pumping excites the dye molecules from the lowest vibrionic level of the ground state S_0 to one of the upper vibronic level of the excited state S_1. From there, they undergo a non-radiative transition to the lower vibronic level of S_1 state which acts as the upper laser level. The role of lower laser level is played by one of the upper vibronic levels of S_0. The levels at S_0 are so closely spaced that they

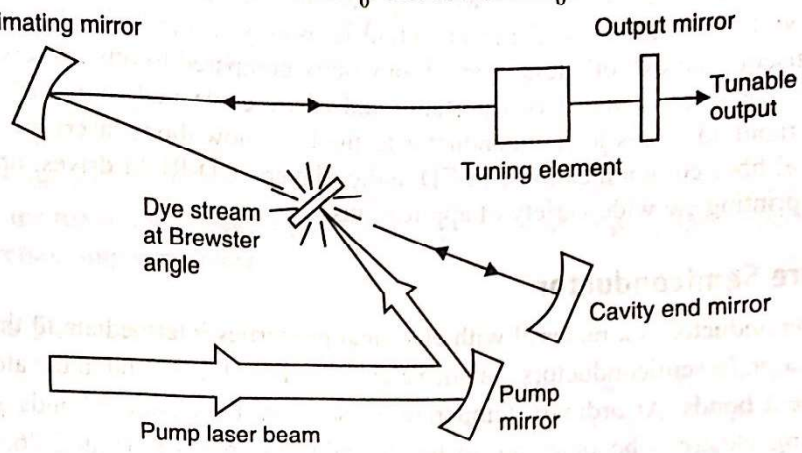

Fig. 2.25. Schematic diagram of a laminar-flow dye laser.

form a continuum. It may be seen from Fig. 2.24 that the laser transition can be to various levels within a range defined by the vibrationally excited sublevels of the ground state. Consequently, the laser operates over a broad range of wavelengths. Thus dye lasers differ from other lasers that emit light at fixed wavelengths. The schematic of a laminar-flow dye laser is shown in Fig. 2.25.

2.6 COMPARISON BETWEEN SOLID, LIQUID AND GAS LASERS

No.	Solid Lasers	Liquid Lasers	Gas Lasers
1.	The active medium is a soild.	The active medium is a liquid or a dye.	The active medium is a gas at low pressure .
2.	Either crystalline or amorphous.	In the form of dye dissolved in organic or inorganic solvent.	Either atomic, ionic or molecular.
3.	Pumping is done usually by optical method.	Liquid laser is excited optically usually by another laser source.	It is excited by electrical discharge method.
4.	Emits a narrow range of wavelengths.	Emits a broad-range of wavelengths.	Emits a narrow range of wavelengths.
5.	Due to imperfections and defects in crystals, inhomogeneties in the output.	Output is optically homogeneous.	Output is highly homogeneous.
6.	Example : Ruby, Nd-YAG, Nd-Glass Fibre laser etc.	Pulse dye laser, Tunable pulsed and CW dye laser etc.	He-Ne, Argon ion, Krypton ion, CO_2 laser etc.

2.7 SEMICONDUCTOR LASERS

A semiconductor laser is a specially fabricated pn-junction device that emits coherent light when it is forward biased. The first semiconductor laser was made in 1962 by R. N. Hall and his coworkers of General Electric R & D Laboratories, U.S.A. It is made from gallium arsenide (GaAs) which operated at low temperature and emitted light in the near IR. Semiconductor lasers working at room temperature and in continuous wave mode are produced by 1970. Now pn-junction

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(diode) lasers are made to emit light almost anywhere in the spectrum from the UV to the IR. Diode lasers are remarkably small in size (0.1 mm long). They have high efficiency of the order of 40%. Modulating the biasing current easily modulates the diode laser output. They operate at low powers. Inspite of their small size and low power requirement, they produce power outputs equivalent to that of He-Ne lasers. However, the laser output is usually in the form of a wide beam, 5 to 15° and as a consequence exhibits less monochromaticity compared to other lasers. The advantage of a semiconductor laser is that it is a portable and easily controlled source of coherent radiation. Because of rapid advances in semiconductor technology, now diode lasers are mass produced for use in optical fiber communications, in CD audio players, CD-ROM drives, optical reading, high speed laser printing etc wide variety of applications.

2.7.1. Pure Semiconductor

A semiconductor is a material with electrical properties intermediate to those of a conductor and an insulator. In semiconductors, valence electrons are tightly bound to the atoms and are locked up in covalent bonds. At ordinary temperatures, some of the covalent bonds are broken and the corresponding electrons become free to travel within the material (Fig. 2.26*a*). The situation is described in the following alternate way. The allowed energy values of the valence electrons in semiconductors occur within two well defined energy bands, separated by a forbidden energy gap, as shown in Fig. 2.26(*b*). A pure semiconductor crystal has exactly enough electrons to fill all the states in the lower band, namely *valence band*. However, a few electrons gain enough energy E_g to jump into the upper band, namely *conduction band*. In case of silicon and germanium, the number of electrons that can jump into the conduction band at room temperature is small. The electron jumping to the conduction band leaves behind a quantum vacancy in the valence band. The vacancy is called a *hole* and is assigned a positive charge along with the other attributes of a particle. In a pure semiconductor the number of electrons in the conduction band and holes in the valence band are equal. When a conduction electron falls into the valence band, it recombines with a hole there. The excess energy E_g is given out in the form of heat or light. If the recombination energy is released in the form of heat as in silicon and germanium crystals, the materials are of no use for laser action.

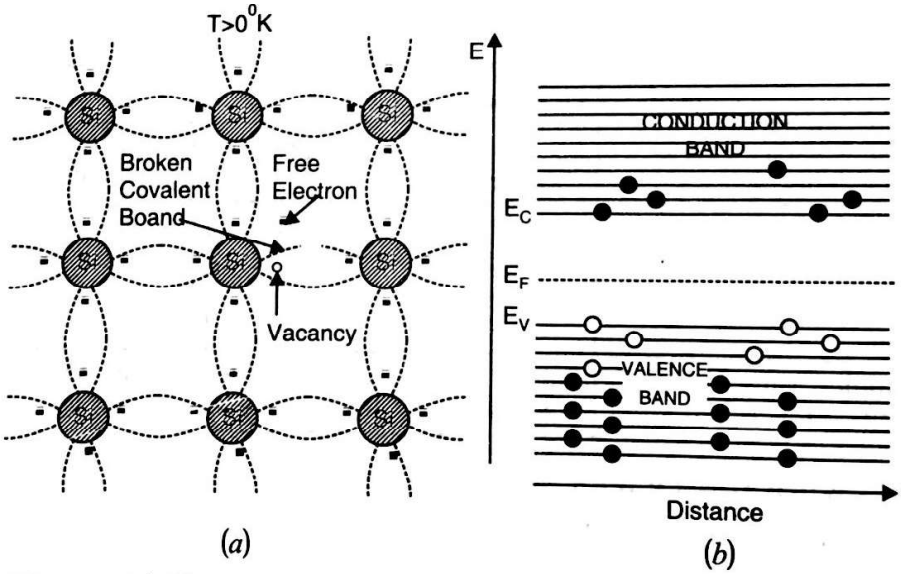

Fig. 2.26. Silicon crystal at temperatures above OK. (a) Thermal vibrations of atoms lead to breaking of covalent bonds. Consequntly, a free electron and a vacancy are simultaneously produced. (b) energy band representation. An energy $E_g = (E_c - E_v)$ causes the transition of electrons from valence band to conduction band leaving behind vacancies.

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Now, if a pure semiconductor material is illuminated by photons of energy $h\nu = E_g$, a photon can be absorbed by an electron in the valence band. The excited electron will jump into the conduction band. If, on the other hand, the photon hits an electron in the conduction band, it can induce electron to make a downward transition to the valence hand where the electron recombines with a hole and a quantum of radiation with energy equal to E_g is released. At ordinary temperatures, the number of electrons at the bottom of the conduction band is very small compared to the number of electrons at the top of the valence band. Therefore, the process of light absorption dominates over the process of stimulated emission. In order to make stimulated emissions to dominate over absorption of light in a semiconductor, the concentration of electrons at the bottom of the conduction band should be made higher than that at the top of the valence band. To create such a situation, pure semiconductors are to be doped with certain impurity atoms.

2.7.2. Impurity Semiconductors

The characteristics of pure semiconductors can be drastically altered in very important ways by the introduction of small amounts of impurities. Pentavalent or trivalent atoms are used as *dopants*, which easily substitute themselves in place of some of the host atoms in the semiconductor crystal. Consider the silicon crystal. Each silicon atom has four valence electrons and therefore each atom has four atoms bonded to it. If the crystal is doped with phosphorous, the phosphorous atoms will fit into the crystal structure, but they have five valence electrons out of which four participate in bonding to neighbour atoms. The fifth electron is superfluous to the structure and therefore is loosely bound to the phosphorous atom. It is readily excited into the conduction band by the thermal energy. Thus, pratically every phsophorous atom introduced into the silicon lattice contributes a conduction electron *without* creating a positive hole. Thus, the addition of the phosphorous greatly increases the number of condution electrons, which become the *majority carriers* in the material. In this case phosphorous is called a *donor* impurity and it makes the silicon crystal an *n-type semiconductor* (Fig. 2.27).

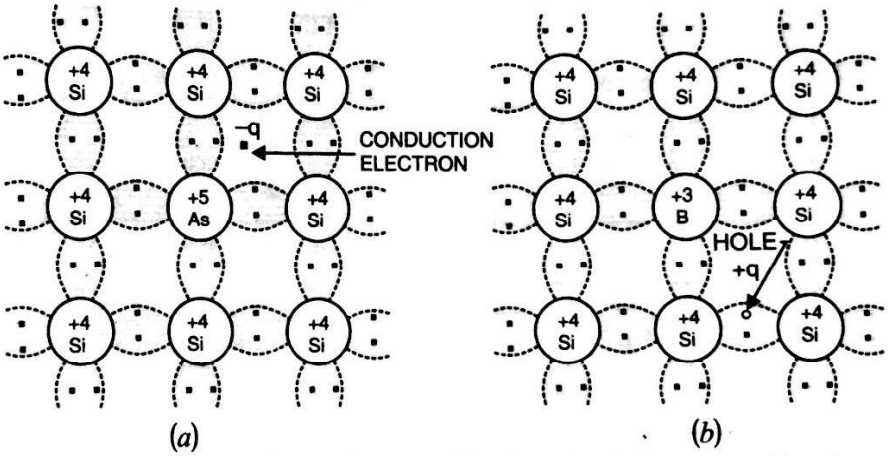

Fig. 2.27. Schematic bond pictures for (a) n-type Si with donor (arsenic) and (b) p-type Si with acceptor (boron).

Boron, on the other hand, has three valence electrons. If it is used as a dopant in silicon crystal, it can supply only three of the four electrons necessary to fit into the silicon lattice. However, thermal excitation is sufficient to cause silicon valence electrons to complete the bonding by attaching themselves to boron atoms. It leaves holes in the valence band. Thus boron is an *acceptor impurity*, which causes as many positive holes as there are boron atoms. The acceptor impurity makes silicon a *p-type semiconductor*.

If the concentration of impurities in the semiconductor material is very high, the semiconductor is said to be heavily doped.

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2.7.3. Population Inversion

Population inversion is required for producing stimulated emission and consequent amplification of light. The way in which population inversion is achieved in semiconductors is very different from the way it is established in other types of lasers. A semiconductor is not a two-level atomic system, but consists of electrons and holes distributed in the respective energy bands. Therefore, laser action in semiconductors involves energy bands rather than discrete levels. Secondly, in many types of lasers, population inversion is obtained by exciting electrons in spatially isolated atoms. In semiconductors, the excited electrons are not associated with specific atoms but are injected into the conduction band from the external circuit. Therefore, the conduction band represents an excited state while the valence band plays the role of the ground state.

Population inversion requires that there is a large concentration of electrons in the conduction band and a large concentration of holes in the valence band. A simple way of achieving population inversion is to use a semiconductor in the form of a *pn*-junction diode with heavily doped *p* and *n* type semiconductors.

2.7.4. *pn*-Junction

Let us first understand the formation of an ordinary *pn* junction. Fig. 2.28 shows the energy band diagrams of *p*-type and *n*-type semiconductors. The Fermi level E_{Fp} of *p*-type material is nearer to the valence band and the Fermi level E_{Fn} of *n*-type material is nearer to the bottom of the conduction band. Fermi level on each side is the reference energy level, analogous to the liquid level in a container. When both the *p* and *n* materials are joined, equilibrium is attained only when equalisation of Fermi levels E_{Fp} and E_{Fn} takes place. When two containers filled with liquid to two different levels are connected, the liquid level in one container falls down while the level in the other rises till both levels are equalized. In a similar manner, when *p* and *n*-type materials are joined, the energy levels in *p*-region move up and those in *n*-region move down till the Fermi levels E_{Fp} and E_{Fn} are equalized. The following events occur in the course of the equalization of Fermi levels.

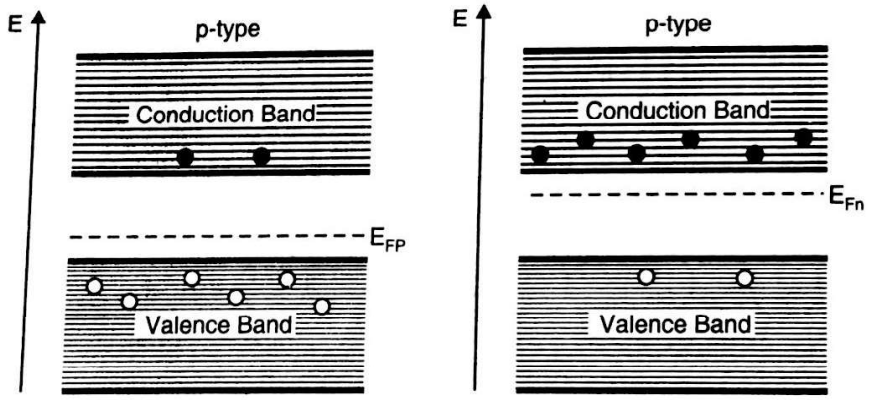

Fig. 2.28. Energy band diagrams of p- and n-type semiconductors.

(i) The electrons are larger in number (majority carriers) on *n*-side and smaller (minority carriers) on *p*-side. Similarly holes are larger in number on *p*-side and smaller on *n*-side. Thus, there is a concentration gradient for majority carriers across the junction. Hence, they tend to diffuse across the junction.

(ii) The electrons and holes diffuse in opposite directions and recombine in the vicinity of junction. Therefore, a narrow region around the junction is left with only immobile impurity atoms and neutral host atoms.

(iii) The immobile ions are negative on the *p*-side and positive on *n*-side. These layers of opposite charges create a potential barrier for the diffusion of majority charge carriers.

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The potential barrier halts movement of electrons from *n*-side and that of holes from *p*-side. As a result, a narrow depletion region devoid of mobile charges forms.

The mutual displacement of the energy levels on both sides of the junction causes a bending of the energy bands around the junction region, as shown in Fig. 2.29.

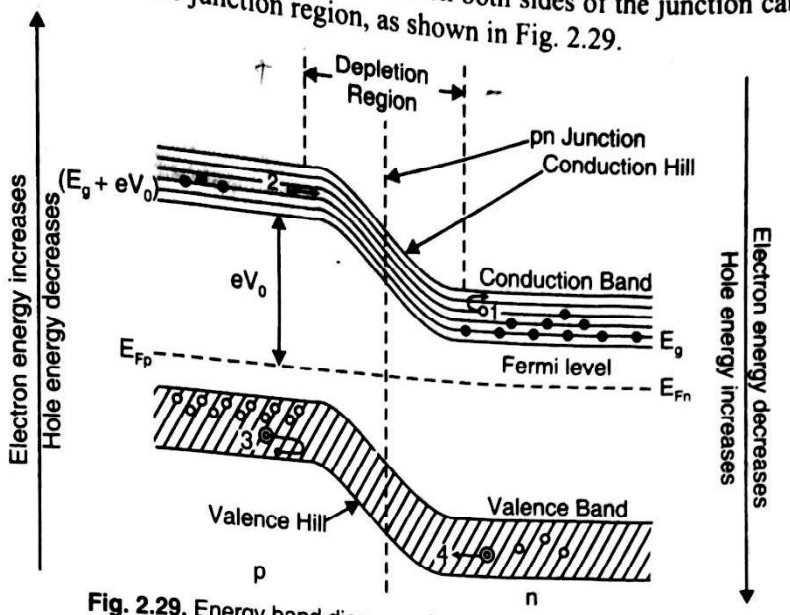

Fig. 2.29. Energy band diagram of pn-junction at equilibrium.

When the doping levels are very high, the Fermi level in *p*-type region will be below the valence band edge and will be above the conduction band edge in *n*-type region.

The energy band diagram of a *pn* junction formed between two heavily doped semiconductors is shown in Fig. 2.30.

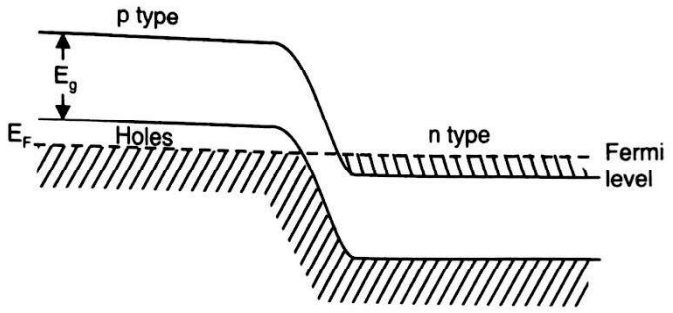

Fig. 2.30. Energy band diagram of a heavily doped *pn*-junction in equilibrium.

The probability of stimulated emission event occurring is low even now because there must be a region of the device where a large number of conduction electrons and a large number of holes would be *simultaneously* present. This condition is never realized in thermal equilibrium. However, when the junction is forward biased with a large enough voltage, electrons and holes (minority carriers) are injected into the junction region in considerable concentrations. In other words carriers are pumped by the dc source. As a result, the region 'd' (Fig. 2.31) contains a large concentration of electrons within the conduction

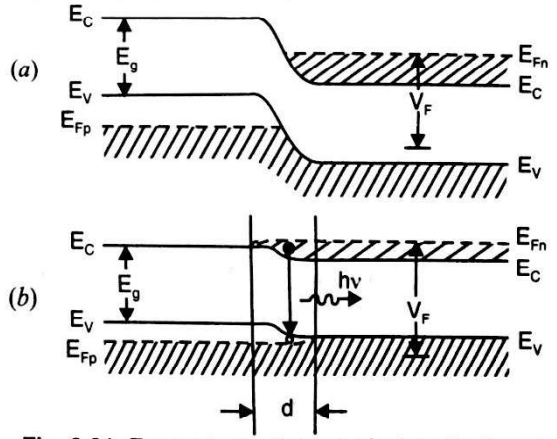

Fig. 2.31. Energy band diagram of a heavily doped *pn*-junction under
(a) forward bias of smaller magnitude
(b) larger forward bias leading to lasing.

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band and large concentration of holes within the valence band. This is the condition of population inversion. The narrow zone over which population inversion occurs is called an *inversion region* or *active region*. The electrons and holes recombine in the active region emitting photons.

2.7.5. Lasing Condition

With reference to Fig. 2.31, it is seen that the electrons occupy the lowermost states of the conduction band upto the level E_{Fn} and the holes occupy the uppermost states of the valence band upto the level E_{Fp}. In the non-equilibrium state E_{Fn} and E_{Fp} represent the electron and hole quasi-Fermi levels respectively. By virtue of pumping a non-thermal equilibrium steady state is obtained in which large densities of electrons and holes simultaneously exist in the same space. For writing the probabilities of induced transitions, knowledge of the electron concentration in the conduction band and hole concentration in the valence band is required, because the existence of an electron at an excited level does not assure that there is a hole in the valence band. The probabilities for transitions are written in terms of the Fermi-Dirac distribution functions. Let a light wave of frequency ν_0 travel through the junction. The beam will induce $a \rightarrow b$ transitions during which light is emitted as well as $b \rightarrow a$ transitions which lead to absorption.

The rate of absorption transitions from a group of levels at energy E_ν in the valence band to a group levels at energy E_C in the conduction band may be expressed as

$$R_{abs} = P[1 - f_c(E_a)] f_\nu(E_b) N \qquad ...(2.1)$$

where f_c and f_ν are Fermi functions in conduction and valence bands respectively, N is the density of photons of energy E, and P is the transition probability. The stimulated emission rate is given by

$$R_{st} = P f_c E_a [1 - f_\nu(E_b)] N \qquad ...(2.2)$$

For emission of light from the *pn*-junction, we require that

$$R_{st} > R_{abs}$$

On comparing eq. (2.1) and (2.2), we find that emission will exceed absorption if

$$f_c(E_a) > f_\nu(E_b) \qquad ...(2.3)$$

Using,
$$f_c(E_a) = \frac{1}{1 + e^{(E_a - E_{Fn})/kT}}$$

and
$$f_\nu(E_b) = \frac{1}{1 + e^{(E_b - E_{Fp})/kT}}$$

into eq. (2.3), we get

$$E_{Fn} - E_{Fp} > (E_a - E_b)$$

But $E_a - E_b = h\nu$

$$\therefore \quad E_{Fn} - E_{Fp} > h\nu \qquad ...(2.4)$$

But it also follows that the energy of the photon emitted due to electron transition must satisfy the condition

$$h\nu \geq Eg. \qquad ...(2.5)$$

On combining Eq. (2.4) and Eq. (2.5), the necessary condition for lasing in the *pn*-junction becomes

$$\{E_{Fn} - E_{Fp}\} \geq h\nu \geq Eg. \qquad ...(2.6)$$

This condition was first obtained by Bernard and Duraffourg. E_g and $(E_{Fn} - E_{Fp})$ constitute the outside limits of the laser spectra. In order to fulfill the condition (2.6), the p and n-regions of the diode has to be doped heavily such that the Fermi levels penetrate the main bands as shown in the Fig. 2.27.

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