Lasers

Laser is an acronym for *light amplification by stimulated emission of radiation*. Here the process of stimulated emission is used to amplify light radiation.

Spontaneous emission: When energy is given to an atom some of its electron moves from ground state to higher energy states and atom is said to be in excited state. The electron remains in the higher state for a very short duration (of the order of ns to μs) and then returns by itself back to the ground state emitting extra energy as light radiation. The process of emission of light radiation this way is called spontaneous emission.

Population inversion: In a system generally the number of atom in the lower energy state is always larger than the number of atoms in the excited energy state. If we externally supply some energy to the system to excite atoms to higher energy states and maintain it such a way the number of atoms in the excited state is more than that in the ground state. The system is said to be in population inversion. Thus the population inversion refers to the state of the system in which the number of atoms in the higher energy levels is more than that in the lower energy levels. The two situations are represented below in energy level diagram. Figure (b) shows population inversion occurring between energy levels E_3 and E_1.

Figure 1. (a) Normal state **(b) State of population inversion**

Stimulated emission: If in a system where there exist population inversion, we allow a photon of energy, equal to the energy difference between the levels between which population inversion exists, then the incident light photon may interact with the excited atom and force it to go back to its ground state emitting thereby an another light photon of same frequency, phase and same state of polarization. These two photons are perfectly coherent In this process the incident photon make emission of another photon from excited atom and is named as **stimulated emission**. It is sort of induced emission and takes place only, if there exist a population inversion in the system. It is basic condition responsible for operation of laser.

Main components of a laser: In any laser there are three main components, namely, the *active medium*, *pumping system* and *optical resonator*. Each of these are described in details as below.

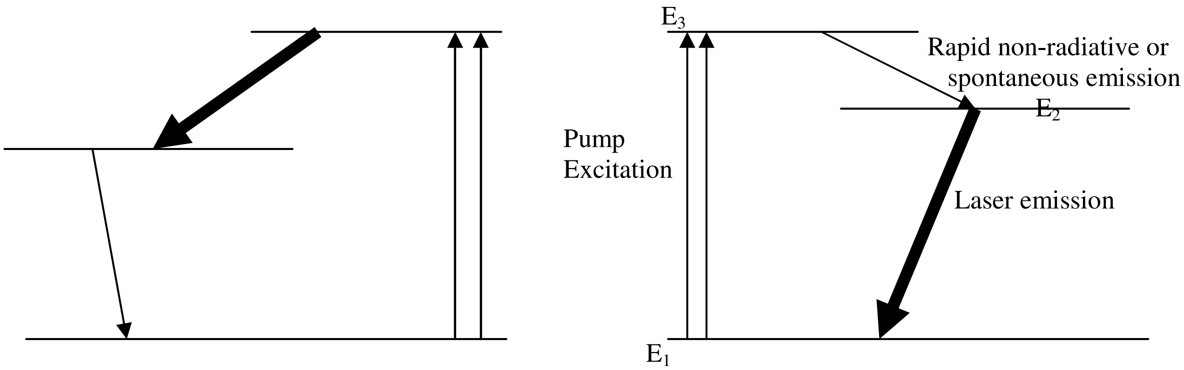
Active medium: It is also called amplifying medium and is consists of a collection of atom, molecules or ions. It may be solid, liquid or gas. Under normal conditions the number of atoms in the lower energy state is always larger than the number of atoms in the excited energy state. A light wave passing through such a collection of atoms would cause more absorption than emissions and therefore the wave will be attenuated. To have laser action by stimulated emission it is necessary to create population inversion between the two atomic states in the medium. A light wave passing through such a collection of atoms, which are in the state of population inversion will cause more stimulated emissions and make the lasing action possible. Many lasers are named after the material used as active medium. For example ruby lasers, He-Ne lases, CO_2 laser and semiconductor laser.

Pumping system: The pumping system consists of an external source that supplies energy to active medium and helps in obtaining the population inversion. The excitation of atoms may occur directly or through atom-atom collision. It can be optical, electrical or thermal in nature. For example in ruby laser it is optical pumping, in He-Ne laser it is electric discharge pumping. The energy supplied by pumping system excites the atoms to higher energy levels and through spontaneous emission or non-radiative process atoms relax to lower levels and in some way the population inversion is established between two energy levels of the active medium.

Optical resonator: It consists of a pair of spherical mirrors having common principal axis. The reflectivity of one of the mirrors is very near to 100% and that of the other is kept somewhat less than 100%. It enables a part of internally reflected beam to escape out as laser beam. It is basically a feedback device that direct the light photons back and forth through the active medium and in the process the number of photon is multiplied due to stimulated emission causing thereby amplification

Classification of Lasers:

Three level lasers: It is impossible to create steady state population inversion between two energy levels by using pumping between these levels. Practically laser action is possible between three or more laser levels. In three levels laser system atoms are excited from ground level E_1 to an upper excited state E_3. As the lifetime of electrons in excited state is few ns, electrons relax down to level E_2. This level is chosen to be a metastable level with lifetime of about few milli seconds. Thus the number of atom having their electrons at E_2 increases and lead to population inversion between E_2 and the ground state. The laser action takes place between these levels.



(a) **(b)**

Figure 2. Energy level diagram of three level lasers (a) it gives continuous wave laser and (b) gives pulsed wave laser

Four level lasers: The energy level diagram of a four level laser system is shown below.

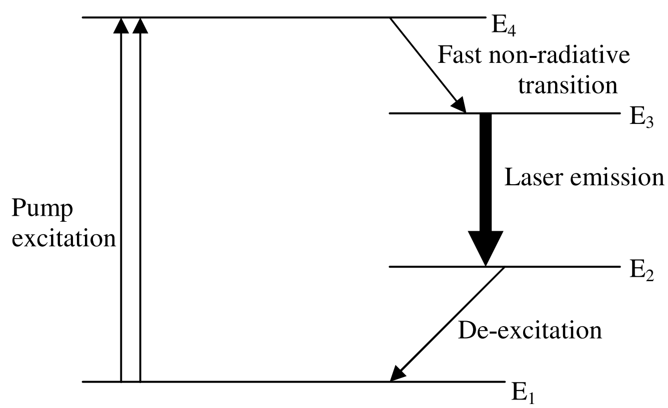


Figure 3. Energy level diagram of four level laser

In order that atom do not accumulate in level E_2 and hence destroy the population inversion between levels E_3 and E_2, level E_2 must have a short lifetime so that atoms are quickly removed to level E_1 ready for pumping to level E_4 again. Level E_4 can be a collection of levels or broad level. In such a case, the pumping source emitting over a broad range can be used to pump atoms from level E_1 to E_2.

Type of lasers:

i) Solid state lasers: Ruby ($Cr:Al_2O_3$) laser, Nd-YAG ($Nd:Y_3Al_5O_{12}$,., Neodymium doped yttrium aluminium garnet) laser, Nd-glass laser.

ii) Gas lasers: He-Ne laser, CO_2 laser, argon ion laser.

iii) Liguid lasers: dye lasers (Organic substances dissolved in water, ethyl alcohal, methanol, ethylene glycol etc.)

iv) Excimer lasers: Excimers are molecules which are bound in their excited electronic states but are unstable in their ground states e.g., Argon fluoride, krypton chloride, Krf, XeBr etc.

v) Semiconductor lasers: Also called junction laser or diode laser and today very important type of lasers having its applications in fiber optics communication.

Ruby laser:

Ruby is a crystal of aluminium oxide Al_2O_3 in which some aluminium ions are replaced by chromium ions. It contains 0.05-0.5 % by wt. of chromium and its colour is pink. It is the energy levels of chromium, which takes part in lasing action. Aluminium oxide is a host material. The energy level diagram of chromium is shown in Figure 4 below.

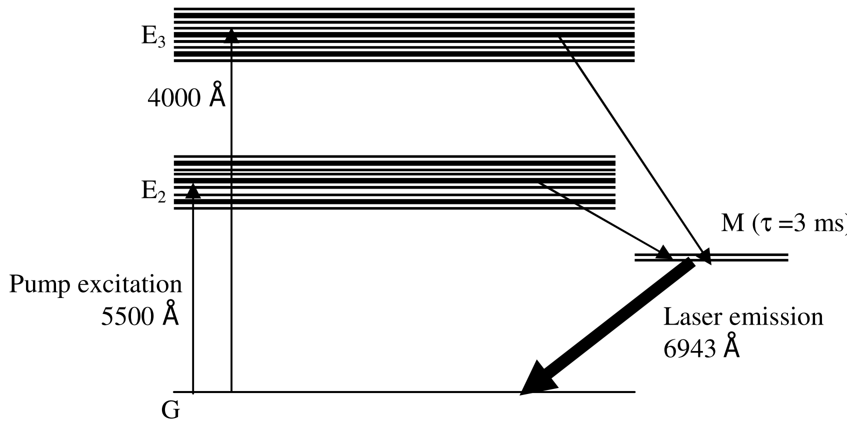


Figure 4: Energy level diagram of chromium ions in ruby laser.

As it is evident from the figure that ruby laser is three level laser. The level indicated G is the ground state of the chromium, the E_1 and E_2 are broad levels and M is a metastable level with a lifetime of about 3 ms.

The pumping of chromium ions is performed with the help of flash lamp (e.g., Xenon or Krypton flash lamp). The chromium ions in the ground state absorb radiation around wavelength of 5500Å and 4000Å and are excited to the broad levels E_1 and E_2. The chromium ions excited to these levels relax rapidly through non-radiative transition (in a time ~ 10^{-8} to 10^{-9} s) to metastable level M which is upper laser level. Once population inversion is established between metastable level M and the ground state G, laser emission starts at an output wavelength of 6943Å**.** The metastable level M is actually consists of a pair of closely spaced levels corresponding to laser wavelengths of 6943 Å and 6929 Å. However laser action takes place predominantly of the 6943 Å because of higher inversion.

The flash lamp operation in ruby laser leads to a pulsed output of the laser. As soon as the flash lamp stops operating the population of the upper level is depleted very rapidly and lasing action stops till the action of next flash.

Figure 5 shows a typical set up of a flush lamp pumped pulsed ruby laser. The helical flash lamp is surrounded by a cylinderical reflector to direct the pump light into the ruby rod efficiently. The ruby rod is placed along the axis of helical flash lamp. The ruby rod is length is typically 2-20 cm with diameters of 0.1 – 2 cm. In an alternate arrangement elliptical pump cavity can also be used in which straight lamp and the ruby rods are placed along the foci of an elliptical cyllinderical reflector. The elliptical reflector focuses the light emerging from one focus into the other focus thus leading to an efficient focusing of the pump light on the ruby rod.

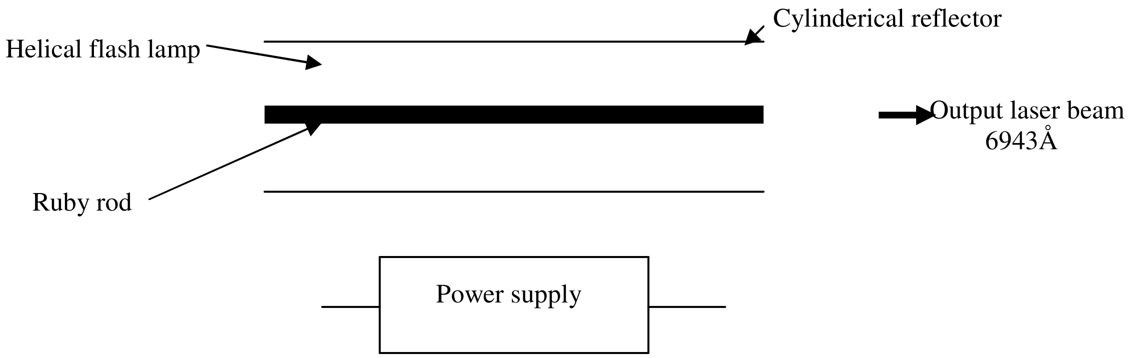


Figure 5: Schematic set up of ruby laser

In spite of the fact it is three level laser, ruby laser still is one of the important practical lasers. The absorption bands of ruby lies is visible spectrum so efficient use of practically available white light amps can be made for pumping. Ruby laser is also attractive from an application point of view, since its output lies in the visible region where photographic films and photodetectors are much more sensitive than they are in the infrared. It also find applications in pulsed holography and interferometery.

Helium Neon Laser:

The solid state lasers requires usually a flash lamp or a continuous high power lamp as pumping system for its operation. Such a technique is efficient if the lasing system has broad absorption bands. As in gases the atoms have sharp energy levels as compared to those in solids, use of an electric discharge can be made to pump the atoms in gaseous form.

Helium neon laser consist a long and narrow discharge tube (diameter ~ 2-8 mm and length 10-100 cm), which is filled with helium and neon gases with typical pressures of 1 torr. And 0.1 torr (1 torr =1mm of Hg), i.e., amount of helium is ten times that of the neon. Figure 6 below shows schematic set up of helium neon laser.

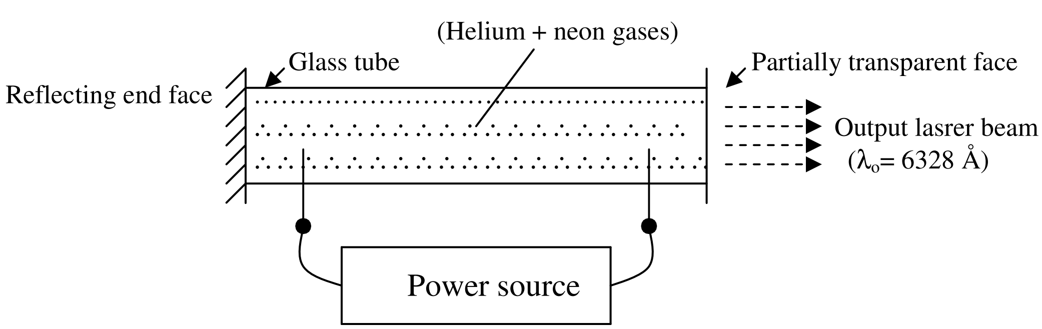


Figure 6: Schematic set up of helium neon laser.

The neon energy levels actually take part in the laser emission and helium is used for selective pumping of the upper laser levels of the neon. The energy levels diagram of helium and neon is shown in the figure 7 below. Excitation of the gas atoms in helium neon laser is accomplished through electric discharge. When electric discharge is passed through the gas the electrons, which are accelerated by electric field collide with helium and neon atoms and excite them to higher energy levels. The helium atoms tend to accumulate at levels F_2 and F_3 due to their longer lifetime of ~10^{-4} and ~ 10^{-6} sec, respectively. Since the levels E_4 and E_6 of neon atoms have almost the same energy as levels F_2 and F_3 of the helium, the excited helium atoms colliding with neon atoms in the ground state can excite them to the states E_4 and E_6. Since, the pressure of helium is 10 times that of neon, the levels E_4 and E_6 of neon are selectively more populated as compared to other level of neon. Thus, the population inversion is established between levels E_6 and E_3, E_4 and E_3 and E_6 and E_5 of neon atoms

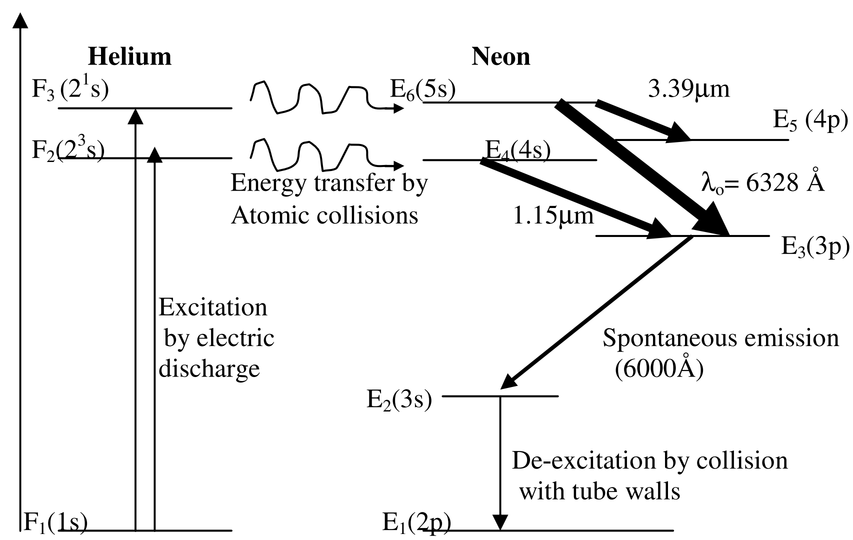


Figure 7: Energy level diagram of helium - neon laser.

Transition between E_6 and E_3 levels produces the very popular 6328Å line of the helium neon laser. Neon atoms at level E_3 de-excite through spontaneous emission to level E_2 (lifetime ~10^{-8} s). Since this time is shorter than the lifetime of level E_6 (~ 10^{-7} s) one can achieve steady state population inversion between E_6 and E_3.The level E_2 is metastable and thus tend to collect atoms. The atoms from this level relax back to ground level mainly through collision with the wall of the glass tube. Since E_2 is metastable level it is possible for atoms in this level to absorb the spontaneously emitted radiation in the $E_3 \rightarrow E_2$ transition to be re-excited to E_3 and. This will have the effect of reducing the inversion between E_6 and E_3. It is for this reason that the gain in this laser transition found to increase with decreasing the tube diameter.

Other two wavelength of He-Ne laser are 3.39μm and 1.15μm corresponding to $E_4 \rightarrow E_3$ and $E_6 \rightarrow E_5$ transitions. Transitions at 3.39μm and 6328Å share the same upper laser levels. Any of the three wavelengths can be selected using an appropriate window at the output end face of the discharge tube. If the resonator mirrors are placed outside the discharge tube then reflections from the ends of the discharge tube can be avoided by placing the windows at the Brewester's angle. In such a case the beam polarized in the plane of incidence suffers no reflection at the windows while the perpendicular polarization suffers reflection losses. This leads to a polarized out of the laser.

Carbon dioxide (CO_2) Laser:

The carbon dioxide laser is a molecular laser and is most important of all the lasers from the point of technological applications point of view. In molecular lasers, the energy levels are provided by the quantization of the energy of vibrational and rotational motions of the constituent gas molecules. The radiations associated with the electronic transitions is usually in the ultra-violet or visible regions, whereas, vibrational roatational transitions are in the far infrared regions. For this reason, the molecular lasers have infrared outputs. The CO_2 molecule is basically a linear arrangement of the two oxygen atoms and a central carbon atom, which can undergo three modes of vibration as shown in the figure below.

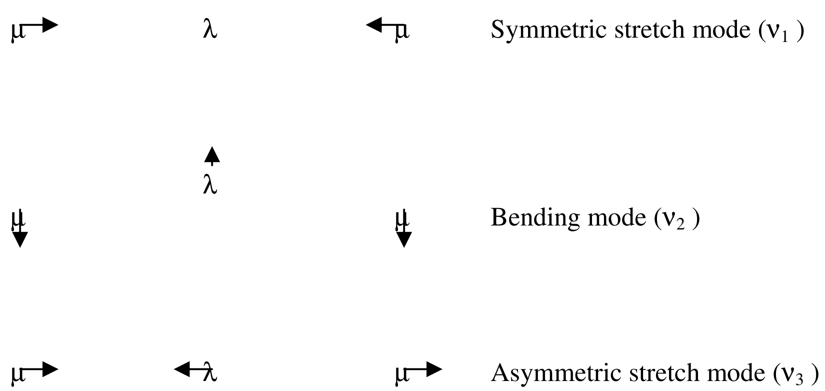


Figure 8: Vibrational modes of CO_2 molecule

At any time, the molecule can be vibrating in any linear combination of the these fundamental modes. The modes of vibration are denoted by three quantum numbers (mnq) which represents the amount of energy or energy quanta associated with each mode of vibration. The set (100) for example means that a molecule in this state is vibrating in a pure symmetric mode with one quanta of energy, it has no energy associated with asymmetric or bending modes. In addition to these vibrational modes, the molecule can also rotate and thus it has closely spaced rotational energy levels associated with each vibrational energy level. The energy separation between these molecular levels is small and the laser output is therefore in the infrared. The energy level diagram of the CO_2 laser is shown in the figure below alongwith the ground state and first excited state of vibrational modes of the nitrogen molecule.

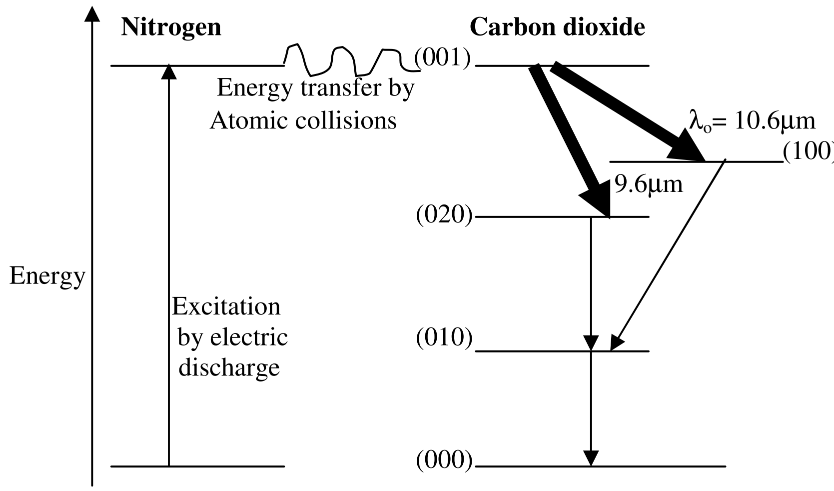


Figure 9: Energy level diagram of carbon dioxide laser.

The schematic arrangement of CO_2 laser is same as that for He-Ne laser. The CO_2 laser contains a mixture of carbon dioxide, nitrogen and helium gases (as active medium) in the ratio 1:4:5 in a glass tube. The gas molecules are excited to the higher energy states by putting an electric discharge in a glass tube. Nitrogen plays a similar role to that of helium in He-Ne laser. The excitation of the carbon dioxide molecules to long lived level (001) occurs both through collisional transfer of energy from excited nitrogen molecules and also from the cascading down of CO_2 molecules from higher energy levels. The (100) and (020) levels of CO_2 have low energy and can not be populated this way so that population inversion is created between the (001) and (100) & ((020) levels resulting in stimulated emission at about 10.6 μm and 9.6 μm. The helium has dual role to play here. Firstly, it increases the thermal conductivity to the walls of the tube, thereby decreasing the temperature of the gas mixture and a consequent broadening of laser beam and in turn increases the gain. Secondly, it increases the laser efficiency by speeding up transition from (100) level to ground state via collisions with the helium atoms.

While other gas lasers have efficiencies of 0.1% or less, the CO_2 laser may have an efficiency upto 30%. Because of this high efficiency it is easy to obtain continuous wave output of 100watt from a metre long tube. The output power of the CO_2 laser is approximately proportional to the tube length. To obtain output of several kilowatts tens of meters long tubes are used. Such high power CO_2 lasers find applications in materials processing, like welding, hole drilling, cutting, melting, alloying etc. In addition atmospheric attenuation is low at 10.6μm, which leads to some applications of CO_2 lasers as ranging ang tracking in laser range finders and in guided missiles. Material ablation is another important area of its applications for forming thin films of alloys of various elements to make superconductors. Operation in infrared region requires special materials (like GaAs, Ge, ZnSe, alkali halides) for windows, mirror and other laser components.

Semiconductor Laser:

It is also known as the diode laser or junction laser as it consists of p-n junction diode. These lasers uses semiconductors as an active medium and are characterizad by specific advantages such as small size, low cost, the capability of monolithic integration with integrated circuits, direct pumping by conventional biasing and compatibility with optical fibres.

Unlike the common gaseous and soild state lasers the transition in a semiconductor laser occur between energu bands rather than between discrete energy levels because of the closeness of the atoms constituting the semiconductor. The semiconductor basically consists of a p-n junction formed between degenerate (heavily doped), semiconducting materials. In n-type degenerate semiconductor there are enough electrons donated by impurities to fill the conduction band upto the Fermi level E_{fn}, which falls within the conduction band (CB). Similarly in p-type degenerate semiconductors holes are added by acceptors down upto the Fermi level E_{fp} in the valence band (VB). When a junction is made of such materials electrons from n-side flow to p-side till an electrical potential barrier is built up which prevents further flow of charge carriers across the junction. Fermi level under such condition lie in same horizontal line throughout the material and energy band diagram appears as shown below in figure 10. Energy difference between the p- and n- type regions is the built-in voltage or the contact potential of the p-n junction.

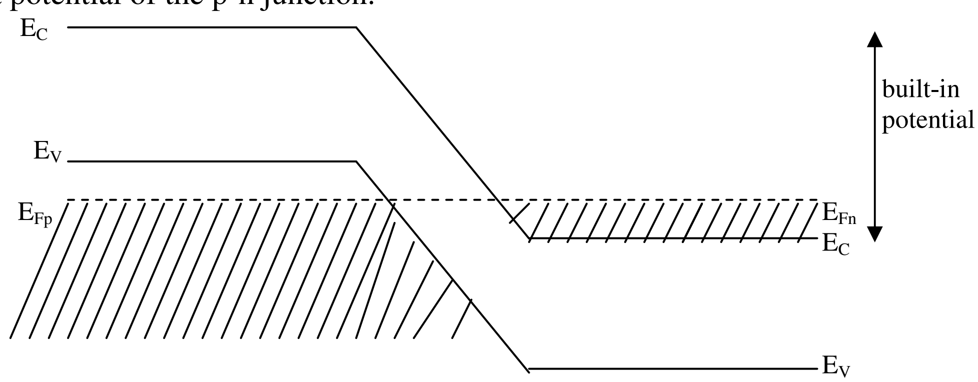


Figure 10: Energy band diagram of junction diode of degenerate material with no forward bias

When the junction is forward biased electrons flow to p-side and holes to n-side and overlap in some part of the junction region called depletion region. This region contains a large concentration of electrons within the conduction band and a large concentration of holes in the valence band. As the semiconductor is heavily doped, these population densities are high enough, a condition of population inversion is thus created at the junction. The recombination of electrons and holes in this region occurs by stimulated emission, which gives rise to coherent light radiation. This laser emission is confined in a very thin planner junction region. At loe currents spontaneous emission begins as is the case in LED's whereas at very high currents stimulated emission dominates giving rise to laser light.

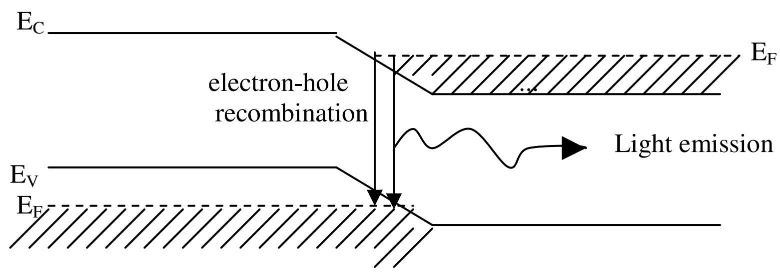


Figure 11: Energy band diagram of the junction diode under large forward bias

In choosing a semiconductor material for junction laser fabrication it is necessary that electron-hole recombination occur directly by giving light emission rather than through non-radiative process or lattice heating such as, are dominant in semiconductors like Si and Ge. The light emitting properties of semiconductors depend on the nature of energy band gap. The band gap in a semiconductor can be direct or indirect type. If the minimum in the CB is directly above the maximum in the VB in the E-k diagram then it is called direct band gap semiconductor. On the other hand if the minimum of the CB is at some other k value than that of the maximum of VB then it called indirect band gap semiconductor. In direct band gap semiconductor the energy is emitted in form of light photons when an electron-hole recombination takes place at the junction, whereas in the case of indirect band gap semiconductor most of energy is lost as heat. So direct band gap semiconductors are good light emitters and preferred for laser diode and light emitting diode (LED) fabrication.

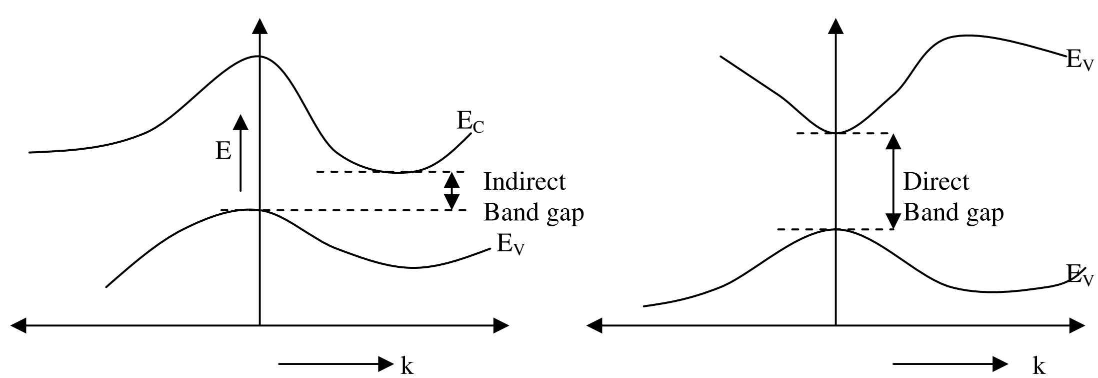


Figure 12: Energy-wave vector (E-k) diagram (a) indirect band gap as in silicon and germanium (b) direct band gap as in GaAs and $Al_xGa_{1-x}As$ semiconductors.

The semiconductors which, are used in LED and laser diode fabrication are III-V compounds. Some of the examples include GaAs, InP, GaP, InAs, and their ternary ($Al_xGa_{1-x}As$) and quaternary ($Al_xGa_{1-x}As_yP_{1-y}$) alloys. The advantage with ternary and quaternary alloys is that their band gap varies with the stochiometry of the alloys.