domiance of surface energy compared to bulk materials.

Optical properties:-

1) Quantum confinement effects:-

Nanomaterials exhibits unique optical properties due to quantum confinement effects, smaller nanoparticles can be discrete energy level result in charges in absorbance, fluroscene and bandgap compared to bulk materials.

2- Explain in brief about shape memory alloys and Piezoelectric alloys-

A) Shapes memory alloys (SMA) are materials that can "remember" their original shape and return to it when subjected to certain stimuli, like temperature change or stress. They can be deformed and then revert to their predetermined shape when the stimulus is applied. This property makes SMAs useful in various applications like robotics, aerospace and medical devices.

Piezoelectric alloys, on the other hand, possess the ability to generate an electric charge when mechanical stress is applied or vice versa. This property allows them to convert mechanical energy into electrical energy and vice versa. They find application in sensors, actuators, ultrasound devices and even in generating electricity from vibrations or mechanical movements.

UNIT 4

1. Explain the construction, working, energy band diagram and application of He-Ne laser.

A) The Helium - Neon (He-Ne) laser is a gas laser commonly used in various application

Construction:-

Gas medium:-

The laser tube contains a mixture of helium and neon gases.

Electrical Discharge:-

Electrical discharge excites the gas molecules leading to the generation of a population inversion.

Resonator:-

The laser cavity consists of mirror at both ~~tran~~ ends, one highly reflective and the other partially transparent, forming an optical resonator

Working:-

Excitation:-

Electrons in helium get excited by an electrical discharge and transfer energy to neon atoms.

Population inversion:-

This excitation result in a population inversion, where more atoms are in higher energy states than lower ones.

Stimulated Emission:-

Stimulated emission occurs as photons stimulate other excited atoms to emit coherent photons.

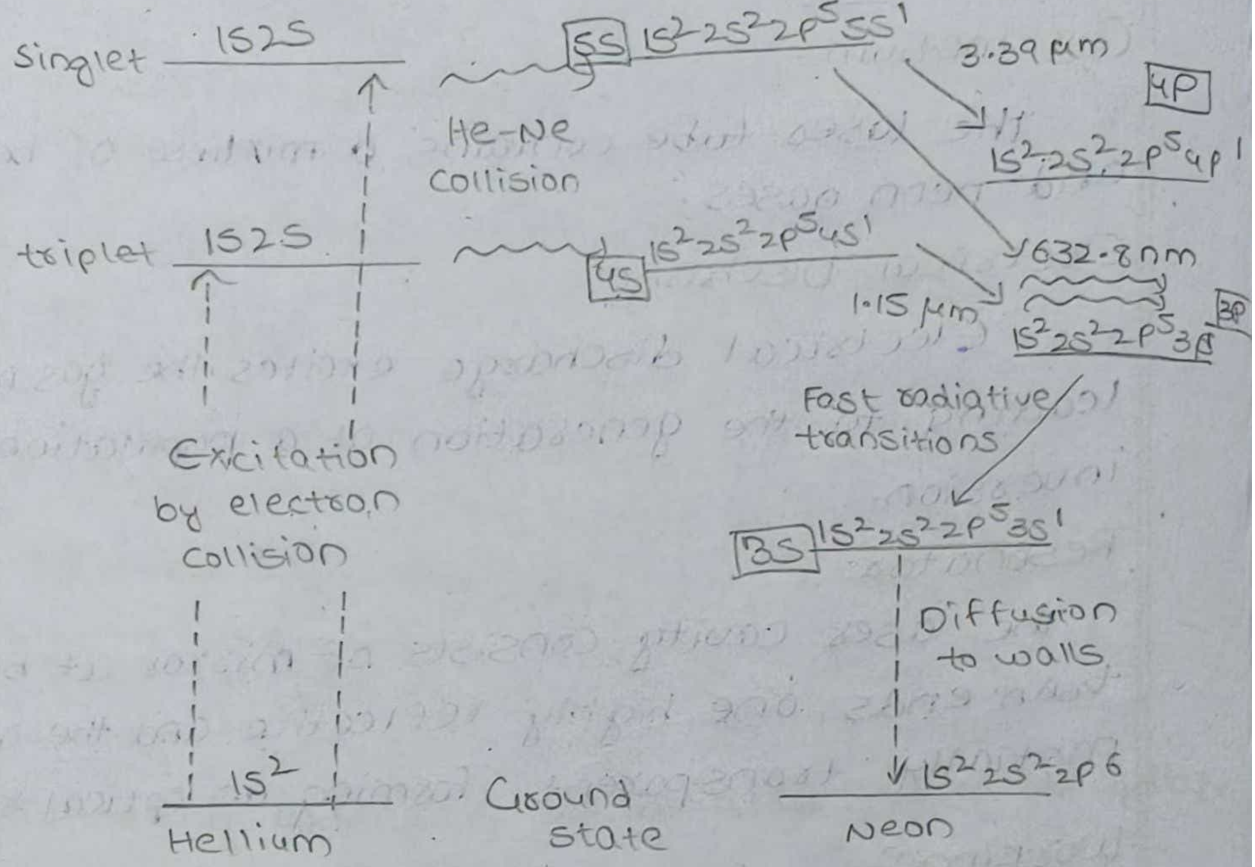
Amplification:-

The optical resonator amplifies these photons as they bounce back and forth between the mirror

Lasser Emission:-

Coherent light is emitted through the partially transparent mirror.

Energy level diagram:-



Application:-

1) Alignment.
2) It is used in surveying and leveling.
3) It is used in Holography
4) It is used in Barcode scanners.
5) It is used in medical Applications.

2. Explain the constouction, wooking and application of ruby lasers.

A) The ruby laser is a type of solid-state laser that operates using a syntheic ruby crystal as the gain medium. Here's a overview of it's construction, working principle, application:

Construction:-

1- Ruby crystal:-

The active medium is a synthetic ruby crystal typically chromium-doped aluminum oxide (Cr_3^+ Al_2O_3). the Chromium ion within the crystal provide the necessary energy levels for laser.

2- Flashlamp:-

The ruby crystal is surrounded by a hight intensity flashlamp that provides an intense pulse of light. this flash of light serves as the pump source to energize the chromium ions in the ruby crystal.

3- Reflections:-

The ends of the ruby crystal are coated with mirrors, forming an optical cavity. one mirrors is highly reflection, while the other in partially transparent, allowing the emitted laser light to pass through.

Working:-

1. pumping:-

The flashlamp delivers a burst of light, pumping energy into the ruby crystal. This causes the chromium ions to move to a higher energy state.

2- Spontaneous Emissions:-

As the chemical Chromium ions return to their lower energy state, they emit identical photons. This process leads to the amplification of light, creating visible red range.

3- Stimulated Emission:-

Photons produced by spontaneous emission stimulate other Chromium ions to emit identical photons This process leads to the amplification of light, creating a coherent, collimated laser beam

4. Population Inversion:-

The laser process relies on achieving a population inversion, where more atoms are in a excited state than in the ground state, end stimulated emission to dominate.

Application:-

1) It is used in medical Applications
2) It is used in scientific Research.
3) It is used in Holography
4) It is used in communication.

3. Explain the construction, working and application of semiconductor laser.

A) Construction :-

1) A semiconductor laser typically consists of a semiconductor diode, commonly made form materials like galium arsenide.

2) The diode is formed by joining p-type and n-type semiconductor materials, creating a p-n junction.

3) Between the p and n regions, there is an active region where the lasing action occurs.

4) the active region is usually doped with materials that facilitate stimulated emission.

working:-

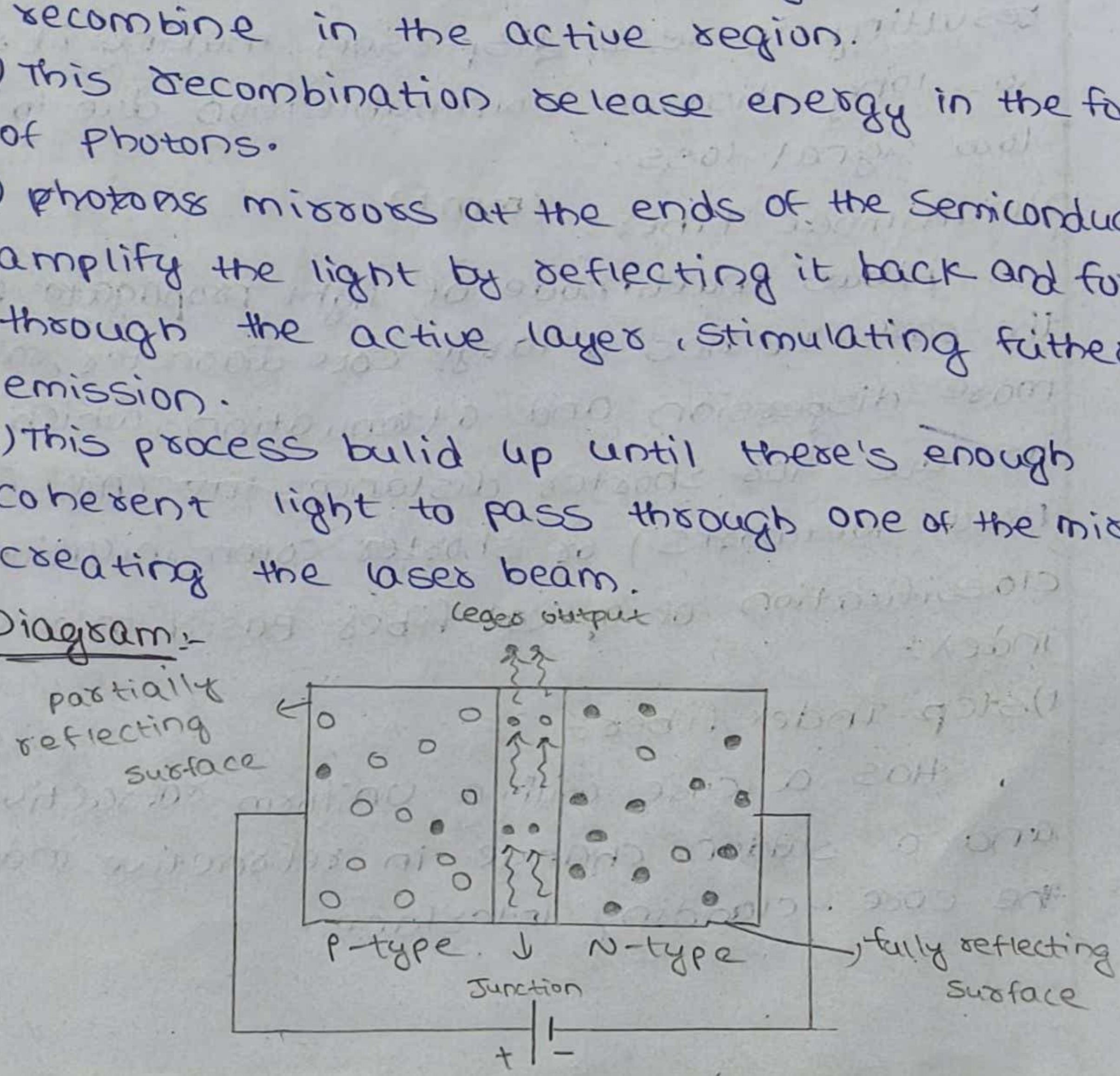
1) when a foward bias voltage is applied across the P-N junction, it causes electrons from the n-type region and holes from the P-type region to recombine in the active region.

2) This recombination release energy in the form of photons.

3) photons mirrors at the ends of the Semiconductor amplify the light by reflecting it back and forth through the active layer, stimulating futher emission.

4) This process bulid up until there's enough coherent light to pass through one of the mirrors creating the laser beam.

Diagram:-



Applications:-
1) It is used in telecommunications.
2) It is used in medical Devices like laser surgery and diagonostic-
3) Consumer electronic, printers, barcodes scanners etc.
4) It is used in Industrial Application like cutting, welding and marking materials.

4. write a note on the classification of optical fiber based on the mode of propagation and refractive index

A) * Classification of optical fiber Based on modes of propagation.

1) Single mode Fiber :- (SMF)
Allows only one mode of light is propagate through the core. It has a smaller core diameter resulting in less dispersion, making it suitable for long-distance communication due to its low signal loss.

2) multimode Fiber :- (MMF)
Allows multimode of light propagate through the core. It has a large core diameter, causing more dispersion and attenuation, which limits its use for shorter distances like LANs (Local Area Networks) or shorter communication Links

Classification of optical fiber Based on refractive index:-

1) step-Index fiber:-
Has a core with a uniform refractive index and a sudden change in refractive index at the core-cladding interface.

2. Graded-Index fiber:-

The core's refractive index varies gradually from the center to the cladding, reducing modal disperison by allowing light rays to travel at different speeds but converge at the ~~in~~ output end, improving signal quality.

5) write note on Numerical Aperture and acceptance angle.

A) 1) Numerical Aperture:-

Numerical Aperture is a measure of the light gathering ability of an optical system, like a microscope or a fiber optic. It's determined by the refractive indices of the medium the lens is in and the medium it's trying to gather light from. Higher NA value to indicate a greater ability to gather light and resolve fine details.

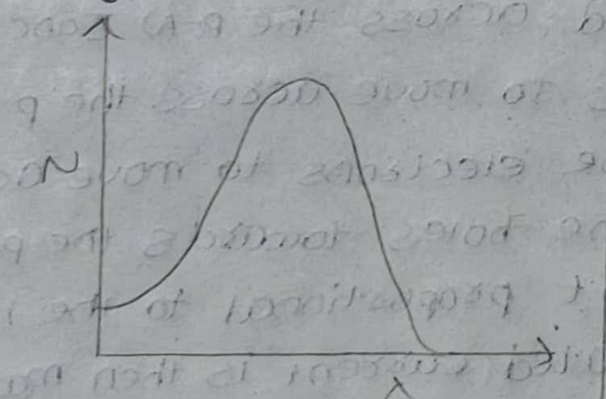
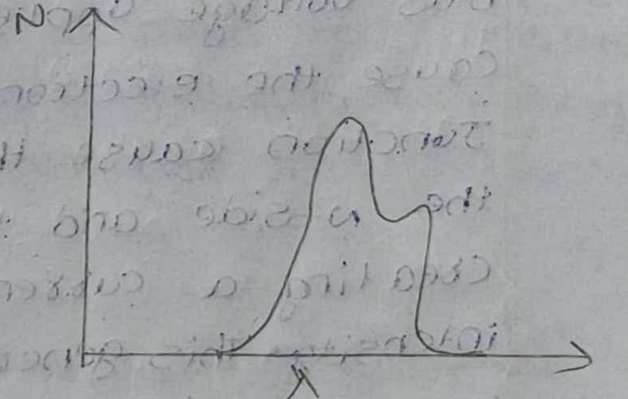
Acceptance Angle:-

Acceptance angle refers to the maximum angle at which light can enter an optical fiber and still be transmitted throught it effectively. It's related to the NA and determines the range of angle at which light can propagate through the fiber without being lost due to total internal reflection.

Both Numerical Appersture and acceptance angle play vital roles in optical systems, especially in deteomining their resolving power and efficiency.

UNIT 5

1. Differentiate between optical absorption and optical emission with an appropiate Diagram.

optical absorption	optional emission.
1) In this process, photons are absorbed by atoms or molecules, leading to the transition of electrons to higher energy levels.	1) this process involves the release of photons when electrons transition from higher energy level to lower ones.
2) the absorbed energy is used to move electrons from a lower energy state to a higher one, creating a excited state.	2) Electron lose energy and emits photons correspond-ing to the energy differ-ence between the higher and lower energy states.
3) A diagram illustrating optical absorption would show photons being abso-rbed by electrons, causing them to move to higher energy levels.	3) A diagram for optical emission would depict electrons returning to lower energy levels, emit photons in the process.
diagram:- 	diagram:- 

2. Explain the construction and working of PIN Photodiode?

A) A PIN photodiode is a type of photodectector used to convert light into electrical current.

It consist of three layers-

1) P-Type Layer:-

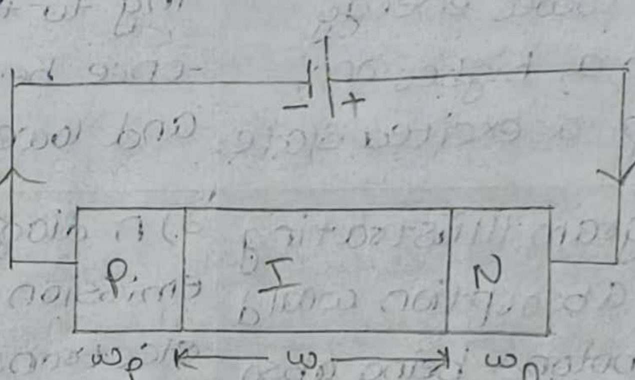
It's the postively Charged layer where the hole are the majority Carriers.

2) Instrinsic layer:-

This layer is high lighly doped and acts electron as a barrier, allowing photons to generate electron-hole pair when light strikes it.

3) N-type layer:-

This layer is negatively charged and electron are the ~~mago~~ majority carriers here.



Working:-

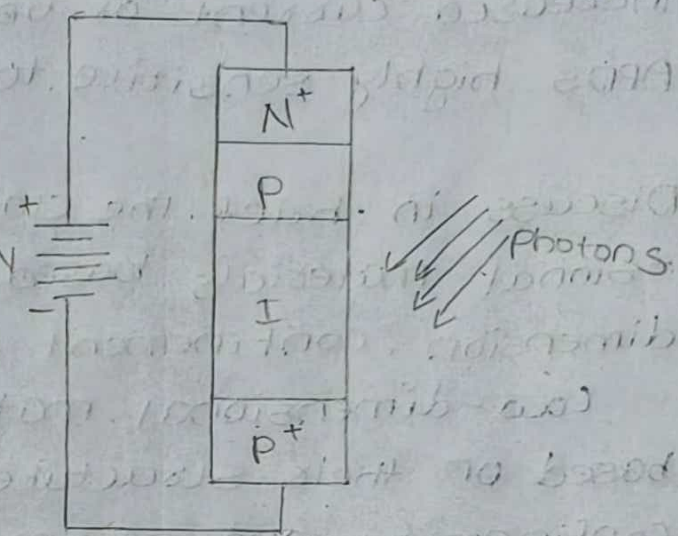
When light photons strike the photondiode, they generate electron-hole pairs in the intrinsic layer. The electric field created by the reverse bias voltage applied across the P-N Junction cause the electrons to move across the P-N Junction cause the electrons to move across the N-side and the holes towards the P-side creating a current proportional to the light intensity. This generated current is then measured or ~~ap~~ amplified to interpert the light intensity or use it for various applications like in optical communication remote sensing or in detecting light in electronic devices.

3- Explain construction and working of Avalanche photodiode.

A) Construction:-

* It consists of a P-n junction formed by doping a semiconductor (like silicon or germanium) with impurities to create regions with different electrical properties.
* The APD typically includes a high-doped region (The multiplication or avalanche region) with in the depletion region of the diode.

diagram:-



working:-

1) Light Detection:-

when photons strike the APD's depletion region they generate electron-hole pairs these pairs are created when the photons transfer their energy to electrons, freeing them from their position in the crystal lattice.

2) Avalanche Effect:-

The electrons and holes produced by the absorbed photons are accelerated by this electric field. If the voltage in high enough these accelerated carriers gain sufficient kinetic energy to collide with other atom in the material releasing more electron-hole pairs through impact ionization.

4. Avalanche multiplication:-

This impact ionization result in a multipli-cation of carriers, leading to an avalanche effect. As a consequence, a single photon can produce a more significant number of electron-holes pairs, significantly amplifying the intial signal.

5. Output:-

The amplified signals is detected as an increased current or voltage output, making APDs highly sensitive to low levels of light.

4. Discuss in brief the classification of low dimen-sional materials based on their structure, dimension, confinement and mobility.

A) Low-dimensional materials are classified based on their structure, dimensionality, confinement and carrier mobility.

1. Based on structure:-

* Layered materials:-

Consist of stacked layers like graphene transition metal dichalcogenides (TMD)s.

* Quasi-0D structures:-

Zero-dimensional structure like quantum dots or nanoparticles where the electrons are confined in all directions.

* 1D structures:-

Such as nanowires, nanorods or nano tubes that exhibit elongated structures.

2. Dimensionality:-

* 2D materials:-

Exhibiting properties in two dimensions (thickness and length but not height) like graphene, hexagonal boron nitride (hBN).

* 1D materials:-

properties along one direct dimension like nanowires or nanotubes.

* 0D - materials:-

possessing properties in all dimensions restricted within a small volume such as quantum dots.

3. Confinement:-

* Quantum confinement:-

Refers to the restriction of electron movement in atleast one dimension, leading to quantum effects. this confinement alters electronic and optical properties.

* Dimensional confinement:-

the confinement charge carriers in one or more dimensions affect their behaviour and transport properties.

4. Carrier mobility:-

* Hight carrier mobility:-

Some low-dimensional materials exhibits exceptional carrier mobility, enabling efficient charge transport. materials like graphene have high carrier mobility, making them promising for high-speed electronics.