Module 4 Modern Physics: Short notes

1. Semiconductors

Energy Band In a crystal due to interatomic interaction, valence electrons of one atom are shared by more than one atom in the crystal. Then splitting of energy level takes place. The collection of these closely spaced energy levels are called an energy band.

Valence Band Valence band are the energy band which includes the energy levels of the valence electrons.

Conduction Band Conduction band is the energy band above the valence band.

Energy Band Gap The minimum energy required for shifting electrons from valence band to conduction band is called energy band gap (E_g).

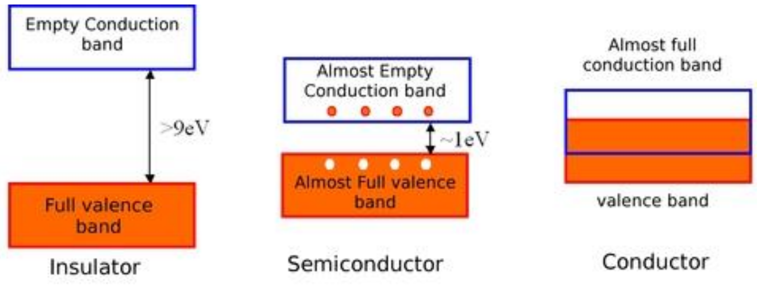
<u>The difference Between Metals, Insulators, and Semiconductors on the basis of their energy bands</u>

Conductors: For a conductor, conduction bands and valence bands are not separated and there is therefore no energy gap. The conduction band is then partially occupied (even at low temperatures), resulting in a "high" electrical conductivity.

Conductors are solids with conductivity in between 10^2 S/m to 10^8 S/m (or resistivity in between 10^{-2} Ω/m to 10^{-8} Ω/m). Here, S/m represents the unit of conductivity and is read as siemens/meter. The siemens is also referred to as mho, the reciprocal of the unit of resistance ohm. Eg: Gold, silver, copper aluminum

A **semiconductor** is primarily an insulator at 0K. However, since the energy gap is lower compared to insulators (~1eV), the valence band is slightly thermally populated at room temperature, whereas the conduction band is slightly depopulated. **Semiconductors** are conductors with less conductivity or insulators with less resistivity. Eg: Silicon, Germanium

Insulators: Materials that are poor conductors of heat and electricity are called Insulators. In insulators, the valence band is completely filled while the conduction band resulting in a large energy gap. Since the energy gap between the conduction band and the valence band is more, there is no movement of electrons from the valence band to the conduction band.



Their with conductivity in between 10^{-11} S/m to 10^{-19} S/m (or resistivity in between 10^{+11} Ω/m to 10^{+19} Ω/m). They offers very high resistance against the flow electrical current through them. Eg: wood, paper, rubber, mica etc

Intrinsic and extrinsic semiconductors

A pure semiconductor is called an **intrinsic** semiconductor.

The conduction properties of a semiconductor can be drastically changed by diffusing a small amount of impurity in it. The addition of impurities to the intrinsic one is called **doping.** This increases the conduction properties of a semiconductor by diffusing a small amount of impurity in it. The dopant has to be such that it does not distort the original pure semiconductor lattice

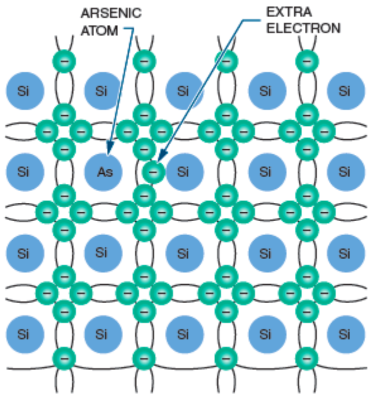
Pure semiconductor when doped with the impurity, it is known as **extrinsic semiconductor**. Extrinsic semiconductors are basically of two types: n-type semiconductors and p-type semiconductors

(a) Doping: Adding impurities to a semiconductor material
(b) Pentavalent : Made of atoms with five valence electrons
(c) Trivalent: Made of atoms with three valence electrons

N type semiconductors

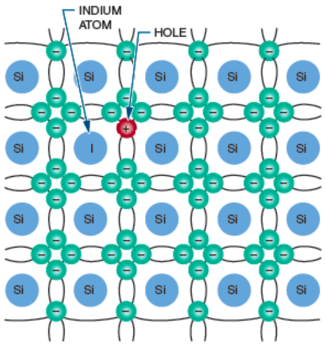
To increase the number of conduction-band electrons in intrinsic silicon, pentavalent impurity atoms are added. This introduces a free electron for conduction along with the available conduction electrons in the intrinsic semiconductor. In n-type semiconductor, electrons are the majority carriers and holes are the minority carriers

Examples for donor impurity atoms with five valence electrons such as Arsenic (As), Phosphorus (P), Bismuth (Bi), and Antimony (Sb).



P type semiconductors:

To increase the number of holes in intrinsic silicon, trivalent impurity atoms are added. Then an extra vacancy is created called holes. In p-type semiconductors, holes are the majority carriers and electrons are the minority carriers. Examples for trivalent impurity/acceptor impurity atoms with three valence electrons are Boron (B), Indium (In), and Gallium (Ga).



NOTE: Both the type of semiconductors are electrically neutral.

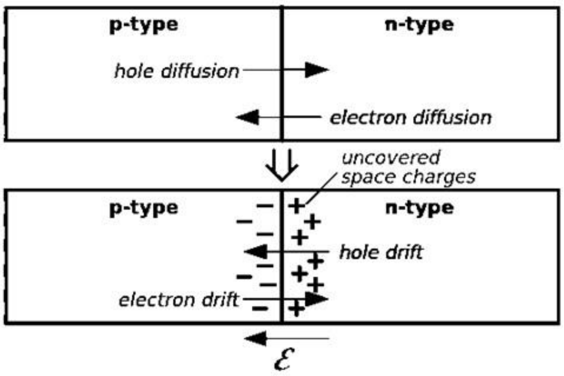
P-N Junction

A p-n junction is formed by joining together two pieces of semiconductor, one doped n-type, the other p-type. When a p-n junction is formed, some of the electrons from the n-region which have reached the conduction band are free to diffuse across the junction and combine with holes. Filling a hole makes a negative ion and leaves behind a positive ion on the n-side. A space charge builds up, creating a depletion region. This zone controls the behavior of the diode.

Diffusion current = the movement of charge carriers caused by variation in the carrier concentration.

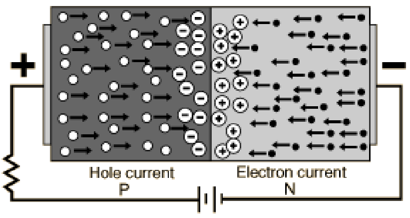
Drift current = the movement charge carriers caused by electric fields.

Direction of the drift current is always in the direction of the electric field.



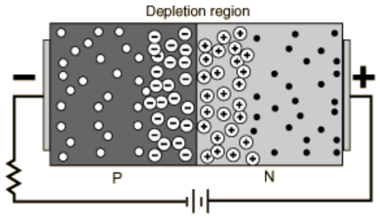
Forward biasing

In a forward bias setup, the P-side of the diode is attached to the positive terminal and N-side is fixed to the negative side of the battery. Forward biasing the p-n junction drives holes to the junction from the p-type material and electrons to the junction from the n-type material. At the junction the electrons and holes combine so that a continuous current can be maintained.

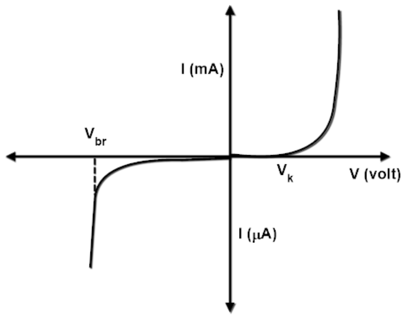


Reverse Biasing

Reverse bias is **when the p-side of the diode is connected to the negative voltage of the battery and the n-side is connected to the positive voltage of the battery**. This causes an increase in the thickness of the depletion layer. This allows very less current to flow through the PN junction.



V-I characteristics of a p-n junctiondiode



When forward-biased, there is a small amount of voltage necessary to get the diode going. In silicon, this voltage is about 0.7 volts. This voltage is needed to start the hole-electron combination process at the junction

When reverse-biased, an ideal diode would block all current. A real diode lets perhaps 10 microamps through -- not a lot, but still not perfect.

Applications of diodes

a) Diode as rectifier: A p-n junction diode offers very low resistance in the forward bias and very high resistance in the reverse bias. So, if an alternating voltage is applied across a diode the current flows only in that part of the cycle when the diode is forward biased. This property is used to rectify alternating voltages and the circuit used for this purpose is called a rectifier.

b) Diode as a voltage regulator (Zener diode): A diode meant to operate in the breakdown region is called an avalanche diode or a Zener diode depending on the mechanism of breakdown. Once the breakdown occurs, the potential difference across the diode does not increase even if the applied battery potential is increased. Such diodes are used to obtain constant voltage output. The current through the diode changes but the voltage across it remains essentially the same.

c**) Photodiodes (photodetectors): used for detecting optical signal**

A Photodiode is again a special purpose p-n junction diode fabricated with a transparent window to allow light to fall on the diode. It is operated under reverse bias. Under illumination electron-hole pairs are generated due to the absorption of photons. Due to electric field of the junction, electrons and holes are separated before they recombine. The direction of the electric field is such that electrons reach n-side and holes reach p-side.(photoelectric effect). Electrons are collected on n-side and holes are collected on p-side giving rise to an emf. When an external load is connected, current flows. The magnitude of the photocurrent depends on the intensity of incident light (photocurrent is proportional to incident light intensity).

d) Light emitting diodes (LED) which convert electrical energy into light: It is a heavily doped p-n junction which under forward bias emits spontaneous radiation. The diode is encapsulated with a transparent cover so that emitted light can come out. When the diode is forward biased, electrons are sent from n → p (where they are minority carriers) and holes are sent from p → n (where they are minority carriers). At the junction boundary on either side of the junction, excess minority carriers are there which recombine with majority carriers near the junction. On recombination, the energy is released in the form of photons. Photons with energy equal to or slightly less than the band gap are emitted.

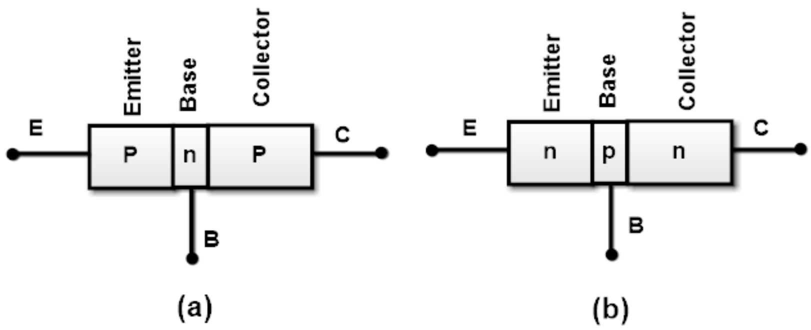
e) Solar Cell: Photovoltaic devices which convert optical radiation into electricity
A solar cell is basically a p-n junction which generates emf when solar radiation falls on the p-n junction. It works on the same principle (photovoltaic effect) as the photodiode, except that no external bias is applied, and the junction area is kept much larger for solar radiation to be incident because we are interested in more power.

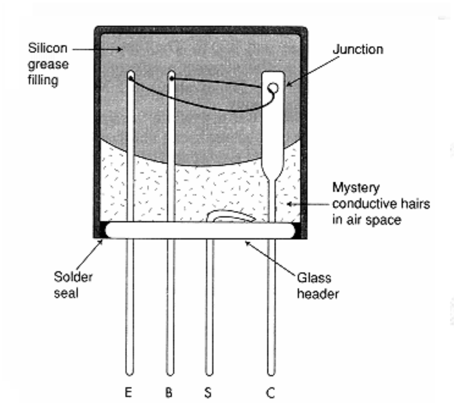
Transistors

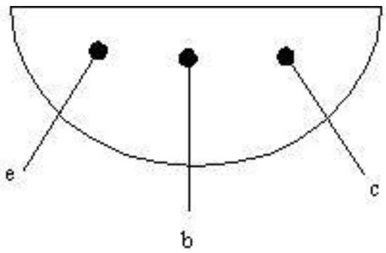
A transistor is formed by sandwiching a thin layer of a p-type semiconductor between two layers of n-type semiconductors or by sandwiching a thin layer of an n-type semiconductor between two layers of p-type semiconductors. All the three regions of a transistor have different thickness and their doping levels are also different. So that the carrier concentration and their mobility, drift and diffusion etc. may be different at different regions.

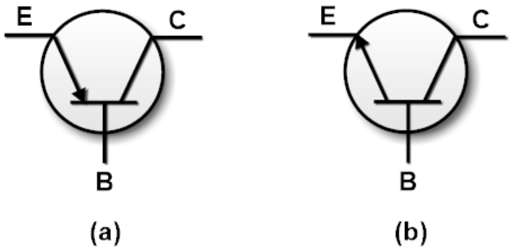
Depending upon the size and doping concentration the different regions in the transistor are designated as Emitter, Base and Collector. Therefore, the transistor is a three-terminal device. Since the transistor is not symmetrically configured, the Collector terminal and Emitter terminals must not be interchanged

a) **Emitter**: It is one of the outer regions with moderate size and somewhat heavily doped so that it can supply a large number of majority carriers for the current flow through the transistor.
b) **Base:** This is the central narrow region with other type of majority charge carriers. It is very thin and lightly doped.
c) **Collector:** The collector part is moderately doped and larger in size as compared to the emitter. This region collects a major portion of the majority carriers supplied by the emitter, hence the name collector









Symbols for (a) pnp transistor and (b) npn transistor

In the n-p-n transistor, there are a large number of conduction electrons (majority charge carriers in n region) in the emitter and a large number of holes (majority charge carriers in p region) in the base. Similarly, In the p-n-p transistor, there are a large number of holes (majority charge carriers in p region) in the emitter and a large number of conduction electrons (majority charge carriers in n region) in the base.
Suitable potential differences should be applied across the two junctions to operate the transistor. This is called biasing the transistor. The biasing of the transistor is done differently for different use.

A transistor can be operated in three different modes: common emitter configuration or CE configuration (here the emitter region is grounded), common collector configuration or CC configuration (here the collector region is grounded) and common base configuration or CB configuration (here the base region is grounded). **In normal operation of a transistor, the emitter–base junction is always forward-biased whereas the collector–base junction is reverse-biased,** or we can say the transistor is in CE configuration

Applications of transistors:

a) Transistor as a switch: The transistor is connected in CE configuration and as long as the input voltage applied across emitter base junction V_{BB} or V_i is low and unable to forward-bias the transistor, the output voltage across the emitter collector junction V_{CC} or V_o is high. If V_i is high enough to drive the transistor into saturation, then Vo is low, very near to zero. When the transistor is not conducting it is said to be switched off and when it is driven into saturation it is said to be switched on. This shows that if we define low and high states as below and above certain voltage levels corresponding to cutoff and saturation of the transistor, then we can say that a low input switches the transistor off and a high input switch it on. Alternatively, we can say that a low input to the transistor gives a high output, and a high input gives a low output. The switching circuits are designed in such a way that the transistor does not remain in active state.

If the transistor is operated in the saturation region then it acts as closed switch and when it is operated in the cut off region then it behaves as an open switch.

b) Transistor as an amplifier: If the transistor is properly biased, the collector (output) current is directly proportional to the base (input) current and the trasnsitor act as a current amplifier. This condition can be written as

$I_C \propto I_B$
i.e., $I_C = \beta I_B$
the quantity β (beta) is called the current gain.

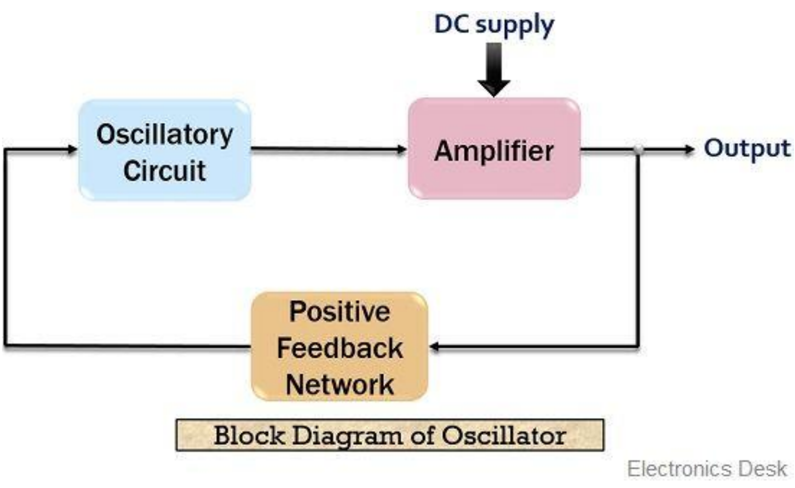
Transistors can act as amplifiers while they are functioning in the active region or when it is correctly biased. The need for transistor as an amplifier arises when we want to increase or amplify the input signal.

c) Transistor as an Oscillator:

A transistor can be operated as an oscillator for producing continuous undamped oscillations of any desired frequency if tank (or oscillatory) and feedback circuits are property connected to it.

Essentials of Transistor Oscillator

(i) Tank Circuit: It consists of inductance (L) connected in parallel with capacitor (C)
(ii) Transistor amplifier: The transistor amplifier receives d.c. power from the battery and changes it into a.c. power for supplying to the tank circuit.
(iii) Feedback circuit:



Photoelectric Effect

When light of sufficient wavelength is incident on some metal surface, electrons are ejected from the metal. This phenomenon is called the **photoelectric effect**. The electrons ejected from the metal are called **photoelectrons**.

1) The photoelectric effect is frequency dependent: There is a particular frequency above which the photoemission of electrons happens. This frequency is called as threshold frequency.

2) The photoelectric current is intensity dependent: The number of photoelectrons generated determines the photocurrent. If the incident wave frequency is higher than or equal to the threshold frequency the photocurrent generated is proportional to the intensity of radiation.

3) Photoelectric effect is an instantaneous process: There is no time lag between the incidence of radiation and emission of photoelectrons for the incident wave with sufficient frequency

Einstein explained these experimental facts about photoelectric effect with the help of Quantum theory of light. It says that the light is not continues flow energy rather it is emitted or absorbed as discrete packets of energy called as Quanta called photon having energy

$$E=h\upsilon=hc/\lambda$$

where, h is the Plank's constant, ν is the frequency of light and λ is the wavelength of light.

Einstein proposed a theory that the incident energy of light is used for removal of electrons from the atom in the metal surface and to give kinetic energy to the released electrons.

$$Incident\ photon\ energy = \text{work function} + \text{kinetic energy}$$

$$h\upsilon = h\upsilon_0 + \tfrac{1}{2}mv^2$$

Applications of Photoelectric Effect

a) Photoelectric cell is used as an illumination meter to measure the illuminating power of light sources.

b) A burglar alarm can be constructed with a photoelectric cell.

c) Photoelectric cell is used in relay circuits.

d) A photo conductive cell is used for detecting infra-red light.

e) Photoelectric cell is used to reproduce sound recorded in a talkie film.

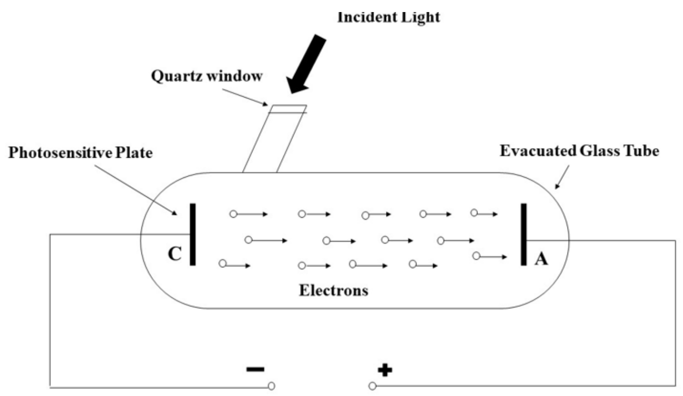
f) An array of photoelectric cell is used in television cameras for the conversion of light into electric signals.

g) Photoelectric cells are used in automatic cameras to detect the ambient light and adjust the lenses to get clear photographs.

Photocells

A photocell or photoresistor is **a sensor that changes its resistance when light shines on it**. The resistance generated varies depending on the light striking at his surface. When light photons fall on it, they force electrons to leap out of it and these are promptly attracted to the positive terminal, which collects them and channels them into a circuit, producing electric power.

A photocell is a common nomenclature used for light sensitive semiconductor electronic devices such as cadmium sulfide cells, LDR (Light Dependent Resistors), photoresistors etc., They are sensors used to detect the light or intensity of light. The working principle of Photocells depends on the phenomenon of electrical resistance and the photoelectric effect



Schematic diagram of a photocell

In order to be able to reach the collector electrode or anode, the photoelectrons generated must have a kinetic energy equal to or greater than the electrical potential energy that they must gain in going between emitter and collector.

If the potential of the anode is made negative with respect to the cathode with the rheostat, the electrons are repelled by the anode. Some electrons go back to the cathode so that the current decreases. At a certain value of this negative potential, the current is completely stopped. The smallest magnitude of the anode potential which just stops the photocurrent, is called the stopping potential. The stopping voltage is independent or the intensity of the incident radiation on emitter electrode. The stopping potential is related to the maximum kinetic energy of the ejected electrons under a given frequency of incident radiation

$$\frac{1}{2}mv^2 \geq eV_0$$

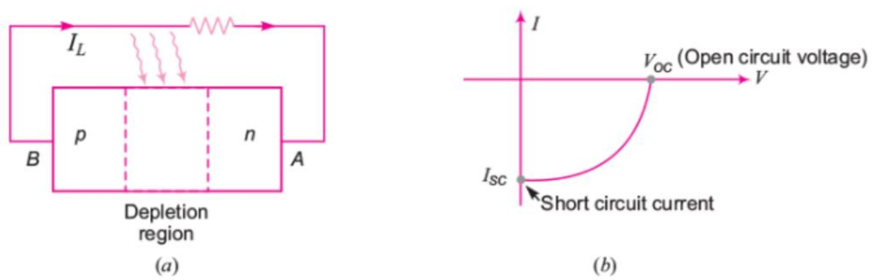
By Einstein's equation, $\frac{1}{2}mv_0 = eV_0 = h\upsilon - \phi = h\upsilon - h\upsilon_0$

Hence the Stopping potential can be written as

$$V_0 = \frac{hc}{e}\left(\frac{1}{\lambda}\right) - \frac{hc}{e}\left(\frac{1}{\lambda_0}\right)$$

The stopping potential V_0 depends on the wavelength of the light and the work function of the metal. It does not depend on the intensity of light.

<u>Solar cells</u>



A **solar cell** (also known as a photovoltaic cell or PV 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.
Individual solar cells can be combined to form modules commonly known as solar panels. The common single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts. By itself this isn't much – but remember these solar cells are tiny. When combined into a large solar panel, considerable amounts of renewable energy can be generated.

Applications of Solar Cells

a) Solar cells along with storage batteries are used in many electrical appliances

b) Solar Cells are used as energy source in satellites and space stations

c) Solar cells are used in calculators

d) Solar Cells are used to power the electric vehicles

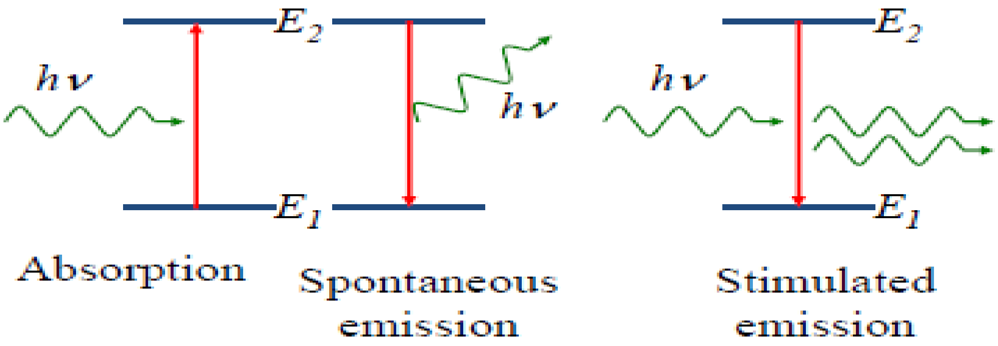
LASER

LASER is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Albert Einstein published the theoretical basis for the laser in 1917, but it was only in 1960 that the first functioning laser was constructed by Theodore Maiman in California, using a ruby crystal to produce laser light.

Absorption, Spontaneous and Stimulated Emission

Absorption: An atom in a lower level absorbs a photon of frequency hν and moves to an upper level.
Spontaneous emission: An atom in an upper level can decay spontaneously to the lower level and emit a photon of frequency hν if the transition between E2 and E1 is radiative. This photon has a random direction and phase.

Stimulated emission: An incident photon causes an upper level atom to decay, emitting a "stimulated" photon whose properties are identical to those of the incident photon. The term "stimulated" underlines the fact that this kind of radiation only occurs if an incident photon is present. The amplification arises due to the similarities between the incident and emitted photons.



$$h\nu = E_2 - E_1$$

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Components of a laser

A laser consists of 3 basic components:

1. **A lasing medium or "gain medium":** A solid (crystals, glasses), liquid (dyes or organic solvents), gas (helium, CO2) or semiconductors medium having a metastable state.

A metastable state, in physics and chemistry, particular excited state of an atom, nucleus, or other system that has a longer lifetime than the ordinary excited states and that generally has a shorter lifetime than the lowest, often stable, energy state, called the ground state. **A population inversion is created between ground level/lower energy level and a higher-energy metastable state**.

2. **An energy source or "pump":** A high voltage discharge, a chemical reaction, diode, flash lamp or another laser
3. **An optical resonator or "optical cavity":**
   Consists of a cavity containing the lasing medium, with 2 parallel mirrors on either side. One mirror is highly reflective and the other mirror is partially reflective, allowing some of the light to leave the cavity to produce the laser's output beam – this is called the output coupler.

The laser is usually named according to the type of lasing medium. This also determines the type of pump required and the wavelength of the laser light which is produced.

Principle of operation

Due to stimulated emission the photons multiply in each step-giving rise to an intense beam of photons that are coherent and moving in the same direction. Hence the light is amplified by Stimulated Emission of the Radiation. Generally, the laser action involves the following processes

1. Pumping: This is the process where the excitation of ground state atom to excited state occurs. There are different pumping methods employed in various lasers.

2. Population inversion: It is the necessary condition to achieve lasing action. The number or excited state atom in a medium is greater than that in the ground state. That is the population of the upper state is greater that that of the lower state.

3) Amplification: The optical cavity or resonator of laser usually consists of two mirrors, curved or plane, between which the amplifying medium is located. If a sufficient population inversion exists in the medium, then the electromagnetic radiation builds up and becomes established as a standing wave between the mirrors. One or both of the mirrors may partially silvered so that this energy is usually breaks out as laser light from the resonator.

4) Coherent emission: The amplified waves in the cavity are in same phase so that the out put laser light is coherent. So that the laser light will have high directionality and high intensity

Methods for producing Population inversion
There are several methods for producing the population inversions necessary for optical amplification to take place. Some of the most commonly used are
1) Optical pumping or photon excitation: In case of optical pumping, an external light source is employed to produce a high population of some particular energy level in the laser medium by selective optical absorption. This method is used in solid state laser. Example ruby laser

2) Electron excitation: This is a type of electrical pumping. Direct electron excitation by gaseous discharge may be used to produce the population inversion. This method is used in some of the gaseous ion lasers such as argon laser.

3)Inelastic atom-atom collisions: This is also another type of electrical pumping. Here also an electric discharge is employed to excite the atoms. But in this method a suitable combination of gases is employed such that two different types of atoms, say A and B, both have some excited states A* and B* that coincide or nearly coincide. In this case the transfer of excitation may occur between the two atoms, as follows
$A*+B \rightarrow A+B*$
If the excited state of one of the atoms, A* is metastable, then the presence of gas B will serve as an outlet for the excitation. As a consequence, it is possible that the excited level of atom B may become more highly populated than some lower level to which the atom B can decay by radiation. This is happening for the helium-neon laser.
4) Chemical reactions: This type of lasers using chemical reaction to produce population inversion are known as chemical lasers. This type of pumping is called a chemical pumping. Here a molecule is caused to undergo a chemical change in which one of the products of the reaction is a molecule or an atom, that is left in an excited state. Under appropriate conditions a population inversion can occur. Example is hydrogen fluoride chemical laser

Characteristics of LASER

a) **Laser light is monochromatic:** The laser radiation is having a single color, or the radiation is having only one wavelength. Since the emitted wave will have the comparable wavelength as that of the energy bandgap.

b) **Laser light is highly coherent:** The individual waves in the laser radiation are in same phase. (same phase and frequency).

c) **Laser light is highly intense:** Since the number of waves per unit area is large and are in same phase, the laser light is highly intense.

d) **Laser light is highly directional and has low divergence:** This is because of the fact that the laser light is highly coherent or the waves are in same phase.

Helium-Neon laser

Helium-Neon laser is a type of gas laser in which a mixture of helium and neon gas is used as a gain medium. Helium-Neon laser is also known as He-Ne laser.

In He-Ne lasers, the optical pumping method is not used instead an electrical pumping method is used. The excitation of electrons in the He-Ne gas active medium is achieved by passing an electric current through the gas.

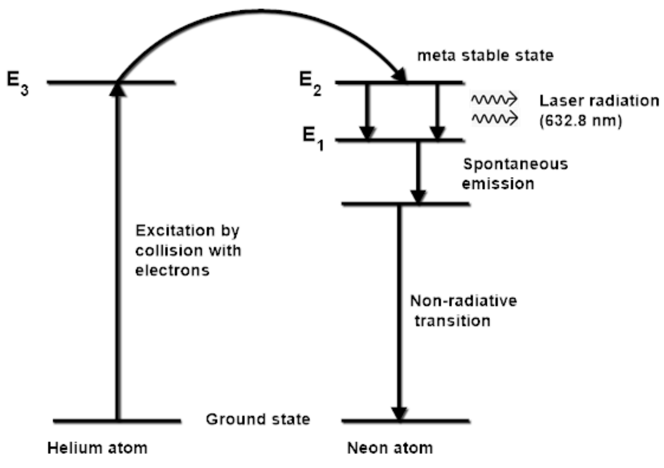
The helium-neon laser operates at a wavelength of 632.8 nanometers (nm), in The helium-neon laser consists of three essential components:

- Pump source (high voltage power supply)
- Gain medium (laser glass tube or discharge glass tube)
- Resonating cavity

When the power is switched on, a high voltage of about 10 kV is applied across the gas mixture. This power is enough to excite the electrons in the gas mixture. The electrons produced in the process of discharge are accelerated between the electrodes (cathode and anode) through the gas mixture.

In the process of flowing through the gas, the energetic electrons transfer some of their energy to the helium atoms in the gas. As a result, the lower energy state electrons of the helium atoms gain enough energy and jumps into the excited states or metastable states. Let us assume that these metastable state is E2. The metastable state electrons of the helium atoms cannot return to ground state by spontaneous emission. However, they can return to ground state by transferring their energy to the lower energy state electrons of the neon atoms.

The energy levels of some of the excited states of the neon atoms are identical to the energy levels of metastable states of the helium atoms. Let us assume that these identical energy states are $E_3 = E_2$



The neon excited electrons continue on to the ground state through radiative and nonradiative transitions. It is important for the continuous wave (CW) operation. The laser radiation will come out through the mirrors which are partially silvered.

Semiconductor LASER

In its simplest form the diode laser consists of a p-n junction in a doped single crystal of a suitable semiconductor, such as gallium arsenide (GaAs). The junction layer is very thin of the order of micrometers in length. And the end faces of the crystal are made partially reflective by polishing to form an optical resonator. When a forward bias is applied to the diode, electrons are injected into the p side of the junction and holes are injected into the n side. The recombination of holes and electrons within the junction region result in recombination radiation. This is the principle for the operation of light emitting diode (LED) device. The threshold current density for gallium arsenide injection laser is about 104 A/cm2 and the emitted radiation is in the near infrared, about 830 to 859 nm.

Applications of LASER

a) Laser can be used as tool for surgery (Ophthalmic surgery).

b) Laser is used for precision cutting, drilling, and welding.

c) Laser beam can be used as a carrier of information (telephone signal through optical fiber cables).

d) Laser based methods are used to guide missiles and pilot-less fighter planes.

e) Laser is used for range finding (measurement of distance of faraway objects).

f) Laser is used in Holography or 3D imaging.

g) Laser is used to initiate fusion reaction.

h) Laser is used to read and write data in CD/DVD systems.

i) Laser is used in printing technology (Laser printer).

j) Laser is used in textile industry to perfectly cut many layers of cloths together

Introduction to Nanotechnology

The study of objects and phenomena at a very small scale (1-100 nanometers) is called **Nanoscience.** In Nanometer scale the material properties are size and shape dependent. The large surface area of Nanomaterials enhance the properties such as reactivity, strength and electrical characteristics.

Nanotechnology is the design, characterization, production and application of structures, devices and systems by controlling shape and size at Nano meter scale.

Distinguishing properties of Nanomaterials.

a) A bulk material should have constant physical properties, but at the nano-scale size-dependent properties are observed.

b) Percentage of atoms at the surface of a material is increased

c) Increased surface area

d) Aspect ratio or surface to volume ratio will increase considerably

Properties of Gold nano particles

Properties	**Gold**	**Gold Nano**
1. Colour	Yellow	Red
2. Electrical conductivity	Conductive	Less conductivity
3. Magnetism	Non-magnetic	Becomes Magnetic
4. Chemical reactivity	Chemically inert	Explisive, catalytic

Characteristics of Nano materials

a) Nano fiber stronger than spider web
b) Nano metal is 100 times stronger than steel
c) Nano catalysts respond more quickly in reaction
d) Nano plastics that conduct electricity.
e) Nano coatings are frictionless
f) Nano materials that change colour and transparency
g) Nano scale powders better than metal for radiation protection