DKP23 - LASERS AND OPTO ELECTRONICS

UNIT I   LASERS
Lasers:
Stimulated and spontaneous emission- Einstein's A & B coefficients- relation between them- condition for light amplification- Population inversion- Pumping methods and schemes- optical resonator-theory and condition for oscillation- modes-Laser Rate equations- solid state lasers: Ruby & Nd:YAG- Gas lasers: He-Ne and Co lasers- Dye laser- semiconductor diode laser
2 Applications: Lasers in mechanical industry, Electronics industry, nuclear energy, medicine, Defence, communication- measurement of distance and velocity

UNIT II   BASICS OF SEMICONDUCTORS
Nature of light - light sources- black body - colour temperature - units of light - radiometric and photometric units - basic semiconductors - PN junction-carrier recombination and diffusion - injection efficiency - hetero junction - internal quantum efficiency - External quantum efficiency - double hetero junction - fabrication of hetero junction - quantum wells and super lattices.

UNIT III   OPTOELECTRONIC DEVICES
Optoelectronic devices - Optical modulators - modulation methods and modulators – transmitters - optical transmitter circuits - LED and laser drive circuits- LED – power and efficiency – double hetero LED - LED structure - LED characteristics - Junction laser operating principles - Condition for laser action - Threshold current – Homo junction – Hetero junction - Double hetero junction lasers - Quantum well laser - Distributed feedback laser - laser modes, strip geometry - gain guided lasers- index guided lasers.

UNIT IV   OPTICAL MODULATORS AND DETECTORS
Modulation of light – birefringence - electro optic effect - EO materials - Kerr modulators - scanning and switching - self electro optic devices - MO devices, AO devices - AO modulators. Photo detectors - thermal detectors – photoconductors – detectors - photon devices - PMT - photodiodes - photo transistors - noise characteristics - PIN diode - APD characteristics - APD design of detector arrays – CCD - Solar cells

UNIT V DISPLAY DEVICES
Display devices – photoluminescence - EL display - LED display - drive circuitry - plasma panel display - liquid crystals – properties - LCD display - numeric displays.

Book for study and reference

1. M.N.Avadhanulu, An Introduction to Lasers: Theory and Applications, S.Chand and Company Ltd, New Delhi, Ist Edition, 2001[For unit I]

2. J. Wilson & J.F.B. Hawkes, "Optoelectronics – An Introduction", Prentice Hall, India, 1996.

3. P. Bhattacharya, "Semiconductor optoelectronic devices", Second Edn Pearson Education, Singapore, 2002.

4. J. M. Senior, "Optical fiber communication", Prentice-Hall India, 1985.

5. J. Gowar, "Optical fiber communication systems", Prentice–Hall, 1995.

6. J .Palais, "Introduction to optical electronics", Prentice– Hall, 1988.

7. Jasprit Singh, "Semiconductor optoelectronics", McGraw–Hill, Inc, 1995.

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Unit – I

LASERS

1.1 Introduction :

The word "LASER" is an acronym for "**Light Amplification by Stimulated Emission of Radiation".** Albert Einstein in 1917 theoretically proved that the process of stimulated emission must exist. But only in 1954, a group of scientists at Columbia University head by Charles H.Townes operated a microwave device for "Microwave Amplification by Stimulated Emission of Radiation (MASTER)". In 1960, T.H.Maiman of the Hughes Research Laboratories first achieved laser action at optical frequency in Ruby. Since 1960 the development of lasers has been extremely rapid.

1.2 Spontaneous and Stimulated Emission of Radiation :

If the radiation interacts with atoms in the lower energy state, say E_1, the atoms absorb the energy and get excited to the higher energy state E_2 by a process called *stimulated absorption*. Instead if the radiation interacts with atoms which are already in the excited state E_2, then de-excitation of those atoms to the lower energy state E_1 occurs with emission of photons of energy hv. This process is called *stimulated emission*. Yet another emission process called *spontaneous emission* is also possible wherein atoms in the excited state drop to the lower energy state after they have stayed in the excited state for a short duration of time called their life time. During this process also photons of energy $hv (= E_2 - E_1)$ are emitted. The absorption and emission processes are illustrated in Fig. 1.1.
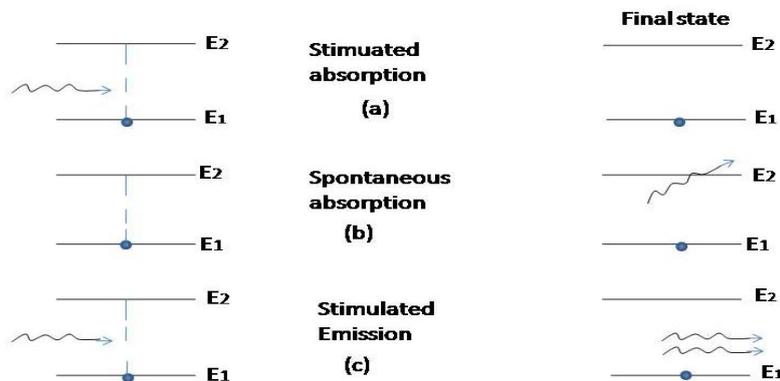

Fig. 1.1. Energy level diagram illustrating (a) stimulated absorption (b) spontaneous emission and (c) stimulated emission. The black dot indicates the state of the atom before and after the transition.

1.3 Einstein's coefficients

In a collection of atoms, all the three transition processes–stimulated absorption, spontaneous emission, and stimulated emission–occur simultaneously. Let N_1 be the number of atoms per unit volume with energy. E_1 and E_2 the number of atoms per unit volume with energy E_2. Let *'n'* be the number of photons per unit volume at frequency v such that $hv = E_2 - E_1$. Then the energy density of interacting photons $\rho(v)$ is given by

$$\rho(v) = nhv \qquad (1.1)$$

When these photons interact with atoms, both upward (absorption) and downward (emission) transitions occur. At equilibrium these transition rates must be equal.

Upward transition

Stimulated absorption rate depends on the number of atoms available in the lower energy state for absorption of these photons as well as the energy density of interacting radiation.

i.e., Stimulated absorption rate $\propto N_1$

$$\propto \rho(v)$$

$$= N_1 \, \rho(v) \, B_{12}$$

Where the constant of proportionality B_{12} is the Einstein coefficient of stimulated absorption.

Downward transition

Once the atoms are excited by stimulated absorption, they 'stay' in the excited state for a short duration of time called the life time of the excited state. After their life time they move to their lower energy level spontaneously emitting photons. This spontaneous emission rate depends on the number of atoms in the excited energy state.

i.e. Spontaneous emission rate $\propto N_2$

$$\propto \rho(v)$$

$$= N_2 \, \rho(v) \, B_{21}$$

where the constant of proportionality B_{21} is the Einstein coefficient of stimulated emission.

During stimulated emission, the interacting photon called the stimulating photon and the photon due to stimulated emission are in phase with each other. Please note that during stimulated absorption, the photon density decreases whereas during stimulated emission it increases.

For a system in equilibrium, the upward and downward transition rates must be equal and hence we have

$$N_1 \, \rho(v) \, B_{12} = N_2 \, \rho(v) \, B_{21} + N_2 \, A_{21} \tag{1.2}$$

hence

$$\rho(v) = \frac{N_2 \, A_{21}}{N_1 \, B_{12} - N_2 \, B_{21}} \tag{1.3}$$

or

$$\rho(v) = \frac{A_{21} / B_{21}}{\dfrac{B_{12}}{B_{21}} \dfrac{N_1}{N_2} - 1} \tag{1.4}$$

The population of the various energy levels of a system in thermal equilibrium is given by Boltzmann distribution law.

$$N_i = g_i \, No \exp\left(\frac{-E_i}{kT}\right) \tag{1.5}$$

Where N_i is the population density of the energy level E_i, N_0 is the population density of the ground state at temperature T, g_i is the degeneracy of the ith level and k is the Boltzmann constant (=1.38 x 10^{-23} joule/K). (The concept of degeneracy occurs since more than one level have the same energy).

Hence

$$N_1 = g_1 \, No \exp - E_1 / kT$$

$$N_2 = g_2 \, No \exp - E_2 / kT$$

$$\frac{N_1}{N_2} = \frac{g_1}{g_2} \exp - \frac{(E_2 - E_1)}{kT}$$

$$= \frac{g_1}{g_2} \exp - \left(\frac{hv}{kT} \right) \qquad (1.6)$$

Substituting equation (1.6) in equation (1.4)

$$\rho(v) = \frac{A_{21} / B_{21}}{\left[\dfrac{g_1}{g_2} \dfrac{B_{12}}{B_{21}} \exp - \left(\dfrac{hv}{kT} \right) - 1 \right]} \qquad (1.7)$$

From Planck's low of black body radiation, the radiation density is given by

$$\rho(v) = \frac{8 \pi h v^3}{c^3} \left[\frac{1}{\exp \left(\dfrac{hv}{kT} \right) - 1} \right] \qquad (1.8)$$

comparing equations (1.7) and (1.8)

$$\frac{g_1}{g_2} \frac{B_{12}}{B_{21}} = 1$$

$$g_1 B_{12} = g_2 B_{21} \qquad (1.9)$$

and

$$\frac{A_{21}}{B_{21}} = \frac{8 \pi h v^3}{c^3} \qquad (1.10)$$

Equations (1.9) and (1.10) are referred to as the Einstein relations.

The ratio of spontaneous emission rate to the stimulated emission rate is given by

$$R = \frac{N_2 A_{21}}{N_2 \rho(v) B_{21}} = A_{21} / \rho(v) B_2$$

from equation (1.7)

$$R = \frac{A_{21}}{\rho(v) B_{21}} = \left[\exp \left(\frac{hv}{kT} \right) - 1 \right] \qquad (1.11)$$

From eq.(1.11) we understand that to make R smaller, $\rho(v)$ the energy density of interacting radiation has to be made larger. Let us consider the ratio of stimulated emission rate to stimulated absorption rate.

$$\frac{\text{Stimulated emission rate}}{\text{Stimulated absorption rate}} = \frac{N_2 \rho(v) B_{21}}{N_1 \rho(v) B_{12}}$$

$$= N_2 / N_1 \ (as \ B_{21} = B_{12} \ ignoring \ degeneracy)$$

At thermal equilibrium $N_2 / N_1 \ll 1$

Thus at thermal equilibrium stimulated absorption predominates over stimulated emission. Instead if we create a situation that $N_2 > N_1$, stimulated emission will predominate over stimulated absorption. If stimulated emission predominates the photon density increases and Light Amplification by Stimulated Emission of Radiation (LASER) occurs. Therefore, in order to achieve more stimulated emission, population of the excited state (N_2) should be made larger than the population of the lower state (N_1) and this condition is called population inversion. Hence, if we wish to amplify a beam of light by stimulated emission then we must

(i) create population inversion and

(ii) increase the energy density of interacting radiation

1.4 Amplification of light :

Let us consider light of intensity I_0 entering a medium of length x. The intensity of light leaving the medium on the other side under thermal equilibrium condition is given by Beer's law

$$I(x) = I_0 \exp(-\alpha x) \qquad (1.12)$$

where α is the absorption coefficient of the medium. Stimulated absorption results in fall in intensity of light. If we can create population inversion in the medium, stimulated emission will predominate over stimulated absorption and hence the light passing through the medium undergoes amplification instead of attenuation.

$$I(x) = I_0 \exp(\beta x) \qquad (1.13)$$

Where β is the gain (i.e. amplification) coefficient. Thus when the medium is under the condition of population inversion, the density of photons (light intensity) passing through the medium increases.

1.5 Gain coefficient

Let n be the number of photons inside the medium at any instant under the condition of amplification. Then (dn/dt) gives the rate at which photon density increases. This is nothing but the difference in stimulated emission rate and stimulated absorption rate (assuming that spontaneous emission rate is negligible).

i.e. $\dfrac{dn}{dt} = B_{21}\, \rho v\, N_2 - B_{12}\rho v\, N_1$

Substituting for B_{21} from equation (11.9)

$$\frac{dn}{dt} = B_{21}\, \rho v\, N_2 - \frac{g_2}{g_1} B_{12}\rho v\, N_1$$

$$= \left(N_2 - \frac{g_2}{g_1} N_1 \right) \rho(v)\, B_{21} \qquad (1.14)$$

Intensity of light is given by

$I = nhvc$ where c is velocity of light.

$$\frac{dI}{dx} = \frac{dn}{dx} hvc$$

$$dn = \left(\frac{dI}{dx}\right) dx. = \frac{1}{hvc}$$

$$\frac{dn}{dt} = \left(\frac{dI}{dx}\right)\left(\frac{dx}{dt}\right)\frac{1}{hvc}$$

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$$= \frac{dI}{dx} \frac{1}{hvc} \left(as \frac{dx}{dt} = c \right)$$

From equation (1.13)

$$= \frac{dI}{dx} = I_0 \exp (\beta x). \beta$$

$$= = \beta I (x)$$

Substituting in the above equation

$$\frac{dn}{dt} = \beta_1 (x) \frac{1}{hv} = \beta nhvc \frac{1}{hv} = \beta nc \qquad (1.15)$$

Comparing equations (11.14) and (11.15)

$$\beta = \left(N_2 - \frac{g_2}{g_1} N_1 \right) B_{21} \frac{\rho(v)}{nc} = \left(N_2 - \frac{g_2}{g_1} N_1 \right) B_{21} \frac{hv}{c} \qquad (1.16)$$

This process causing light amplification by stimulated emission of radiation is the underlying basis for laser action. This is possible (i.e., β is positive) only when N_2 is greater than $\frac{g_2}{g_1} N_1$

i.e. only when population inversion is achieved.

1.5 Population Inversion

The population inversion condition required for light amplification is a non-equilibrium distribution of atoms among the various energy levels of the atomic system. Boltzmann distribution law specifies what fraction of atoms are found in any particulars energy state for any given equilibrium temperature. If N_0 is the number of atoms in the ground state, N_i is the number of atoms in the excited state of energy E_i measured relative to the ground state, then (ignoring degeneracy).

$$\frac{N_1}{N_0} = \exp \left(\frac{-E_i}{kT} \right) \qquad (1.17)$$

Where T is the absolute temperature in degree Kelvin; and $k = 1.38 \times 10^{-23}$ joule/K . Since the right hand side of the above equation is exponential of a negative quantity, maximum possible value attainable is 1. That happens when $kT >> E_i$. Even then at this extreme (impossible) case, N_i can be equal to N_0 but it will never exceed N_0. Hence from this it is very obvious that by feeding energy required for exciting the atoms from lower energy level to the higher energy level, higher level can never be made more populated than the lower level. i.e. by direct pumping population inversion is not possible. Then how is population inversion achieved?

From the above we have understood that if two energy levels are involved, by direct pumping the higher level cannot be made more populated than the lower level. The restrictions imposed on a two level scheme have been overcome in three and four level schemes by pumping atoms in the active medium indirectly to the upper state of transition involving more than two energy levels.

1.6 Three level scheme

Fig.1.2(a) shows distribution of atomic state population obeying Boltzmann law. If the collection of atoms is intensely pumped – for example, with a xenon flash lamp – a large number of atoms are excited through stimulated absorption to the highest energy level E_2. If

the level E_2 has very short lifetime, the atoms decay fast to level E_1. If the level E_1 has relatively longer lifetime (a state known as metastable) atoms tend to accumulate at E_1. With intense pumping from E_0 to E_2, because of rapid decay to E_1, it is possible to bring in non-equilibrium distribution of atoms viz E_1 more populated than E_0 and laser transition takes place between level E_1 (called upper laser level) and level E_0 (called lower laser level) as shown in Fig. 1.2(b). Since ground level E_0 happens to be the lower laser level, more than one-half of the ground state atoms must be pumped to the upper state to achieve population inversion $(N_1 > N_0)$. Therefore, three level pumping schemes generally require very high pump powers. If pumping continues when the condition $(N_1 > N_0)$ is reached, stimulated emission rate exceeds stimulated absorption rate. This immediately depopulates the upper laser level and populate the lower laser level. Hence it is not possible to continuously maintain the upper laser level more populated than the lower laser level, Such a system therefore works in pulsed mode only. The Ruby laser is the best example for a three level system.
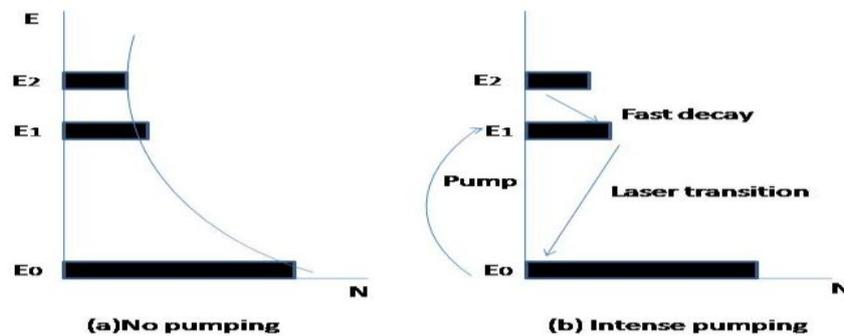

Fig.1.2 Population of energy levels by pumping in a three level system

1.7 Four level scheme: In four level scheme as shown in Fig.1.3, on pumping, the atoms are lifted from the ground state to the highest of the four levels involved in the process. From this level, the atoms decay to the metastable state E_2, and the population of this state grows rapidly. If the lifetime of the $(3 \rightarrow 2)$ transition is short and that of the $(2 \rightarrow 1)$ is long, a population inversion on the $(2 \rightarrow 1)$ transition can be achieved and maintained with moderate pumping.
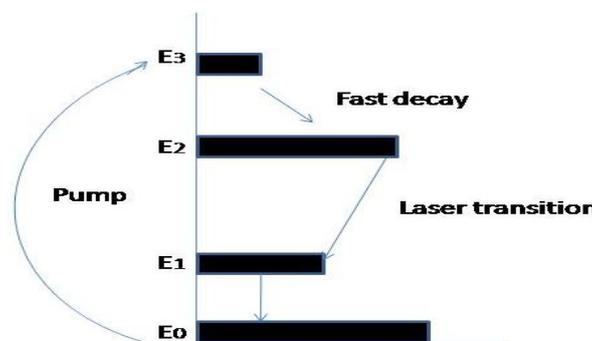

Fig. 1.3 Population of energy levels in a four level system. Population inversion is achieved by pumping to a high energy state (E_3) followed by fast decay to a lower energy state (E_2) which happens to be the upper laser level.

Since ground level is not the lower laser level there is no need to pump more then one-half of the population to the higher level. Since in this scheme level is the E_1 is the lower laser level, it is relatively easier to maintain population inversion between levels E_2 and E_1 continuously with moderate pumping and get continuous wave (CW) output. For this to happen $(1 \rightarrow 0)$ transition must be very fast. If this transition is relatively slow, even four level laser will work in pulsed mode only. $He-Ne$ laser is a good example for a four level laser working in CW mode while N_2 laser is an example for pulsed mode of operation.

1.8 Pumping mechanisms – creation of population inversion

There are different mechanisms applied to pump the atoms of the active medium to higher energy states to create population inversion. They are

(i) optical pumping
(ii) electric discharge
(iii) chemical reaction
(iv) injection current etc.

Optical pumping is the very first mechanism applied to Ruby laser. Solid state lasers are optically pumped using Xenon flash lamps. Since these materials have very broad band absorption, sufficient amount of energy is absorbed from the emission band of flash lamp and population inversion created. Recently flash lamps are being replaced by laser diodes thus making systems more efficient and reliable. Examples of optically pumped lasers are Ruby, $Nd:YAG, Nd:Glass,$ Dye, etc., Since gas lasers have very narrow absorption band, pumping them using any flash lamp is not possible. In most of the cases inversion is created by means of electric discharge. Examples of such systems are $He-Ne,$ Argon ion, Carbon dioxide etc.

Chemical reaction may also result in excitation and hence creation of population inversion in few systems. Examples of such systems are HF, DF and atomic iodine lasers.

In semiconductor lasers, the injection current through the junction results in creation of population inversion among charge carriers.

1.9 Resonator

Resonator mirrors are generally coated with multilayer dielectric materials to reduce the absorption loss in the mirrors. Moreover these resonators act as frequency selectors and also give rise to directionality to the output beam. Since the resonator mirrors provide feedback to the photons amplified by the achre medium.

1.10 Modes of a rectangular cavity

The electric field of an e.m wave satisfies the equation $\Delta^2 E = \dfrac{1}{C^2}\dfrac{\partial^2 E}{rt^2}$ (1.18)

where c is the velocity of light. The simplest plane wave solution of Eq.(1.18) is

$$E(r,t) = E_0 \exp{(i(k.r - wt) - \delta}$$ (1.19)

Where E_0 is the amplitude and k the wave vector. The complete solution with real spatial parts is

$$E_x(t) = E_{ox}(t)\cos k_x X \sin k_y y \ \sin k_z z$$

$$E_y(t) = E_{oy}(t) \sin k_x X \cos k_y y \ \sin k_z z$$

$$E_z(t) = E_{oz}(t) \sin k_x X \sin k_y y \cos k_z z$$

with $k_2 = k_x{}^2 + k_y{}^2 + k_z{}^2$ (1.20)

Eq. (3) have to satisfy Maxwell's equation $\Delta.E = 0$

$$\therefore k_x E_{ox}(t) + k_y E_{oy}(t) + k_z E_{oz}(t) = 0$$

(ie) $k.E(t) = 0$

Hence k is perpendicular to E. The waves have to satisfy a boundary condition at the walls. (i) the tangential components of the field must vanish at the walls. For simplicity, let us assume the cavity to be a cube of length L as shown in Fig. 1.4.
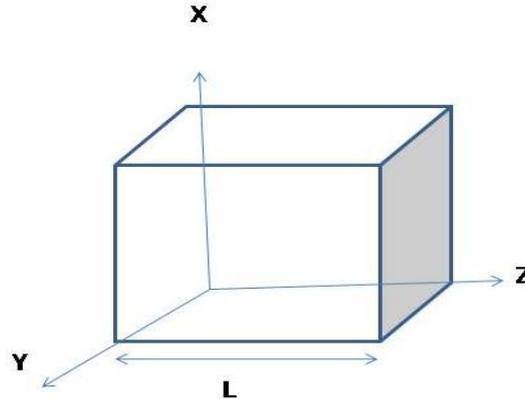

Fig.1.4 Cubic cavity

As $E_x(t)$ must vanish at x = 0 and y = L.

y = 0 and z = L.

$$k_y = \frac{n\pi}{L} \quad k_z = \frac{q\pi}{L} \qquad\qquad (1.21a)$$

Similarly $E_x(t)$ must vanish at x = 0 and x = L.

$$k_x = \frac{m\pi}{L} \qquad\qquad (1.21b)$$

Where m, n, q = 0, 1, 2. The boundary conditions force the wave vector components to take discrete values specified by m, n, q. Each set of integers (m,n,q) defines a mode of vibration. These modes are known as Transverse Electromagnetic modes and are denoted by TEM $_{mnq}$ where m and n are tranverse indices and q is the longitudinal index. Each mode has a characteristic distribution of amplitude and phase. This distribution in a plane perpendicular to the resonator axis is described by transverse indices m,n. A given combination of m, n defines a transverse mode regardless of the value of q. This is denoted as TEM $_{mnq}$ mode. For each combination of mn, there are modes different values of q. These are called longitudinal or axial modes. Thus there is an infinite number of resonant frequencies corresponding to different values of m, n, q. Any excitation of the electro magnetic field observed in the resonator can be expressed as a linear combination of these modes.

Number of modes per unit volume

We can plot the wave vectors k in a three dimensional space with the components k_x, k_y, k_z as shown in Fig.1.5. This is called k space. The allowed values of k are given by

Eq.(1.21). These form a cubic point lattice with spacing between consecutive points being π/L. Each point in k space is surrounded by volume $\left(\pi/L\right)^3$.
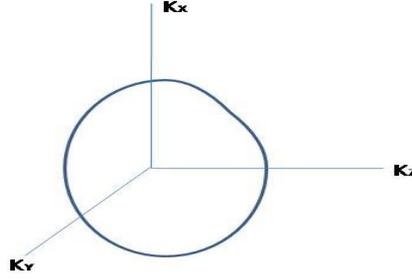

Fig.1.5 k-space

To find number of normal modes of standing waves with wave vectors lying between k and k+dk, consider the volume between the consecutive shells only in the positive octant. (ie) the volume of such positive octant is $\frac{1}{8}4\pi k^2 dk$

Hence the required number of modes
$$= f(k)dk = \frac{\frac{1}{8}4\pi k^2 dk}{\left(\pi/L\right)^3}$$
$$= \frac{L^3 k^2 dk}{\pi^2}$$

Thus, the number of modes per unit volume of the cavity (ie) the density of modes k dk is given by

$$\rho_k d_k \frac{k^2 dk}{\Pi^2}$$

Since $k=\omega/c,$ number of modes per unit volume of the cavity having their frequency ω and $\omega+d\omega$ is

$$\rho_\omega d\omega \frac{\omega^2 d\omega}{c^2 \pi^2} \qquad (1.22)$$

Consider the following example where we calculate the number of modes per unit volume falling within a line width $d\gamma=2.5 x10^{14} Hz$ of a line at $\lambda=6000\text{A}^0$ (ie) $\gamma=5x10^{14}$ Hz

$$\rho_\omega d\omega \frac{\omega^2 d\omega}{c^2 \pi^2} = \frac{8\Pi\gamma^2 d\gamma}{c^3} = 5x10^{12} / cm^3$$

(ie) This large number of modes exists and the intensity resulting from their superposition will be far from monochromatic. From Eq. (1.22) it is seen that with increasing frequency, there will be condensation of spectra.

Now the problem is how to ensure that there are only a small number of modes. One way of doing this is to use a cavity resonator of the dimension of the order or radiation wavelength. In the above example $\lambda=6000\text{A}^0$, if we have a cavity with its linear dimension λ (ie) with its volume $V = \lambda^3 = \frac{8\pi^3 c^3}{\omega^3}$

The number of modes in this volume

$$=V \frac{\omega^2 d\omega}{c^3 \pi^2} = \frac{8\pi^3 C^3}{\omega^3} \frac{\omega^2 d\omega}{c^3 \pi^2} = \frac{8\pi d\omega}{\omega}$$

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(ie) The number of modes will go on decreasing with increasing frequency. Construction of such a resonator is not practical. Moreover, such a small volume of active medium is useless because it does not yield output power. To solve the above difficulties, Schawlow and Townes suggested the use of open resonators.

1.11 Threshold condition (Schawlow and Townes equation)

Schawlow and Townes and Prokhorov initiated the concept of laser. They independenly discussed the conditions necessary for laser. As it is not possible to construct an optical resonator of the dimensions of light wavelength, they suggested two plane parallel reflecting surfaces as a suitable resonator. If the atoms are placed between two such morrors, the emitted light can built up into a standing wave. The mirrors reflect the light back into the collection of atoms, thereby serving as a means of achieving feedback (Fig.1.6)

If L is the length of the cavity and η is the refractive index of the medium, the optical length is $L=L\eta$. The condition for reinforcement is

$$L=L\eta=\frac{q\lambda}{2} \text{ where q is an integer}$$

$$\text{As} \quad \gamma=\frac{c}{\lambda}, \frac{\gamma}{c}=\frac{q}{2L\eta}$$
(1.23)

If the frequency γ satisfies the above equation, optical standing waves can be set up in a cavity of length L. In the case of solid state laser, the mirrors are deposited on the end faces of the material and hence $L=\eta L$ where as in the case of gas lasers they are outside the active materials.
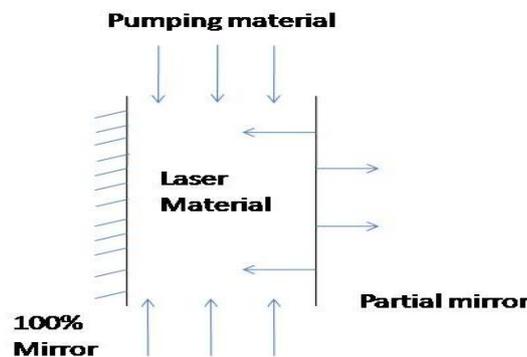

Fig.1.6 Optical resonator

Not all the intersity of light I, falling on the mirror is reflected. If I_r is the intensity of the reflected light,

$$I_r=r I$$
(1.24)

where r the fraction of light intensity reflected, is called the reflection coefficient. If one of the mirrors is partially transparent, a useful output beam can be extracted. The reflection coefficient of such a mirror must be less than 1. Normally, when a beam of light passes through a material, its intensity decreases as a function of length z as

$$I_r(z)=I_r(o)\exp(-\alpha z)$$
(1.25)

If α is negative, there will be amplification and the intensity will increase by a factor exp(k,n) (ie)

$$I_r(z)=I_r(o)\exp(k_\gamma z)$$
(1.26)

Where $K_\gamma = -\alpha$ is called unsaturated gain coefficient. It determines the gain that exists before amplification. Let r_1 r_2 be the reflection coefficients of the two mirrors. Then the energy of the wave in one complete passage back and forth will diminish by a factor $r_1 r_2$ (ie)

$$r_1 r_2 = e^{-2\gamma}$$

$$\gamma = -\frac{1}{2} \ln r_1 r_2 \qquad (1.27)$$

where γ is positive and it is measure of loss of light in a single passage. (ie) After each passage, intensity will be diminished by $e^{-\gamma}$ (ie) I reduces to $Ie^{-\gamma}$. Assuming that reflection losses are the only losses present in the cavity, the intensity in each passage change from I to $l \exp\left(k_\gamma L_{-\gamma}\right)$. For oscillations to be sustained in a laser, the amplification must be sufficient to compensate for the energy lost. For oscillations to build up

$$\exp\left(k_\gamma L_{-\gamma}\right) > 1 \; or \; k_\gamma L > \gamma \qquad (1.28)$$

Hence threshold will be reached when

$$k_\gamma L = \gamma \qquad (1.29)$$

A laser with length L and given mirror reflectivity will operate only if

$$k\gamma^3 \, \gamma / L \qquad (1.30)$$

$$k_\gamma = -\alpha = \frac{\eta c^2 \pi_2 h^2 A_{21}}{g_1 \omega_\circ^2}\left(\frac{g_1}{g_2} N_2 - N_1\right) g(\omega) \qquad (1.31)$$

where $g(\omega)$ accounts for the distribution in the line. Thus in the case of a line profile dominated by Lorentz broadening, the gain coefficient is given by

$$k_{\gamma L}(\omega) = \frac{\eta c^2 \pi^2 g_{21} N_1}{g_1 \omega_\circ^2}\left(\frac{g_1}{g_2} \frac{N_2}{N_1} - 1\right) \frac{\gamma}{2\pi} \frac{1}{(\omega + \omega_\circ) 2\gamma^2/4} \qquad (1.31)$$

The maximum value of the gain coefficient is obtained at $\omega = \omega_\circ$

$$k^0{}_{\gamma L}(\omega_\circ) = \frac{2\eta c^2 \pi^2 g_2 N_1}{g_1 \omega_\circ^2}\left(\frac{g_1}{g_2} \frac{N_2}{N_1} - 1\right) \qquad (11)$$

$$\left[\therefore \gamma = \frac{1}{\tau_{21}} = A_{21}\right]$$

(ie) The maximum gain decreases as the square of the transition frequency increases. This explains why laser oscillations are easier to achieve in the infrared region than in the visible and ultra violet regions.

For lasers to operate

$$= \frac{\eta c^2 \pi^2 g_2 A_{21}}{g_1 \omega_\circ^2}\left(\frac{g_1}{g_2} N_2 - N_1\right) g(\omega) > \frac{\gamma}{L} \qquad (1.32)$$

The laser will operate in the frequency interval in which the above condition is satisfied.
At the threshold, the condition becomes,

$$\frac{g_1}{g_2} N_2 - N_1 = \frac{\gamma g_1 \omega_\circ^2}{\eta L c^2 \pi^2 g_2 A_{21}} \qquad (1.33)$$

For non-degenerate states

$$N_2 - N_1 = \frac{\gamma \omega_\circ^2}{\eta L c^2 \pi^2 A_{21} g(\omega)} \tag{1.34}$$

This value of population inversion is known as the critical inversion. The above formula suggests that for the onset of oscillations, γ and L must be properly adjusted.

Eqn (1.34) can be expressed in a different form. Let $P_\circ$ be the number of photons travelling back and forth in a laser. The number of photons after m passenger will be

$$P = P_\circ e^{-gm} \tag{1.35}$$

It τ_L is the time taken by a photon for a single passage, the time taken for m passage will be $t = m\tau_L$)

$$P = P_\circ \exp(-\gamma t / \tau_L) \tag{1.36}$$

The average life time τ_p of a photon is the time by which $P_\circ$ is rreduced to $P_\circ/e$

$$\tau_p = \frac{\tau_L}{\gamma} = \frac{L^|}{c\gamma} \left[\because \tau_L = \frac{L^|}{c}\right]$$

$$\gamma = \frac{L^|}{c\tau_p} \tag{1.37}$$

Using this, Eq. (1.34) can be expressed in the form

$$N_2 - N_1 = \frac{L \omega_\circ^2 \tau_{21}}{\eta L c^2 \pi^2 A_{21} g(\omega)}$$

$$\left[\because A_{21} = \frac{1^|}{\tau_L}\right]$$

Since, $L' = \eta L$

$$N_2 - N_1 = \frac{\omega_\circ^2 \tau_{21}}{c^3 \tau_p \pi^2 g(\omega)} \tag{1.38}$$

As $g(\omega) = \dfrac{2}{\pi \Delta\omega_\circ}$, the above equation becomes

$$N_2 - N_1 = \frac{\omega_\circ^2 \tau_{21}}{2c^3 \tau_p \pi^2} \Delta\omega_\circ \tag{1.39}$$

This equation is known as *Schawlow–Townes condition for laser oscillations*. The population difference required to make laser oscillations depends on the two life times, the spontaneous life time of the upper energy level and the effective decay time of the cavity
.

Rate equations : Two level system:

Consider the time evolution of the population of a two level energy system in the presence of a monochromatic electro magnetic wave. If the frequency of the electromagnetic, wave is equal to the transition frequency ω_{21}, some of the atoms will absorb

energy and come to the upper level. Let N_1, N_2 be the populations of the two levels per unit volume and N_0 the total population which is constant (ie)

$$N_1 + N_2 = N_0 \qquad (1.40)$$

$$\text{Let } N_1 + N_2 = \Delta N \qquad (1.41)$$

Combining Eqs (1.40) and (1.41) we get

$$N_1 = \frac{N_\circ + \Delta N}{2}$$

$$N_2 = \frac{N_\circ + \Delta N}{2} \qquad (1.42)$$

Excited atoms come to the lower level by spontaneous and stimulated emission. Apart from radiative transition, atoms can make nonradiative transitions by giving their excess energy to the surrounding atoms in the case of a gas or to the lattice in the case of a solid. The probability of spontaneous transition is represented by $1/\tau_{sp}$ $(=A_{sp})$ Similarly the probability of non radiative transition is represented by $1/\tau_{nr}$. τ_{sp} and τ_{nr} are the spontaneous emission decay time and life time of non radiative transition is represented by $1/\tau_{nr}$. τ_{sp} and τ_{nr} are the spontaneous emission decay time and life time of non radiative process respectively.

The overall time decay τ is given by

$$\frac{1}{\tau} = \frac{1}{\tau_{sp}} + \frac{1}{\tau_{nr}} \qquad (1.43)$$

The rate of change of the population of the upper level is given by

$$\frac{dN_2}{dt} = B_{12}\rho(\omega_{21})N_1 - B_{21}\rho(\omega_{21})N_2 - \frac{N_2}{\tau} \text{ where } \rho \text{ is the density of radiation } [\because B_{12} = B_{21}]$$

$$= B_{12}\rho(\omega_{21})\Delta N - \frac{N_2}{\tau}$$

Where B_{12}, B_{21} are Einstein's coefficients. The second term on the RHS represents both spontaneous and non radiative transitions.

In the steady state, $dN_2/dt = 0$

$$= B_{12}\Delta N\rho(\omega_{21}) - \frac{N_2}{\tau} = \frac{N_\circ - \Delta N}{2\tau}$$

$$\text{(ie) } 2B_{12}\Delta N\rho(\omega_{21})\tau = N_\circ - \Delta N$$

$$\Delta N + |2B_{12}\Delta N\rho(\omega_{21})\tau = N_\circ$$

$$\Delta N = \frac{N_\circ}{1 + 2B_{12}\rho(\omega_{21})\tau} \qquad (1.44)$$

This equation shows that the population difference between the two levels in a steady state depends on the decay time of the upper level and on the density of incident radiation $\rho(\omega_{21})$ $B_{12}\rho(\omega_{21})$ is the probability per unit time that the atoms are excited to the upper level and is called the pumping rate. We represent it by Ω.

$$\therefore \Delta N = \frac{N_\circ}{1 + 2\Omega\tau} \qquad (1.45)$$

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We see that whatever the value of Ω, ΔN is always positive and hence inversion is not possible.

$$\text{If } \Omega \to \infty, \Delta N \to 0 \,(ie)\, N_1 = N_2 = N_0 / 2$$

Hence a two level system is not suitable for optical pumping. The pump power absorbed by the material per unit volume, to maintain a given population difference ΔN is

$$\frac{d\rho}{dv} = \hbar\omega_{21} B_{12}\rho(\omega_{21})\Delta N = \frac{\hbar\omega_{21} B_{12}\rho(\omega_{21})N_\circ}{1 + 2B_{21}\rho(\omega_{21})\tau}$$

If $B_{12}\rho(\omega_{21}) >> 1$, then

$$\frac{d\rho}{dv} = \frac{\hbar\omega_{21} N_\circ}{2\tau} \qquad (1.46)$$

Thus the pump power also depends upon the decay time τ

Rate equation – Three level system:

Let us now consider a three level system as shown in Fig. 1.7. Of all the atoms pumped into level 3 from level 1, some go back to level 1 by spontaneous and stimulated emissions and some to level 2 by radiative and non radiative processes.
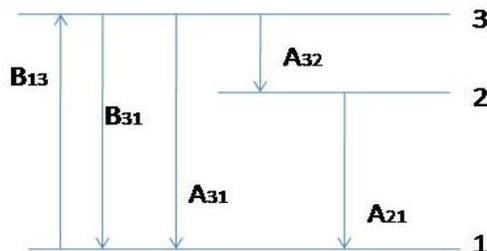

Fig.1.7 Three level system

The rate equations in the steady state are

$$\frac{dN_3}{dt} = N_1 B_{13}\rho(\omega_{31}) - N_3 B_{31}\rho(\omega_{31}) - N_3 A_{31} - N_3 S_{32} = 0 \qquad (1.47a)$$

where
  i. the 1$^{\text{st}}$ term represents number of atoms arriving at the level 3 per unit time per unit volume due to induced or stimulated absorption.
  ii. 2$^{\text{nd}}$ term represents the number of stimulated emissions
  iii. 3$^{\text{rd}}$ term represents is the number of spontaneous emissions.
  iv. 4$^{\text{th}}$ term represents transition to the level 2 due to radiative and no radiative processes S_{32} is the probability of transitions.

$$\frac{dN_2}{dt} = N_3 S_{32} - N_3 B_{31}\rho(\omega_{31}) - N_3 A_{31} - N_3 S_{32} = 0 \qquad (1.47b)$$

Here the last two terms represent induced transitions between levels 1 and 2 due to the presence of laser radiation.

$$\frac{dN_1}{dt} = N_3 B_{13}\rho(\omega_{31}) + N_3 A_{31} + N_2 B_{12}\rho(\omega_{31})N_2 A_{21} - N_1 B_{13}\rho(\omega_{31}) - N_1 B_{12}\rho(\omega_{21}) = 0 \qquad (1.47c)$$

$$N_0 = N_1 + N_2 + N_3$$

From eqs. 1.47(a) (b) (c), we see that

$$\frac{dN_1}{dt} + \frac{dN_2}{dt} + \frac{dN_3}{dt} = 0 \qquad (1.48)$$

Which is consistent with Eq.(1.47).

Solving these equations for N_1 and N_2 and finding $N_2 - N_1$, We get

$$N_2 - N_1 = \frac{N_\circ \left\{ \dfrac{B_{13}\rho(\omega_{31})S_{32}}{B_{13}\rho(\omega_{31}) + A_{31} + S_{32}} \right\}}{2B_{12}\rho(\omega_{21}) + A_{21} + \dfrac{B_{13}\rho(\omega_{31})S_{32} + B_{13}\rho(\omega_{31})\{B_{12}\rho(\omega_{31}) + A_{21}\}}{B_{13}\rho(\omega_{31}) + A_{31} + S_{32}}} \qquad (1.49)$$

From Eq. (1.47a), number of atoms arriving per unit time at the

Level 2 is $\qquad N_3\, S_{32} = \dfrac{N_1 B_{13}\rho(\omega_{31})S_{32}}{B_{13}\rho(\omega_{31}) + A_{31} + S_{32}}$

Hence, the probability Ω that an atom arrives at level 2 is

$$\Omega = \frac{B_{13}\rho(\omega_{31})S_{32}}{B_{13}\rho(\omega_{31}) + A_{31} + S_{32}}$$

Using this in Eq. (1.49)

$$N_2 - N_1 = \frac{N_\circ(\Omega - A_{21})}{2B_{12}\rho(\omega_{21}) + A_{21} + \dfrac{B_{13}\rho(\omega_{31})S_{32} + B_{13}\rho(\omega_{31})\{B_{12}\rho(\omega_{31}) + A_{21}\}}{B_{13}\rho(\omega_{31}) + A_{31} + S_{32}}}$$

For population inversion (ie) $N_2 - N_1$ is positive, it is necessary that $\Omega > A_{21}$

$$\text{(ie)} = \frac{B_{13}\rho(\omega_{31})S_{32}}{B_{13}\rho(\omega_{31}) + A_{31} + S_{32}} > A_{21}$$

Using a beam of suitable intensity, it is possible to produce the required population inversion. The quantity $\Omega_{inv} = A_{21}$ is called the inversion threshold pumping rate.

1.12 Types of lasers:

The types of laser considered are.

      (a) Solid state lasers : For eg. Ruby, Nd: YAG, Nd: glass;

      (b) Gas lasers : For eg. He-Ne, Argon ion, and CO_2

      (c) Liquid lasers : for eg, dyes, chemical lasers

      (d) Excimer lasers ;

      (e) Semiconductor Lasers

These laser systems are in widespread use today for different applications.

(a) Ruby Laser The first laser to be operated successfully was the ruby laser which was fabricated by Maiman in 1960.

It consists of a ruby cylindrical rod whose ends are optically flat and accurately parallel is shown in Fig.1.8. One end is fully silvered and the other is only partially silvered. The road is surrounded by a glass tube. The glass tube is surrounded by a helical xenon flash tube which acts as the optical pumping system. The ruby rod is a crystal of aluminium oxide (AI_2O_3) doped with 0.05% chromium oxide (Cr_2O_3), so that some of the aluminium atoms in the crystal lattice are replaced by Cr^{3+} ions. The energy level diagram of these chromium ions is shown in Fig. 1.9. The Cr ions are excited from level E_1 to level E_3 by the absorption of light of wave length 550 nm from the xenon flash tube. The excited ions quickly undergo non radiative transitions with a transfer of energy to the lattic thermal motion, to the level E_2.
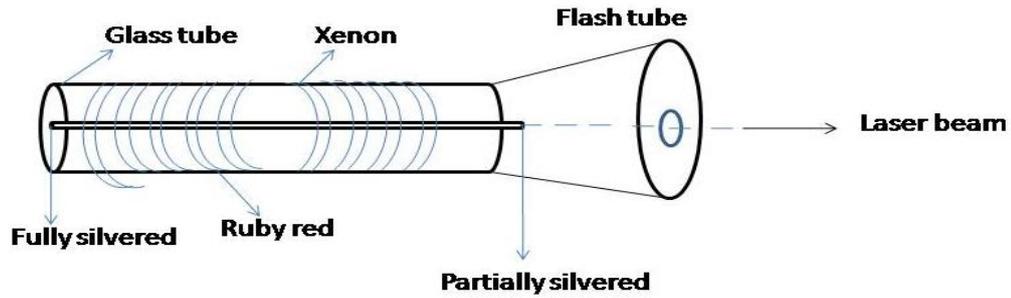
Fig.1.8 Ruby laser

The level is a metastable state with a life time of about $3 x 10^{-3}$ sec (usual atomic lifetime are = 10^{-8} sec). Now the population of the E_2 level becomes greater than that of the E_1 level. Thus "Population inversion" is achieved.
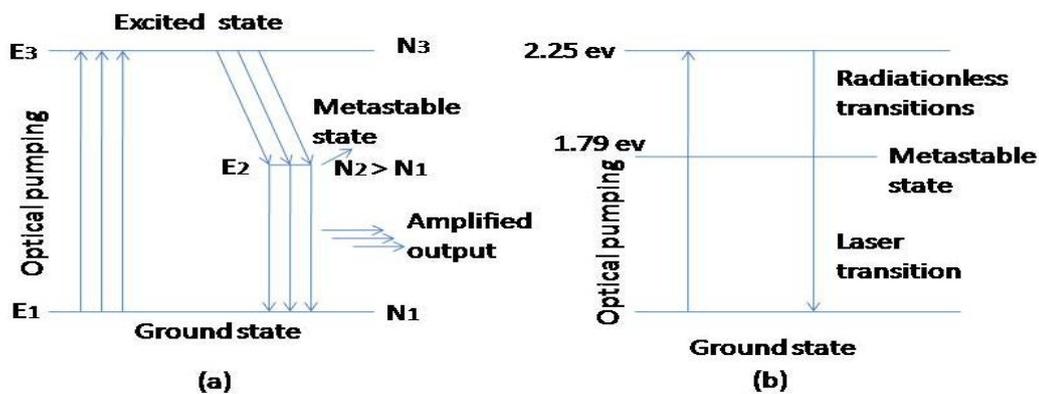

Fig. 1.9 Energy level diagram of Cr^{3+} ions in ruby

Some photons are produced by spontaneous transition from E_2 to E_1 and have a wave length of 694.3 nm (ruby rod). The ends of the ruby rod act as reflecting mirrors. Therefore, photons that are not moving parallel to the ruby rod escape from the side, but those moving parallel to it are reflected back and forth. These stimulate the emission of similar other photons. The chain reaction quickly develops a beam of photons all moving parallel to the rod, which is monochromatic and is coherent. When the beam develops sufficient intensity, it emerges through the partially silvered end. Once all the chromium ions in the metastable level have returned to ground level, the laser action stops. It is then necessary to send one more flash of pumping radiation through the rod. Thus the ruby laser operates only in pulses.

The output of a pulsed ruby laser, if examined with a photocell and on oscillograph, is found to consists of a series of pulses of duration of a microsecond or less. Duration of an individual spike is of the order of $0.1 - 1$ μs; the time interval between two adjacent spikes is about $- 1$-10 μs; the power of each spike is of the order of $10^4 - 10^5$ W. Such spikes were first observed in expts with ruby by Collins et al.

(b) Neodymium based Lasers

The Nd : YAG laser (YAG stand for Yttrium Aluminium Garnet which is $Y_3 AI_5 O_{12}$) and the Nd:glass laser are two very important solid state laser systems in which the energy

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levels of the neodymium ion take part in laser emission. They both correspond to a four level laser.Using neodymium ions in a YAG (or) glass host has specific advantages and applications.

(i) Since glass has an amorphous structure the fluorescent linewidth of emission is very large leading to a high value of the laser threshold. On the other hand YAG is a crystalline material and the corresponding linewidth is much smaller which implies much lower thereholds for laser oscillation.

(ii) The larger linewidth of the glass host than the YAG host can be made use of in the production of ultra short pulses using mode locking. The pulsewidth obtainable by mode locking is the inverse of the oscillating linewidth.

(iii) The larger linewidth in glass leads to a smaller amplification coefficient and thus the capability of storing a larger amount of energy before the occurrence of saturation.

(iv) As compared to YAG, glass has a much lower thermal conductivity which may lead to induced birefringence and optical distortion.

(v) Glass does not absorb the laser emission.

(vi) Glass materials are optically homogeneous and lend themselves for doping in high concentration of impurities.

From the above discussion, for continuous or very high pulse repetition rate operation, the Nd: YAG laser will be preferred over Nd:glass. On the other hand for high energy pulsed operation, Nd:glass lasers may be preferred.

Nd: YAG Laser :   The Nd:YAG laser is a four level laser system. The active medium for this laser is Yttrium Aluminium Garnet $(Y_3AI_5O_{12})$ with the rare earth metal ion neodymium Nd^{3+} present as an impurity. The Nd^{3+} ions, which are randomly distributed as substitutional impurities on lattice sites normally occupied by the yttrium ions, provide the energy levels for both the lasing transitions and pumping. The energy level diagram of the neodymium ion is shown in Fig. 1.10(a)
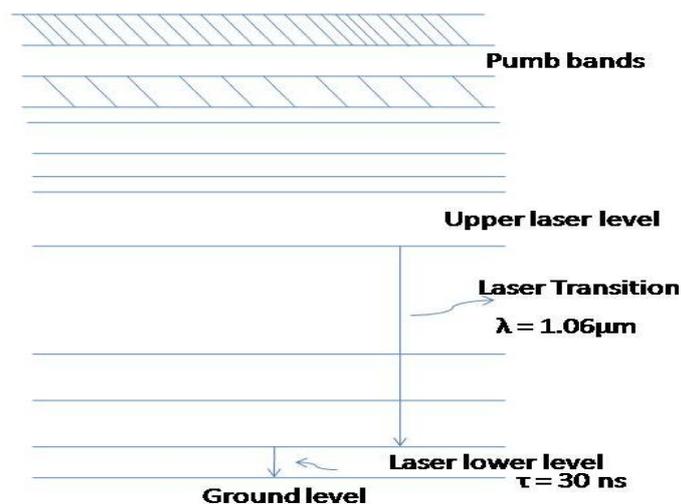

Fig 1.10(a) : The energy levels of neodymium ion in the Nd:YAG laser

The laser emission occurs at $\lambda_0 = 1.06\,\mu m$. Since the energy difference between the lower laser level and the ground level is ~0.26 ev, the ratio of its population to that of the ground

state at room temperature (T = 300 K) is $e^{-\Delta EKT} = e^{-9} \ll 1$. Thus the lower laser level is almost unpopulated and hence inversion is easy to achieve.

The main pump bands for excitation of the neodymium ions are in the 0.81 μm and 0.75 μm wave length region and pumping is done using arc lamps (e.g. Krypton arc lamp). Typical neodymium ion concentrations used are Δv~1.2 x 10^{11}Hz which corresponds to Δλ~ 4.5A°. Already we know that the Nd: YAG laser has a much lower threshold of oscillation than a ruby laser.

The usual arrangement of Nd:YAG laser is shown in the Fig.1.10(b), a linear flash tube and the lasing medium in the form of a rod are placed inside a highly reflecting elliptical cavity. If the falsh tube is along one focal axis and the other laser rod along the other, then the properties of the ellipse ensure that most of the radiation from the flash tube passes through the laser. The flash tube is fired by discharging a capacitor bank through the tube; the discharge is often initiated by using a secondary high voltage ($\approx 20kv$) trigger pulse.

The optical cavity may be formed by grinding the ends of the Nd:YAG rod flat and parallel and then silvering them. More usually, external mirrors are used as shown in the Fig.1.10(b) one mirror is made totally reflecting while the other is about 10% transmitting to give an output.
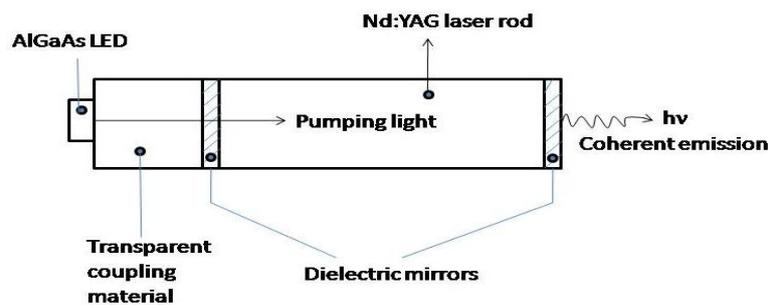

Fig.1.10(b) Schematic diagram of an end pumped Nd:YAG laser

(c) Gas Lasers:

Generally is gases, optical pumping is not used, because only insignificant, of the optical power will be utilized for the excitation of the active centres and the major part of it will be wasted in heating the gas. Instead, atoms are lifted to the higher level by electrical pumping. The only case in laser action has been observed in a gas by means of optical pumping is that of Cs, pumped by a discharge lamp containing He. The helium line was used to irradiate Cs vapour, which gave a very efficient pumping and continuous laser amplification and oscillation was observed at 7.18μ.

Helium – Neon Laser

The main problem in a gas laser is, how the atoms can be selectively excited to proper levels in quantities sufficient to achieve the required population inversion. The primary mechanism for excitation used in a gas lasers is by electron impact. Fig.1.11 shows the schematic diagram of a He – Ne laser. The laser tube is approximately 5mm in diatmeter and 0.5m long. It contains a helium – neon mixture, in the ratio of 5:1 at a total pressure of 1 Torr. The tube has parallel mirrors, one of them partly transparent at both ends.
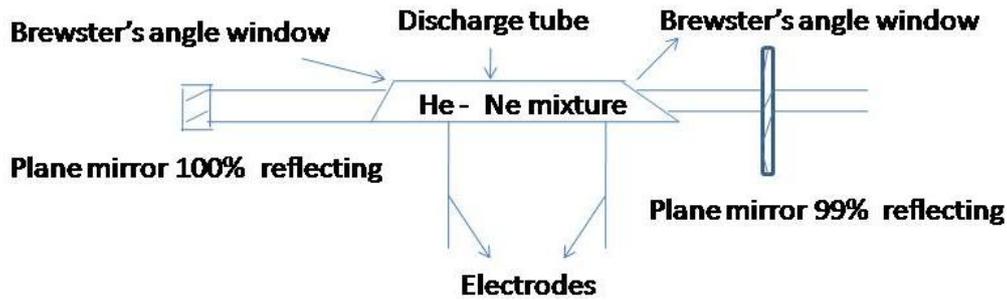
Fig.1.11 Schematic diagram of the He – Ne Laser

The spacing of the mirrors is equal to an integral number of half wavelength of the laser light. The He-Ne mixture contained in the gas discharge tube is ionized by passing a dc current through the gas. Helium atoms are excited very efficiently by electron impact into the 2s level. (Fig 1.12), while the neon atoms are much less readily excited by the electrons. This excited 2s state of helium is relatively long lived. The energy of this level (20.61ev) is almost the same as the energy of the 5s level (20.66 ev) in neon. Hence energy of the helium atoms is easily transferred to the neon atoms when they collide. This preferential transfer of the neon atoms to the 5s state results in a population inversion between the 5s and 3p states. The purpose of the He atoms is thus to help achieve a population inversion in the Ne atoms. The spontaneous transitions from the 5st state to the 3p state, produce photons of wavelength 632.8 nm, which then trigger stimulated transitions.
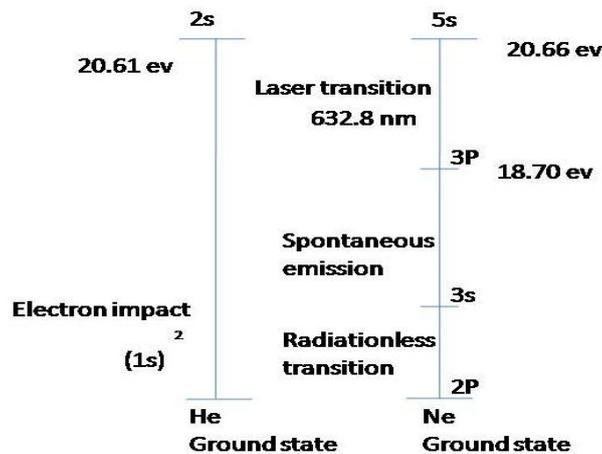

Fig. 1.12. Energy levels of the He – Ne system.

Photons that travelling parallel to the tube are reflected back and forth between the mirrors placed at the ends, and rapidly build up into an intense beam which escapes through the end with the lower reflectivity. The Brewster's angle window allow light of one polarization to pass through without any reflection losses. Because the electron impacts that excite the He and Ne atoms occur all the time, a He – Ne laser operates continuously. Here Brewster angle is an angle of incidence of a light ray such that it satisfies the condition tan $\theta_B = \eta$ where θ_B is the angle between the normal to the Brewster window and the resonator axis and η is the refractive index. The 6328 A^0 He – Ne laser is one of the most popular and most widely used

lasers. The commercial model of this type of laser requires 5 to 10 W of excitation power and produces 0.5 to 50 m W of cw laser output.

CO$_2$ laser :

The lasers so far discussed use transitions among the various excited electronic states of an atom or an ion. In a CO$_2$ laser one used the transitions occurring between different vibrational states of the carbon dioxide molecule. Fig.1.13 shows the carbon dioxide molecule consisting of a central carbon atom with two oxygen atoms attached one on either side. Such a molecule can vibrate with three independent modes of vibration shown in Fig. 1.13. These correspond to the symmetric stretch, the bending and the asymmetric stretch modes. Each of these modes is characterized by a definite frequency of vibration.
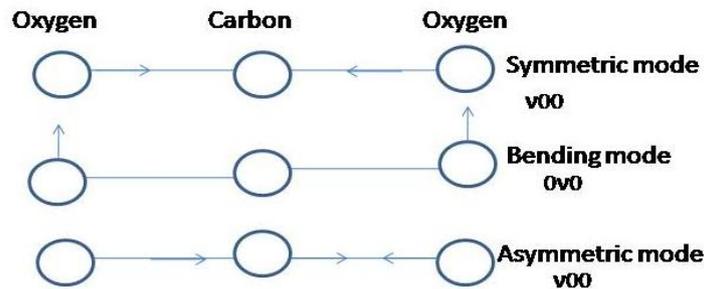

Fig. 1.13 Vibrational modes of the CO$_2$ molecule

The modes of vibrations are denoted by a set of three quantum number (v_1, v_2, v_3) which represent the amount of Random amplitude fluctuation in the output power. Energy or number of energy quanta associated with each mode. The set (100), for example, means that a molecule in this state is vibrating in a pure symmetric mode with one quantum of vibrational energy, it has no energy associated with the 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 rotational levels are designated by an integer J. The energy separation between these molecular levels is small and the laser output is therefore in the infrared. The important part of the CO$_2$ energy level arrangement as shown in Fig. 1.14 which also shows the ground state and first excited state of the vibrational modes of nitrogen.
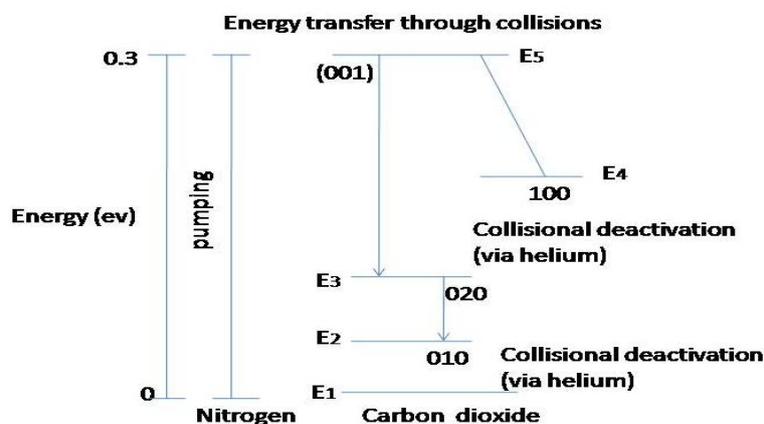

Fig.1.14 Simplified energy level diagram for the CO2 laser

Many CO_2 lasers contain a mixture of CO_2, nitrogen, helium in the ratio 1:4:5 Nitrogen plays similar role to that of helium in the He-Ne laser. Excited nitrogen molecules transfer energy to the CO_2 molecules in resonant collisions ; exciting them to the (001) levels. The (100) CO_2 levels have a lower energy and cannot be populated in this way, so that population inversion is created between the (001) and (100) levels giving stimulated emission at about $10.6\,\mu m$. The helium has a dual role. Firstly, it increases the thermal conductivity to the walls of the tube, thereby decreasing the temperature and Doppler broadening, which inturn increases the gain. Secondly it increases the laser efficiency by indirectly depleting the population of the (100) level, which is linked by resonant collisions to the (020) and (010) levels, the later being depleted via collisions with the helium atoms. The CO_2 laser possesses an extremely high efficiency of ~30%. This is because of efficient pumping to the (001) level and also because all the energy levels involved are close to the ground level. Thus the atomic quantum efficiency which is the ratio of the energy difference corresponding to the laser transition to the energy difference of the pump transition, ie

$$\eta = \frac{E_5 - E_4}{E_5 - E_1}$$

is quite high (~45%). Thus a large portion of input power can be converted into useful laser power. Output powers of several watts to several kilowatts can be obtained from CO_2 lasers. High power CO_2 lasers find applications in materials processing, welding, hole drilling, cutting etc., because of their very high output power. In addition the atmospheric attenuation is low at $10.6\,\mu m$ which leads to some applications of CO_2 lasers in open air communications

(d) Semiconductor lasers
   (i) Homojunction laser
        Semiconductor lasers are not very different in principle from the light emitting diodes. A p-n junction provides the active medium. To obtain laser action we have to create population inversion and provide optical feedback. To obtain stimulated emission, there must be a region in the device where there are many excited electrons and holes present together. This is achieved by forming a homojunction from very heavily doped n and p materials. In such n+ type material, the Fermi level lies within the conduction band. Similarly, for the p+ type material Fermi level lies in the valence band. Fig.1.15 shows the heavily doped p-n junction a) in equilibrium and b) with forward bias condition. When the junction is forward biased with a voltage that is nearly equal to the energy gap voltage (Eg/e), the electrons and holes are injected across the junction in sufficient number to create a population inversion in a narrow zone called the active region (Fig.1.16). If doping level of n region is higher thatn that of p region, then the junction current is carried mainly by electrons. If L_e is the diffusion length of electrons injected into the p region, the thickness t of the active region can be approximated to L_e. for heavily doped *GaAs* at room temperature L_e is l-$3\,\mu m$. Since *GaAs* has direct bandgap, the electrons and holes have a higher probability of radiative recombination. The photons thus produced may either interact with valence band electrons and be absorbed (stimulated absorption), or interact with the conduction band electrons thereby stimulating radiative recombination (stimulated emission) producing further photons of the same energy *(Eg=hv).*
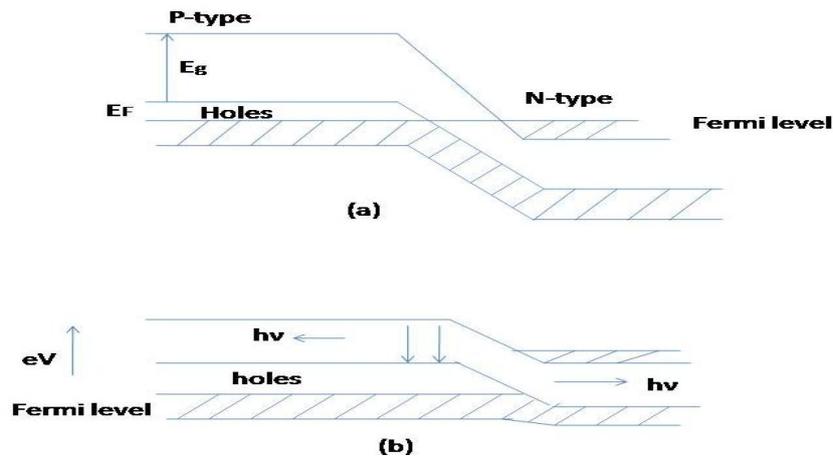
Fig.1.15 Heavily doped p-n junction (a) in equilibrium and (b) with forward bias.
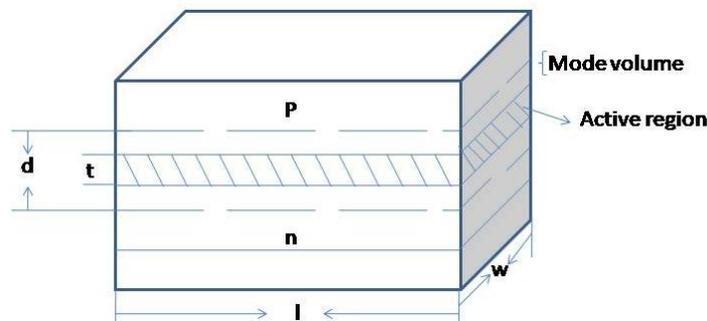

Fig.1.16 Diagram showing the active region and mode volume of a semiconductor laser

If the injected carrier concentration is large, the stimulated emission can exceed the absorption so that optical amplification is achieved in the active region. To provide feedback, there is no need to use external mirrors in the case of diode lasers. The diode is cleaved along natural crystal plane normal to the plane of the junction so that the end faces are perfectly parallel. For *GaAs,* the junction plane is (100) and the cleaved faces are (110) planes. The high refractive index (≤ 3.6) of *GaAs* ensures sufficiently high reflection at the material / air interface so that there is no need for separate external mirrors to provide optical feedback. Laser oscillations occur when the round trip gain exceeds the total losses. In semiconductors, the major losses are due to scattering at optical inhomogeneties in the semiconductor material and free carrier absorption.

In the active region additional charge carriers present increases its refractive index above that of the surrounding material, thereby forming a dielectric waveguide. Since the difference in refractive index between the centre waveguiding layer and the surrounding regions is very less (about 0.02 only), the waveguiding effect is not very efficient. Therefore the radiation generated in the active region extends to some extend beyond the active region, thereby forming the mode volume. The waveguiding effect achieved in simple homojunction laser diodes of the form shown in Fig.1.17 just allows the laser action on vigorous pumping. They can be operated only in the pulsed mode at room temperature because of very high

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threshold pumping current density (typically of the order of 400 Amm^{-2}). The onset of laser action at the threshold current density is indicted by a sudden increase of light output intensity at the emitting region as shown in Fig. 1.18(a). Below threshold, spontaneous emission takes place and output, emission is observed to be spectrally wide. Above threshold there is a marked decrease in spectral width and abrupt increase in intensity of the output, as illustrated in Fig.1.18(b).
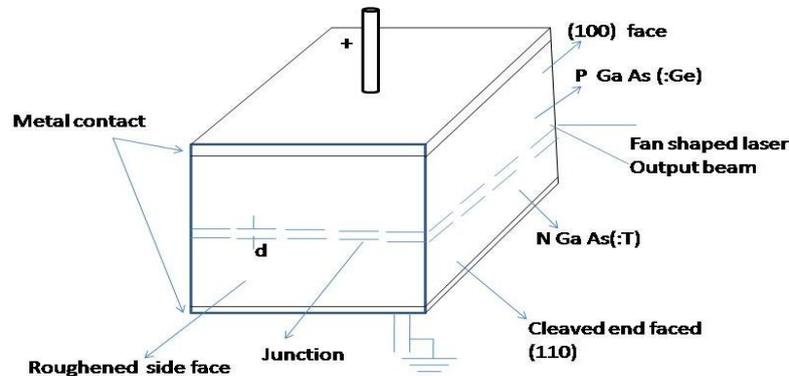

Fig. 1.18 Schematic construction of a *GaAs* homojunction semiconductor diode laser having side lengths 200- -400 μm .The emission is confined to the junction region.

The *GaAs* laser emits light at 900nm (infrared) while a *GaAsP* laser radiatedsat 650nm (visible red region). Unlike other lasers, for diode lasers divergence is high since the active region emitting radiation acts as a narrow single slit diffracting the output. Along the direction parallel to the layer, divergence is around 10° while in the direction normal to the active layer it is around 40°.
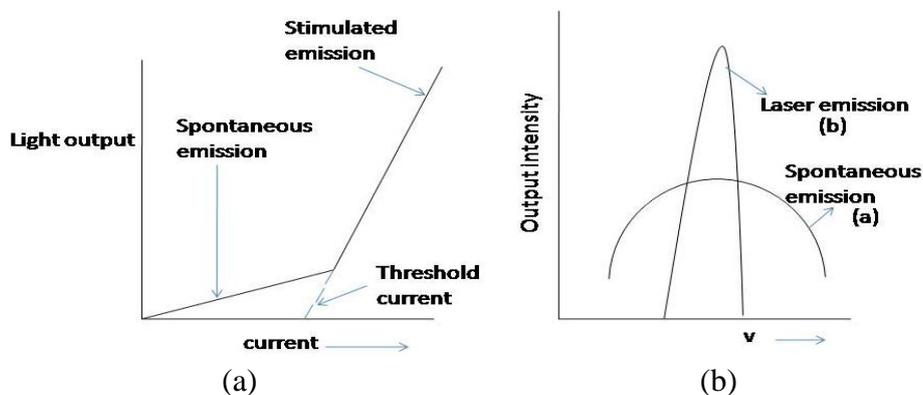

(a)   (b)

Fig.1.19 (a) Light output – current characteristics of a ideal semiconductor laser (b) Radiant output as a function of frequency for a p-n junction laser.

ii) Heterojunction lasers:
 We have seen that the threshold current density for homojunction lasers is very large due to poor optical and carrier confinement. Heterojunction lasers have high efficiency even at room temperatures. Threshold current density reduces to 10Amm^{-2} and CW operation is possible. Using multilayers in the laser structure, carriers are confined to a narrow region so that population is built up at lower current levels. With operating currents of less than 50mA, output powers of about 10mW can be produced. Lasers with lifetimes in excess of 40,000 hours are now available corresponding to continuous operation over a five –year period. In

optical fibre communications, it is desirable to have a laser emitting at wavelengths in the region 1.1 to 1.6 μm, where present optical fibres have minimum attenuation and dispersion. From lasers fabricated with quaternary compounds such as $Ga_xIn_{1-x}As1_{-y}P_y$, wavelengths in this range can be obtained.

1.13 Applications of Lasers

In 1960, when invented laser was called "an invention in search of applications". Nobody was knowing what to do with such an intense, highly directional beam. Very first application of laser was in the field of medicine but within an year in quite a lot of areas, lasers started finding their applications. We can now say that there is no field in which lasers are not being used. Let us see applications of lasers in few fields.

Lasers in Industry : In manufacturing industry lasers are used for welding, cutting and drilling applications.

Welding : With increased power output, it is possible to use the laser (primarily CO_2) as a welding tool. The advantages of laser welding are:

- ❖ Very high welding rates are possible (with 10kW CO_2 laser 5 mm thick stainless steel plates can be welded at a speed of 10 cm/sec).
- ❖ Dissimilar metals can be welded
- ❖ Minimum amount of distortion of the surrounded are (i.e.very less heat affected zone?
- ❖ Any extremely complex shaped contours can be welded using computers for controlling the deflection of the laser beam.
- ❖ Microwelding is done with great ease.
- ❖ Being non-contact method, the work piece is not stressed.

Cutting : Lasers cut through a wide variety of materials, rapidly and precisely.

- ❖ With low – power CO_2 laser, insulation from electrical wires and cables are striped off. While the insulation material absorbs are radiation metal conductor reflects the same. Hence without any damage to the electrical wire the insulation can be removed.
- ❖ With high power levels, glass and quart are easily cut with CO_2 laser. With 250 watt CO_2 laser 3 mm thick quartz plate can be cut at a rate of 2 cm/sec.

Solid State Physics

- ❖ With the same laser quoted above, oxygen assisted laser cutting can be done at a rate of 1cm /sec in a low-carbon steel plate of 1 cm thick.
- ❖ Any desired shape can be cut.
- ❖ Cut finish used to be very smooth (cosmetic) requiring no further treatment such as grinding and polishing.
- ❖ Lasers are used to cut a large number of models and sizes of dresses and suits. Synthetic fabrics are particularly suited to this technique, since the cut edges are melted by the beam and any fraying is prevented.

Drilling : Most drilling systems operate in a pulsed mode. To get the drill of desired depth and size, number of pulses, and the energy of each pulse are to be controlled.

- • One of the first application of the laser was to drill diamond dies used in the extrusion of wire.

- Lasers are used to drill aerosol nozzles and control orifices within the required precision.
- Lasers are used to drill holes in 'difficult to drill' materials such as ceramics etc.
- Holes of micron order can be easily drilled using lasers. (In this small range drill bits can not be used).

Head treatment : Head treatment is common in the tooling and automotive industry. Wherever it is desirable to treat only a portion of a large item, lasers are very useful. For example, an automobile piston ring alone has to be heat treated and hardened without affecting the entire piston.

The greatest advantage of use of laser system in industry is that a single system can be used for all the above applications by proper adjustment of its power. Being non contact method the entire region is stress free.

Lasers in electronic industry: Lasers are widely used for material processing in electronic industry. Let us see few such important applications.

Scribing

Scribing involves drawing fine lines in brittle ceramic and semiconductor wafers. When bent they break along the line scribed. Low power CO_2 lasers are generally used for this purpose.

Soldering

'Difficult to solder' material such as platinum, silver, palladium are soldered using lasers. Sheets as thin as 25 micron can be soldered without any damage to the sheet. This is a fluxless soldering and non – contact method. Nd: YAG laser is used for this process.

Trimming

Film resistor trimming is effectively carried out using Nd: YAG laser. First a film of higher thickness and hence lower resistance value is taken. Using pulsed laser without thermal damage to the substrate, the resistance material is gradually removed from the surface and its resistance is continuously monitored and controlled.

Lasers in Medicine

The very first application of laser was in the field of medicine :

- Ophthalmologists started using Argon ion lasers for welding retinal detachment. The retina is the light sensitive layer at the back of the eye. If it is torn and extends it may lead to blindness. The green beam of Argon ion laser is strongly absorbed by red blood cells of the retina and welds the retina back to the eye ball. Since this beam passes through the eye lens and the vitrious chamber without being absorbed, this treatment is done without surgery.
- For cataract removal lasers are used
- Using ultraviolet radiation from Excimer laser, eye lens curvature correction is being carried out. This is based on photoablative effect invented by Prof.Srinivasan.
- Laser scalpels are used for bloodless surgery. When the tissues are cut the blood veins cut are fused at their tips by the infrared laser and hence there is no blood loss.
- In laser angioplasty for removal of artery block Nd: YAG lasers are used. The laser radiation is sent through fiber to the region of block, burns the excess growth and regulates the blood flow without need for bypass surgery.

- In dermatology, lasers are used to remove freckles, acne, birth marks and tattoo. When such regions are illuminated with blue-green laser light, the radiation is absorbed by the blood and heats up. The blood vessels are closed and excess blood flow is stopped.
- Lasers are used in destroying kidney stones and gallstones. Laser pulses sent through optical fibers shatter the stones into small pieces.
- Lasers are used in cancer diagnosis and therapy. When suscept growth region is illuminated with ultraviolet laser, the porferin, a natural dye accumulated in cancerous region glows with red colour indicating the presence of cancerous cells. When photosensitive dye is injected into the patient's body, the dye is concentrated in cancer cells. When suscept areas are illuminated with laser of approximate wavelength, cancer cells are destroyed.

Lasers in Scientific Fields

It is impossible to list out all the applications of lasers in scientific fields. Let us see few important applications.

Lasers in metrology

When Amstrong landed in the moon in 1969, he placed a reflecting mirror there. A pulsed laser pulse was sent from the earth to the moon; its reflected signal was received and the distance between the earth and the moon was calculated with centimetre accuracy. Now-a-days for surveying and aligement lasers are used. Using laser interferometry any displacement can be measured with an accuracy of nanometer (10^{-9}m).

Lasers in defence

Lasers are finding wide range of applications such as ranging, guiding weapons to the intended target and beam itself acting as a weapon.

- Pulsed laser beam directed towards the target returns after reflection. The time-delay in its round-trip is measured to determine the range of the target. If the object is in motion, the reflected signal is Doppler shifted and by measuring this shift the velocity of the moving object is also calculated. Nd: YAG or Nd: glass lasers are used for this purpose.
- Lasers are used to guide the missiles. The head of the missile sends a laser beam to the target and from the collection of light scattered from the target, the angle of line of sight is determined. The difference, if any, between the glide angle of the trajectory of bomb and the angle of line of sight is fed to servo loop acting as the error signal. The error correcting signal controls the direction of motion of the bomb and brings it onto the target. Since infrared radiation is not absorbed by fog, smoke or haze in the atmosphere, CO_2 lasers are used for this purpose.
- Laser weapons have two uses in defence ; one to disable the enemy weapons and another to destroy them. Lasers with moderate powers are used to damage the infrared sensors on guided missies or the sensitive electronic eyes of spy satellites. To destroy the weapons very high powers (of megawatts order) are required. Still there are many problems associated with such programmes.

Lasers in nuclear energy

- Nuclear fusion offers a low cost and pollution free energy. Extremely high temperature and pressures are required in order to make light nuclei to overcome

their mutual repulsion and combine to release energy. Laser assisted inertial confinement method generates highly compressed plasma of heavy isotopes of hydrogen, namely deuterium D and tritium T. In the presence of such high compression, the core reaches a temperature of about 10^8K. To achieve these conditions enormous amount of laser pulse energy is needed. Many countries are in the process of development of laser fusion projects.

- Lasers are used for isotope separation. Isotopes are chemically almost identical. Each isotope absorbs light at different characteristic wavelength. Using a tunable dye laser it is possible to ionize one isotope without disturbing the other. Ionized isotope can be separated from the other using electrostatic fields. From natural U-238, ionized U=235 atoms are separated using this method.

Lasers in optical communications

The amount of information that can be sent over an electro magnetic wave is proportional to the bandwidth of the wave. Since lasers operate with exceedingly large bandwidth, optical communication using lasers is very attractive.

Lasers are used in two types of communication, one, open space communication and another fibre optic communication.

- Open space communication requires the environment free from fog, dust and rain. Since lasers are highly directional laser communication is very attractive when compared to microwave communication (To achieve the directionality as that of the laser of beam waist I mm diameter, the microwave antenna must be 100m in diameter)
- Now-a-days conventional metallic cables are replaced by fiber optic cables because of the following advantages.
  1. Enormous bandwidth (as large as 10^5 GHz)
  2. Electrical isolation
  3. Immunity to interference and cross talk
  4. Signal security
  5. Small size and weight
  6. Low transmission loss
  7. Ruggedness and flexibility
  8. Low cost

Lasers in consumer electronics industry

Diode lasers as well as low power He-Ne lasers are used in different consumer electronic industries. They are used every day in different fields.

Supermarket scanners.

Now-a-days on almost all consumer items, bar codes are printed. When laser light scans the bar code label, the dark lines of the code absorb light while the bright lines reflect light. This light modulation is registered by a photosensitive light detector. This information passes to the computer which in turn identifies the product and displays the price. Such bar codes are used in libraries also.

Unit - II

Basics of Semiconductors

2.1. Nature of Light:

The scientific study of the behavior of light is called optics and covers reflection of light by a mirror or other object, refraction by a lens or prism, diffraction of light as it passes by the edge of an opaque object, and interference patterns resulting from diffraction. Also studied is the polarization of light. Any successful theory of the nature of light must be able to explain these and other optical phenomena.

(a) The Wave, Particle, and Electromagnetic Theories of Light:

The earliest scientific theories of the nature of light were proposed around the end of the 17th century. In 1690, Christian Huygens proposed a theory that explained light as a wave phenomenon. However, a rival theory was offered by Sir Isaac Newton in 1704. Newton, who had discovered the visible spectrum in 1666, held that light is composed of tiny particles, or corpuscles, emitted by luminous bodies. By combining this corpuscular theory with his laws of mechanics, he was able to explain many optical phenomena.

For more than 100 years, Newton's corpuscular theory of light was favored over the wave theory, partly because of Newton's great prestige and partly because not enough experimental evidence existed to provide an adequate basis of comparison between the two theories. Finally, important experiments were done on the diffraction and interference of light by Thomas Young (1801) and A. J. Fresnel (1814–15) that could only be interpreted in terms of the wave theory. The polarization of light was still another phenomenon that could only be explained by the wave theory. Thus, in the 19th century, the wave theory became the dominant theory of the nature of light. The wave theory received additional support from the electromagnetic theory of James Clerk Maxwell (1864), who showed that electric and magnetic fields were propagated together and that their speed was identical with the speed of light. It thus became clear that visible light is a form of electromagnetic radiation, constituting only a small part of the electromagnetic spectrum. Maxwell's theory was confirmed experimentally with the discovery of radio waves by Heinrich Hertz in 1886.

(b) Modern Theory of the Nature of Light:

With the acceptance of the electromagnetic theory of light, only two general problems remained. One of these was that of the luminiferous ether, a hypothetical medium suggested as the carrier of light waves, just as air or water carries sound waves. The ether was assumed to have some very unusual properties, e.g., being massless but having high elasticity. A number of experiments performed to give evidence of the ether, most notably by A. A. Michelson in 1881 and by Michelson and E. W. Morley in 1887, failed to support the ether hypothesis. With the publication of the special theory of relativity in 1905 by Albert Einstein, the ether was shown to be unnecessary to the electromagnetic theory.

The second main problem, and the more serious of the two, was the explanation of various phenomena, such as the photoelectric effect, that involved the interaction of light with matter. Again the solution to the problem was proposed by Einstein, also in 1905. Einstein extended the quantum theory of thermal radiation proposed by Max Planck in 1900 to cover not only vibrations of the source of radiation but also vibrations of the radiation itself. He thus suggested that light, and other forms of electromagnetic radiation as well, travel as tiny bundles of energy called light quanta, or photons. The energy of each photon is directly proportional to its frequency.

With the development of the quantum theory of atomic and molecular structure by Niels Bohr and others, it became apparent that light and other forms of electromagnetic radiation are emitted and absorbed in connection with energy transitions of the particles of the substance radiating or absorbing the light. In these processes, the quantum, or particle, nature of light is more important than its wave nature. When the transmission of light is under consideration, however, the wave nature dominates over the particle nature. In 1924, Louis de Broglie showed that an analogous picture holds for particle behavior, with moving particles having certain wavelike properties that govern their motion, so that there exists a complementarity between particles and waves known as particle-wave duality. The quantum theory of light has successfully explained all aspects of the behavior of light.

2.2. Light sources:

There are many sources of light. The most common light sources are *thermal*: a body at a given temperature emits a characteristic spectrum of black-body radiation. A simple thermal source is sunlight, the radiation emitted by the chromosphere of the Sun at around 6,000 kelvins (5,730 degrees Celsius; 10,340 degrees Fahrenheit) and roughly 44% of sunlight energy that reaches the ground is visible.

Another example is *incandescent light bulbs*, which emit only around 10% of their energy as visible light and the remainder as infrared. A common thermal light source in history is the glowing solid particles in flames, but these also emit most of their radiation in the infrared, and only a fraction in the visible spectrum.

Atoms emit and absorb light at characteristic energies. This produces "emission lines" in the spectrum of each atom. Emission can be spontaneous, as in light-emitting diodes, gas discharge lamps (such as neon lamps and neon signs, mercury-vapor lamps, etc.), and flames (light from the hot gas itself—so, for example, sodium in a gas flame emits characteristic yellow light). Emission can also be stimulated, as in a laser or a microwave maser.

Deceleration of a free charged particle, such as an electron, can produce visible radiation: cyclotron radiation, synchrotron radiation, and bremsstrahlung radiation are all examples of this. Particles moving through a medium faster than the speed of light in that medium can produce visible *Cherenkov radiation.*

Certain chemicals produce visible radiation by *chemoluminescence*. In living things, this process is called *bioluminescence*. For example, fireflies produce light by this means, and boats moving through water can disturb plankton which produce a glowing wake. Certain substances produce light when they are illuminated by more energetic radiation, a process

known as *fluorescence*. Some substances emit light slowly after excitation by more energetic radiation. This is known as *phosphorescence*. Phosphorescent materials can also be excited by bombarding them with subatomic particles. Cathodoluminescence is one example. This mechanism is used in cathode ray tube television sets and computer monitors.

The two important semiconductor light sources widely used are LED's and LASER diodes. The dominant operating process for the LED is spontaneous emission and for the LASER, it is stimulated emission.

Certain other mechanisms can produce light:

(i) *Bioluminescence* (ii) *Cherenkov radiation* (iii) *Electroluminescence* (iv) *Scintillation* (v) *Sonoluminescence* (vi) *Triboluminescence*.

When the concept of light is intended to include very-high-energy photons (gamma rays), additional generation mechanisms include: (i) *Particle–antiparticle annihilation* (ii) *Radioactive decay*

General characteristics of light sources: Some of the important characteristics of light sources have been discussed in the following.

(i) **Drive current vs light output:** When injected carriers cross the junction, they can recombine by a radiative process which produces light or by a nonradiative process which produces heat. The ratio between these two processes is dependent on the current density (Amp/cm^2) of semiconductor junction area. At low forward voltages, the diode current is dominated by the nonradiative recombination current, mainly due to surface recombination's near the perimeter of the LED chip. At higher forward voltages, the diode current is dominated by the radiative diffusion current. At even higher voltages, the diode current will be limited by the series resistance. Also, at high forward drive currents the junction temperature of the semiconductor increases due to significant power dissipation. This increase in temperature results in a decrease in the radiative recombination efficiency. As the current density is further increased, internal series resistance effects will also tend to reduce the light generating efficiency of the light source.

(ii) **Quantum efficiency:** Quantum efficiency (η) is defined as the ratio of the radiative recombination rate (Rr) to total recombination rate (Rt) and is given by

$$\eta = Rr/Rt \cdots \qquad (2.2)$$

(iii) **Switching speed:** The term switching speed refers to how fast a light source can be turned on and off by an electrical signal to produce a corresponding optical output pattern. Laser diodes offer faster switching speeds than LED's.

(iv) **Peak spectral wavelength:** The wavelength at which the maximum amount of light is generated is called the peak wavelength (λP). It is determined by the energy band gap of the semiconductor material used.

(v) Spectral width: The range of wavelengths over which a light source emits light. The light source needs to emit light within a narrow spectral width. The spectral width of the LASER diode is very narrow compared to LED.

2.3. Black body:

A black body is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. A white body is one with a "rough surface [that] reflects all incident rays completely and uniformly in all directions. A black body in thermal equilibrium (that is, at a constant temperature) emits electromagnetic radiation called black-body radiation. The radiation is emitted according to Planck's law, meaning that it has a spectrum that is determined by the temperature alone, not by the body's shape or composition. A black body in thermal equilibrium has two notable properties:

(i) It is an ideal emitter: at every frequency, it emits as much energy as – or more energy than – any other body at the same temperature. (ii) It is a diffuse emitter: the energy is radiated isotropically, independent of direction.

An approximate realization of a black surface is a hole in the wall of a large enclosure. Any light entering the hole is reflected indefinitely or absorbed inside and is unlikely to re-emerge, making the hole a nearly perfect absorber. The radiation confined in such an enclosure may or may not be in thermal equilibrium, depending upon the nature of the walls and the other contents of the enclosure. Real materials emit energy at a fraction—called the *emissivity*—of black-body energy levels. By definition, a black body in thermal equilibrium has an emissivity of $\varepsilon = 1.0$. A source with lower emissivity independent of frequency often is referred to as a gray body. Construction of black bodies with emissivity as close to one as possible remains a topic of current interest. In astronomy, the radiation from stars and planets is sometimes characterized in terms of an effective temperature, the temperature of a black body that would emit the same total flux of electromagnetic energy.

2.4. Colour temperature:

The colour temperature of a light source is the temperature of an ideal black-body radiator that radiates light of comparable hue to that of the light source. Colour temperature is a characteristic of visible light that has important applications in lighting, photography, videography, publishing, manufacturing, astrophysics, horticulture, and other fields. In practice, colour temperature is only meaningful for light sources that do in fact correspond somewhat closely to the radiation of some black body, i.e., those on a line from reddish/orange via yellow and more or less white to blueish white; it does not make sense to speak of the color temperature of, e.g., a green or a purple light. Colour temperature is conventionally expressed in Kelvin, using the symbol K, a unit of measure for temperature based on the Kelvin scale.

Colour temperatures over 5,000K are called cool colours (bluish white), while lower color temperatures (2,700–3,000 K) are called warm colours (yellowish white through red). This

relation, however, is a psychological one in contrast to the physical relation implied by Wien's displacement law, according to which the spectral peak is shifted towards shorter wavelengths (resulting in a more blueish white) for higher temperatures.

Categorizing different lighting: The colour temperature of the electromagnetic radiation emitted from an ideal black body is defined as its surface temperature in Kelvin, or alternatively in mireds (micro-reciprocal Kelvin). This permits the definition of a standard by which light sources are compared.

To the extent that a hot surface emits thermal radiation but is not an ideal black-body radiator, the colour temperature of the light is not the actual temperature of the surface. An incandescent lamp's light is thermal radiation, and the bulb approximates an ideal black-body radiator, so its colour temperature is essentially the temperature of the filament. Thus a relatively low temperature emits a dull red and a high temperature emits the almost white of the traditional incandescent light bulb.

 Many other light sources, such as fluorescent lamps, or LEDs (light emitting diodes) emit light primarily by processes other than thermal radiation. This means that the emitted radiation does not follow the form of a black-body spectrum. These sources are assigned what is known as a *correlated color temperature* (CCT). CCT is the color temperature of a black-body radiator which to human colour perception most closely matches the light from the lamp. Because such an approximation is not required for incandescent light, the CCT for an incandescent light is simply its unadjusted temperature, derived from the comparison to a black-body radiator.

 The Sun closely approximates a black-body radiator. The effective temperature, defined by the total radiative power per square unit, is about 5,780 K. The colour temperature of sunlight above the atmosphere is about 5,900 K. As the Sun crosses the sky, it may appear to be red, orange, yellow or white depending on its position. The changing colour of the Sun over the course of the day is mainly a result of scattering of light and is not due to changes in black-body radiation. The blue colour of the sky is caused by Rayleigh scattering of the sunlight from the atmosphere, which tends to scatter blue light more than red light. Some early morning and evening light (golden hours) has a lower color temperature due to increased low-wavelength light scattering by the *Tyndall effect*. This effect was especially pronounced with the increase in small dust particles in the atmosphere after the eruptions of Mount Tambora in 1815 and Krakatoa in 1883, which gave rise to intense red sunsets around the world. Daylight has a spectrum similar to that of a black body with a correlated color temperature of 6,500 K or 5,500 K (daylight-balanced photographic film standard)

Applications: Some of the applications of colour temperature is given below.

(i) **Lighting** - For lighting building interiors, it is often important to take into account the colour temperature of illumination. For example, a warmer (i.e., lower colour temperature) light is often used in public areas to promote relaxation, while a cooler (higher color temperature) light is used to enhance concentration in offices.

(ii) Aquaculture - In fishkeeping, colour temperature has different functions and foci, for different branches. In freshwater aquaria, colour temperature is generally of concern only for producing a more attractive display. Lights tend to be designed to produce an attractive spectrum, sometimes with secondary attention to keeping plants alive.   In a saltwater/reef aquarium, colour temperature is an essential part of tank health. Within about 400 to 3000 nanometers, light of shorter wavelength can penetrate deeper into water than longer wavelengths, providing essential energy sources to the algae hosted in (and sustaining) coral.

(iii) Digital photography - In digital photography, colour temperature is sometimes used interchangeably with white balance, which allow a remapping of colour values to simulate variations in ambient colour temperature.

(iv) Photographic film: Photographic film is made for specific light sources (most commonly daylight film and tungsten film), and used properly, will create a neutral colour print. Matching the sensitivity of the film to the colour temperature of the light source is one way to balance colour. If tungsten film is used indoors with incandescent lamps, the yellowish-orange light of the tungsten incandescent lamps will appear as white (3,200 K) in the photograph. Colour negative film is almost always daylight-balanced, since it is assumed that colour can be adjusted in printing (with limitations; see above). Colour transparency film, being the final artefact in the process, has to be matched to the light source or filters must be used to correct colour. Filters on a camera lens, or colour gels over the light source(s) may be used to correct colour balance.

(v) Desktop publishing: In the desktop publishing industry, it is important to know a monitor's colour temperature. Colour matching software, such as Apple's ColorSync for Mac OS, will measure a monitor's color temperature and then adjust its settings accordingly. Common monitor color temperatures, along with matching standard illuminants in parentheses, are as follows:

   5,000 K (D50),   5,500 K (D55),   6,500 K (D65),   7,500 K (D75),   9,300 K.

Digital cameras, web graphics, DVDs, etc., are normally designed for a 6,500 K colour temperature. The sRGB standard commonly used for images on the Internet stipulates (among other things) a 6,500 K display whitepoint.

(vi) TV, video, and digital still cameras : Most video and digital still cameras can adjust for colour temperature by zooming into a white or neutral coloured object and setting the manual "white balance" the camera then shows true white as white and adjusts all the other colours accordingly. White-balancing is necessary especially when indoors under fluorescent lighting and when moving the camera from one lighting situation to another. Most cameras also have an automatic white balance function that attempts to determine the colour of the light and correct accordingly. While these settings were once unreliable, they are much improved in today's digital cameras, and will produce an accurate white balance in a wide variety of lighting situations.

2.5. Units of Light:

Table 2.1 SI Radiometry units

Quantity		Unit	
Name	*Symbol*	*Name*	*Symbol*
Radiant energy	Qe	joule	J
Radiant energy density	w_e	joule per cubic metre	J/m^3
Radiant flux	Φe	watt	W
Spectral flux	Φe,ν (or) Φe,λ	watt per hertz (or) watt per metre	W/Hz (or) W/m
Radiant intensity	Ie,Ω	watt per steradian	W
Spectral intensity	Ie,Ω,ν	watt per steradian per hertz	W·sr−1·Hz−1
Radiance	Le,Ω	watt per steradian per square metre	$W{\cdot}sr^{-1}{\cdot}m^{-2}$
Spectral radiance	Le,Ω,ν	watt per steradian per square metre per hertz	$W{\cdot}sr^{-1}{\cdot}m^{-2}{\cdot}Hz^{-1}$
Irradiance	Ee	watt per square metre	W/m2
Radiosity	Je	watt per square metre	W/m^2
Spectral radiosity	Je,ν	watt per square metre per hertz	$W{\cdot}m^{-2}{\cdot}Hz^{-1}$
Radiant exitance	Me	watt per square metre	$W/m^2\ M{\cdot}T^{-3}$
Spectral exitance	Me,ν	watt per square metre per hertz	$W{\cdot}m^{-2}{\cdot}Hz^{-1}$
Radiant exposure	He	joule per square metre	J/m^2
Spectral exposure	He,ν	joule per square metre per hertz	$J{\cdot}m^{-2}{\cdot}Hz^{-1}$
Hemispherical emissivity	ε		
Spectral hemispherical	$ε_ν$		
Directional emissivity	$ε_Ω$		
Spectral directional emissivity	$ε_{Ω,ν}$		
Hemispherical absorptance	A		
Spectral hemispherical absorptance	$A_ν$		
Directional absorptance	$A_Ω$		
Spectral directional absorptance	$A_{Ω,ν}$		
Hemispherical reflectance	R		
Spectral hemispherical reflectance	$R_ν$		
Directional reflectance	$R_Ω$		
Spectral directional reflectance	$R_{Ω,ν}$		
Hemispherical transmittance	T		
Spectral hemispherical transmittance	$T_ν$		
Directional transmittance	$T_Ω$		
Spectral directional transmittance	$T_{Ω,ν}$		

Hemispherical attenuation coefficient	μ	reciprocal metre	m^{-1}
Spectral hemispherical coefficient attenuation	$μ_v$	reciprocal metre	m^{-1}
Directional attenuation coefficient	$μ_Ω$	reciprocal metre	m^{-1}
Spectral directional attenuation coefficient.	$μ_{Ω,v}$	reciprocal metre	m^{-1}

Table 2.2. SI photometric units:

Quantity		Unit	
Name	*Symbol*	*Name*	*Symbol*
Luminous energy	*Q_v*	*lumen second*	lm·s
Luminous flux / luminous power	*$Φ_v$*	*lumen (= cd·sr)*	lm
Luminous intensity	I_v	candela (= lm/sr)	cd
Luminance	L_v	candela per square metre	cd/m^2
Illuminance	E_v	lux (= lm/m^2)	lx
Luminous exitance / luminous emittance	M_v	lux	lx
Luminous exposure	H_v	lux second	lx·s
Luminous energy density	$ω_v$	lumen second per cubic metre	$lm·s·m^{-3}$
Luminous efficacy	η	lumen per watt	lm/W
Luminous efficiency / luminous coefficient	V		

2.6. Semiconductor Basics:

(i) Intrinsic semiconductors: Semiconductors materials such as silicon (Si), germanium (Ge) and gallium arsenide (GaAs), have electrical properties somewhere in the middle, between those of a "conductor" and an "insulator". They are not good conductors nor good insulators (hence their name "semi"-conductors). They have very few "free electrons" and are able to flow, but only under special conditions. The ability of semiconductors to conduct electricity can be greatly improved by replacing or adding certain donor or acceptor atoms to this crystalline structure thereby, producing more free electrons than holes or vice versa. That is by adding a small percentage of another element to the base material, either silicon or germanium. On their own Silicon and Germanium are classed as intrinsic semiconductors, that is they are chemically pure, containing nothing but semi-conductive material. But by controlling the amount of impurities added to this intrinsic semiconductor material it is possible to control its conductivity. Various impurities called donors or acceptors can be added to this intrinsic material to produce free electrons or holes respectively. This process

of adding donor or acceptor atoms to semiconductor atoms (the order of 1 impurity atom per 10 million (or more) atoms of the semiconductor) is called *Doping*.

A Silicon Atom Structure: The diagram shows the structure and lattice of a 'normal' pure crystal of Silicon (Fig.2.1)
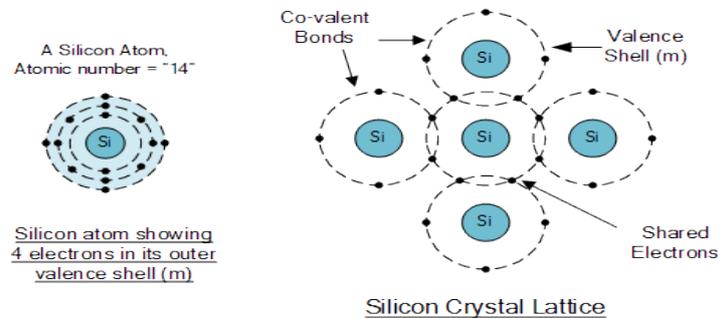

Fig.2.1 A Silicon Atom Structure

The as the doped silicon is no longer pure, these donor and acceptor atoms are collectively referred to as "impurities", and by doping these silicon material with a sufficient number of impurities, we can turn it into a semi-conductor. The most commonly used semiconductor basics material by far is Silicon. Silicon has four valence electrons in its outermost shell which it shares with its neighbouring silicon atoms to form full orbital's of eight electrons. The structure of the bond between the two silicon atoms is such that each atom shares one electron with its neighbour making the bond very stable. As there are very few free electrons available to move around the silicon crystal, crystals of pure silicon (or germanium) are therefore good insulators, or at the very least very high value resistors. Silicon atoms are arranged in a definite symmetrical pattern making them a crystalline solid structure. A crystal of pure silica (silicon dioxide or glass) is generally said to be an intrinsic crystal (it has no impurities) and therefore has no free electrons. But simply connecting a silicon crystal to a battery supply is not enough to extract an electric current from it. To do that we need to create a "positive" and a "negative" pole within the silicon allowing electrons and therefore electric current to flow out of the silicon. These poles are created by doping the silicon with certain impurities.

(ii) Extrinsic semiconductors

(a) N-type Semiconductor Basics: In order for our silicon crystal to conduct electricity, we need to introduce an impurity atom such as Arsenic, Antimony or Phosphorus into the crystalline structure making it extrinsic (impurities are added). These atoms have five outer electrons in their outermost orbital to share with neighbouring atoms and are commonly called "Pentavalent" impurities. This allows four out of the five orbital electrons to bond with its neighbouring silicon atoms leaving one "free electron" to become mobile when an electrical voltage is applied (electron flow). As each impurity atom "donates" one electron, pentavalent atoms are generally known as "donors". Antimony (symbol Sb) or Phosphorus (symbol P), are frequently used as a pentavalent additive to the silicon as they have 51 electrons arranged in five shells around their nucleus with the outermost orbital having five

electrons. The resulting semiconductor basics material has an excess of current-carrying electrons, each with a negative charge, and is therefore referred to as an N-type material with the electrons called "Majority Carriers" while the resulting holes are called "Minority Carriers". When stimulated by an external power source, the electrons freed from the silicon atoms by this stimulation are quickly replaced by the free electrons available from the doped Antimony atoms. But this action still leaves an extra electron (the freed electron) floating around the doped crystal making it negatively charged. Then a semiconductor material is classed as N-type when its donor density is greater than its acceptor density, in other words, it has more electrons than holes thereby creating a negative pole as shown in Fig.2.2.
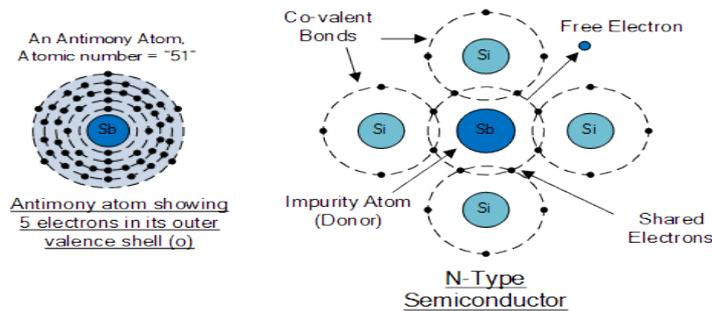
Fig.2.2 Antimony Atom and Doping

(b) P-Type Semiconductor Basics: If we go the other way, and introduce a "Trivalent" (3-electron) impurity into the crystalline structure, such as Aluminium, Boron or Indium, which have only three valence electrons available in their outermost orbital, the fourth closed bond cannot be formed. Therefore, a complete connection is not possible, giving the semiconductor material an abundance of positively charged carriers known as holes in the structure of the crystal where electrons are effectively missing. As there is now a hole in the silicon crystal, a neighbouring electron is attracted to it and will try to move into the hole to fill it. However, the electron filling the hole leaves another hole behind it as it moves. This in turn attracts another electron which in turn creates another hole behind it, and so forth giving the appearance that the holes are moving as a positive charge through the crystal structure (conventional current flow). This movement of holes results in a shortage of electrons in the silicon turning the entire doped crystal into a positive pole. As each impurity atom generates a hole, trivalent impurities are generally known as "Acceptors" as they are continually "accepting" extra or free electrons.

 Boron (symbol B) is commonly used as a trivalent additive as it has only five electrons arranged in three shells around its nucleus with the outermost orbital having only three electrons. The doping of Boron atoms causes conduction to consist mainly of positive charge carriers resulting in a P-type material with the positive holes being called "Majority Carriers" while the free electrons are called "Minority Carriers". Then a semiconductor basics material is classed as P-type when its acceptor density is greater than its donor density. Therefore, a P-type semiconductor has more holes than electrons.

Boron Atom and Doping: The diagram shows the structure and lattice of the acceptor impurity atom Boron (Fig.2.3)
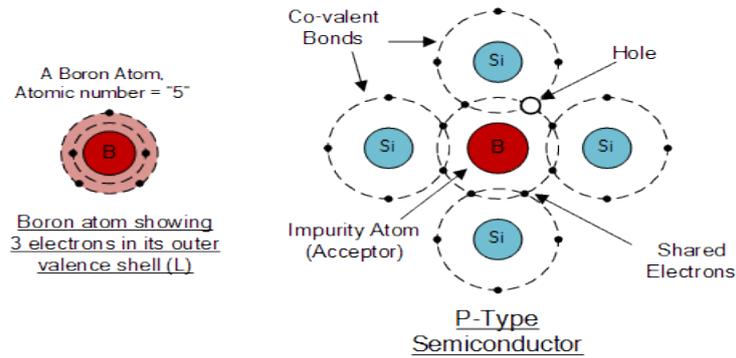

Fig.2.3 Boron Atom and Doping

2.7. P-N Junction:

A p–n junction is a boundary or interface between two types of semiconductor material, p-type and n-type, inside a single crystal of semiconductor. The "p" (positive) side contains an excess of electron holes, while the "n" (negative) side contains an excess of electrons. The p-n junction is created by doping, for example by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant). If two separate pieces of material were used, this would introduce a grain boundary between the semiconductors that would severely inhibit its utility by scattering the electrons and holes

p–n junctions are elementary "building blocks" of most semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place. For example, a common type of transistor, the bipolar junction transistor, consists of two p–n junctions in series, in the form n–p–n or p–n–p. A Schottky junction is a special case of a p–n junction, where metal serves the role of the p-type semiconductor.

(a) Structure and principle of operation:

(i) Structure: A p-n junction consists of two semiconductor regions with opposite doping type as shown in Figure 2.4. The region on the left is p-type with an acceptor density Na, while the region on the right is n-type with a donor density Nd. The dopants are assumed to be shallow, so that the electron (hole) density in the n-type (p-type) region is approximately equal to the donor (acceptor) density. The junction is biased with a voltage Va as shown in Figure 2.4. We will call the junction forward-biased if a positive voltage is applied to the p-doped region and reversed-biased if a negative voltage is applied to the p-doped region. The contact to the p-type region is also called the anode, while the contact to the n-type region is called the cathode, in reference to the anions or positive carriers and cations or negative carriers in each of these regions.
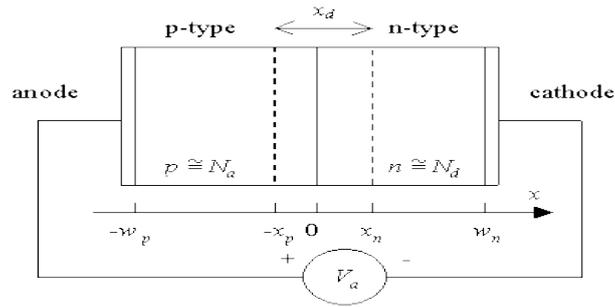
Figure 2.4: Cross-section of a p-n junction

(ii) Formation of the Depletion Region: At the instant of the PN junction formation free electrons near the junction diffuse across the junction into the P region and combine with holes. Filling a hole makes a negative ion and leaves behind a positive ion on the N side. These two layers of positive and negative charges form the depletion region, as the region near the junction is depleted of charge carriers (Fig.2.5). As electrons diffuse across the junction a point is reached where the negative charge repels any further diffusion of electrons. The depletion region now acts as a barrier.

(iii) Barrier Potential: The electric field formed in the depletion region acts as a barrier. External energy must be applied to get the electrons to move across the barrier of the electric field. The potential difference required to move the electrons through the electric field is called the barrier potential. Barrier potential of a PN junction depends on the type of semiconductor material, amount of doping and temperature. This is approximately 0.7V for silicon and 0.3V for germanium
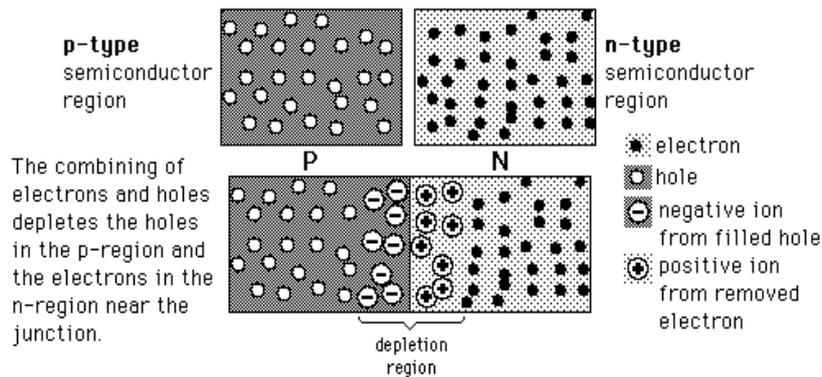
Fig.2.5 Formation of the depletion region

(iv) Energy Diagrams of PN Junction: The valence band and conduction band in N-Type material are slightly lower than that of P-Type material As diffusion occurs the depletion region forms and the energy level of the N region conduction band drops, causing alignment of the top of the N region conduction band and the bottom of the P region conduction band. At this point the energy bands are at equilibrium. There is an energy gradient across the depletion region that a N region electron must climb to get to the P region (Fig.2.6).
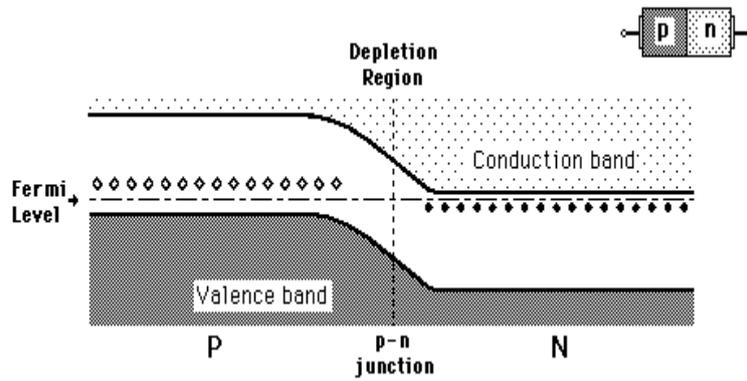
Fig.2.6 Energy Diagrams of PN Junction

(b) Biasing the PN Junction.

(i) Forward Bias: An external D.C. voltage is applied to a PN junction to bias it (Fig.2.7(a)). Forward bias allows current through a PN junction. Bias voltage imparts sufficient energy to the free electrons so they overcome the barrier potential and move into the P region. Conduction occurs with electron current in the N-Type material and hole current in the P-Type material. As more electrons and holes flow in the depletion region the number of positive and negative ions is reduced, causing the depletion region to narrow. The energy loss in overcoming the barrier potential results in a voltage drop across the PN junction equal to the barrier potential. (0.7V for Si, 0.3V for Ge.) . When a PN junction is forward biased the N region conduction band is raised to a higher level that overlaps with the P region conduction band (Fig.2.7(b)).

(a)   **(b)**
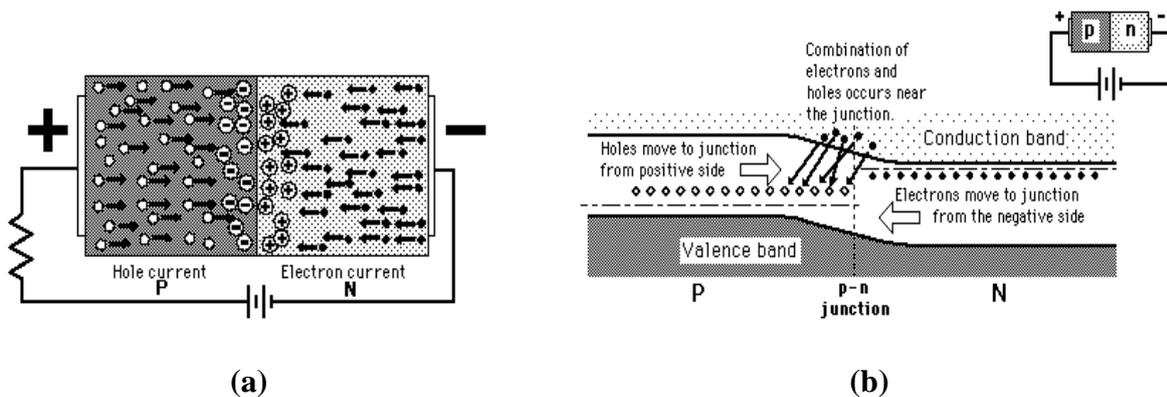
Fig.2.7 Biasing the PN Junction. (a) Forward bias (b) Energy band diagram

(ii) Reverse Bias : Reverse bias prevents current flow through a PN junction (Fig2.8(a)). Reverse bias potential attracts the majority carriers away from the PN junction widening the depletion region. The potential across the depletion region is equal to the bias voltage. Reverse current can flow through the PN junction due to minority carriers. When a PN junction is reverse biased the energy hill increases (Fig.2.8(b)).

(iii) Reverse Breakdown: If the reverse bias voltage is increased to the breakdown voltage, the reverse current will drastically increase. This is due to collisions of fast minority carriers

with atoms, knocking out valence electrons. This process avalanches and results in a high reverse current damaging the PN structure.

<div align="center">(a) (b)</div>

Fig.2.8 Biasing the PN Junction. (a) Reverse bias (b) Energy band diagram

(c) Generation and recombination processes:

Carrier generation and recombination occur when an electron makes transition from the valence band to conduction band in a semiconductor, as a result of interaction with other electrons, holes, photons, or the vibrating crystal lattice itself. These processes must conserve both quantized energy and momentum, and the vibrating lattice plays a large role in conserving momentum as photons carry very little momentum in relation to their energy. Recombination and generation are always happening in semiconductors, both optically and thermally, and their rates are in balance at equilibrium. The product of the electron and hole densities ($\mathbf{n}$ and $\mathbf{p}$) is a constant ($\mathbf{n_0\,p_0\ =n_i^2}$)   at equilibrium, maintained by recombination and generation occurring at equal rates. When there is a surplus of carriers (i.e., $\mathbf{n\,p>n_i^2}$), the rate of recombination becomes greater than the rate of generation, driving the system back towards equilibrium . Likewise, when there is a deficit of carriers (i.e**., $\mathbf{n\,p<n_i^2}$**), the generation rate becomes greater than the recombination rate, again driving the system back towards equilibrium. As the electron moves from one energy band to another, the energy and momentum that it has lost or gained must go to or come from the other particles involved in the process (e.g. photons, electron, or the system of vibrating lattice atoms). The following models are used to describe generation and recombination, depending on which particles are involved in the process.

(i) Shockley–Read–Hall (SRH) process: In Shockley-Read-Hall recombination, also called trap-assisted recombination, the electron in transition between bands passes through a new energy state (localized state) created within the band gap by an impurity in the lattice; such energy states are called deep-level traps. The localized state can absorb differences in momentum between the carriers, and so this process is the dominant generation and recombination process in silicon and other indirect bandgap materials. It can also dominate in direct bandgap materials under conditions of very low carrier densities (very low level injection). The energy is exchanged in the form of lattice vibration, a phonon exchanging thermal energy with the material.

(ii) Radiative recombination: During radiative recombination, a form of spontaneous emission, a photon is emitted with the wavelength corresponding to the energy released. This effect is the basis of LEDs. Because the photon carries relatively little momentum, radiative recombination is significant only in direct bandgap materials. When photons are present in the material, they can either be absorbed, generating a pair of free carriers, or they can stimulate a recombination event, resulting in a generated photon with similar properties to the one responsible for the event. Absorption is the active process in photodiodes, solar cells, and other semiconductor photodetectors, while stimulated emission is responsible for laser action in laser diodes.

(iii) Auger recombination: In Auger recombination the energy is given to a third carrier, which is excited to a higher energy level without moving to another energy band. After the interaction, the third carrier normally loses its excess energy to thermal vibrations. Since this process is a three-particle interaction, it is normally only significant in non-equilibrium conditions when the carrier density is very high. The Auger effect process is not easily produced, because the third particle would have to begin the process in the unstable high-energy state.

2.8 Heterojunction; A heterojunction is the interface that occurs between two layers or regions of dissimilar crystalline semiconductors. These semiconducting materials have unequal band gaps as opposed to a homojunction. It is often advantageous to engineer the electronic energy bands in many solid state device applications including semiconductor lasers, solar cells and transistors ("heterotransistors") to name a few. The combination of multiple heterojunctions together in a device is called an heterostructure although the two terms are commonly used interchangeably. The requirement that each material be a semiconductor with unequal band gaps is somewhat loose especially on small length scales where electronic properties depend on spatial properties. A more modern definition of heterojunction is the interface between any two solid-state materials, including crystalline and amorphous structures of metallic, insulating, fast ion conductor and semiconducting materials.

(a) Energy band alignment: The behaviour of a semiconductor junction depends crucially on the alignment of the energy bands at the interface. Semiconductor interfaces can be organized into three types of heterojunctions: *straddling gap (type I), staggered gap (type II) or broken gap (type III)* as seen in the Figure (2.9). Away from the junction, the band bending can be computed based on the usual procedure of solving Poisson's equation. Various models exist to predict the band alignment. The simplest (and least accurate) model is Anderson's rule, which predicts the band alignment based on the properties of vacuum-semiconductor interfaces (in particular the vacuum electron affinity). The main limitation is its neglect of chemical bonding(Fig.2.10).

A common anion rule was proposed which guesses that since the valence band is related to anionic states, materials with the same anions should have very small valence band offsets. This however did not explain the data but is related to the trend that two materials with different anions tend to have larger valence band offsets than conduction band offsets.
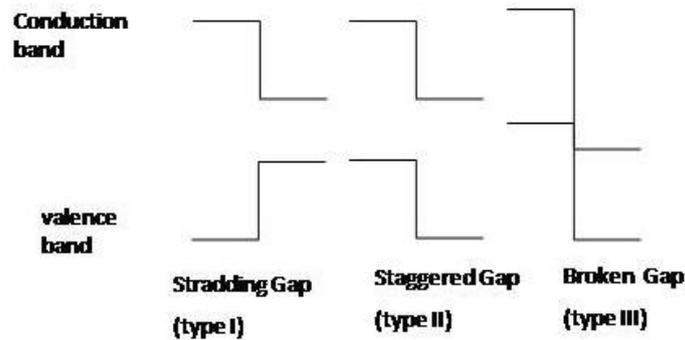
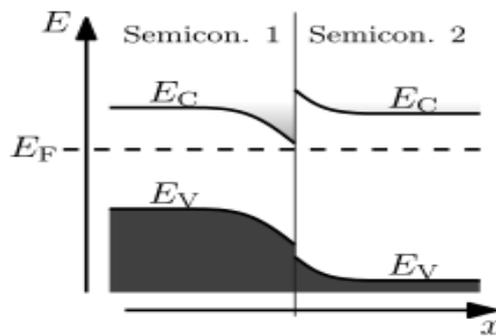**Fig. 2.9 Three types of semiconductor heterojunctions organized by band alignment**

Fig. 2.10 Band diagram for straddling gap , n-n semiconductor heterojunction at equilibrium

Tersoff proposed a gap state model based on more familiar metal-semiconductor junctions where the conduction band offset is given by the difference in Schottky barrier height. This model includes a dipole layer at the interface between the two semiconductors which arises from electron tunneling from the conduction band of one material into the gap of the other (analogous to metal-induced gap states). This model agrees well with systems where both materials are closely lattice matched such as GaAs/AlGaAs. The 60:40 rule is a heuristic for the specific case of junctions between the semiconductor GaAs and the alloy semiconductor $Al_xGa_{1-x}As$. As the x in the $Al_xGa_{1-x}As$ side is varied from 0 to 1, the ratio $\Delta E_C / \Delta E_V$ tends to maintain the value 60/40. For comparison, Anderson's rule predicts $\Delta E_C / \Delta E_V = 0.73 / 0.27$ for a GaAs/AlAs junction (x=1).

(b) The hetero p-n junction: The heterojunction p-n diode is in principle very similar to a homojunction. The main problem that needs to be tackled is the effect of the bandgap discontinuities and the different material parameters, which make the actual calculations more complex even though the p-n diode concepts need almost no changing. The flatband energy band diagram of a heterojunction p-n diode is shown in the Figure 2.11. As a convention we will assume ΔE_c to be positive if $E_{c,n} > E_{c,p}$ and ΔE_v to be positive if $E_{v,n} < E_{v,p}$.
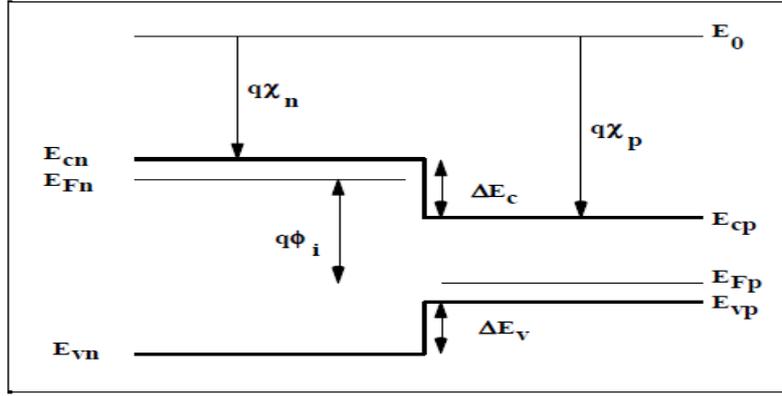
Fig.2.11 Flat band energy band diagram of a p-n junction

(i) Calculation of the contact potential (built-in voltage):

The built-in potential is defined as the difference between the Fermi levels in both the n-type and the p-type semiconductor. From the energy diagram we find:

$$q\phi_i = E_{F,n} - E_{F,p} = E_{F,n} - E_{c,n} + E_{c,n} + E_{c,p} - E_{F,p} \qquad (2.1)$$

which can be expressed as a function of the electron concentrations and the effective densities of states in the conduction band:

$$q\phi_i = \Delta E_c + kT \ln \frac{n_{n0} N_{c,p}}{n_{p0} N_{c,n}} \qquad (2.2)$$

The built-in voltage can also be related to the hole concentrations and the effective density of states of the valence band:

$$q\phi_i = -\Delta E_v + kT \ln \frac{p_{p0} N_{v,n}}{p_{n0} N_{v,p}} \qquad (2.3)$$

Combining both expressions yields the built-in voltage independent of the free carrier concentrations:

$$q\phi_i = \frac{\Delta E_c - \Delta E_v}{2} + kT \ln \frac{N_d N_a}{n_{i,n} n_{i,p}} + \frac{kT}{2} \ln \frac{N_{v,n} N_{c,p}}{N_{c,n} N_{v,p}} \qquad (2.4)$$

where n_{in} and n_{ip} are the intrinsic carrier concentrations of the n and p-type region, respectively. ΔEc and ΔEv are positive quantities if the bandgap of the n-type region is smaller than that of the p-type region and the sum of both equals the bandgap difference. The above expression reduces to that of the built-in junction of a homojunction if the

material parameters in the *n*-type region equal those in the *p*-type region. If the effective densities of states are the same the expression reduces to:

$$q\phi_i = \frac{\Delta E_c - \Delta E_v}{2} + kT\ln\frac{N_d N_a}{n_{i,n} n_{i,p}} \tag{2.5}$$

$$x_d = x_n + x_p = \sqrt{\frac{2\varepsilon_{s,n}\varepsilon_{s,p}}{q}\frac{(N_a + N_d)^2(\phi_i - V_a)}{N_a N_d(N_a\varepsilon_{s,p} + N_d\varepsilon_{s,n})}} \tag{2.6}$$

The capacitance per unit area can be obtained from the series connection of the capacitance of each layer:

$$C_j = \frac{1}{\dfrac{x_n}{\varepsilon_{s,n}} + \dfrac{x_p}{\varepsilon_{s,p}}} = \sqrt{\frac{q\varepsilon_{s,n}\varepsilon_{s,p}}{2}\frac{N_a N_d}{(N_a\varepsilon_{s,p} + N_d\varepsilon_{s,n})(\phi_i - V_a)}} \tag{2.7}$$

(c) Quantum efficiency: The quantum efficiency η_{qu} is defined as

$$\eta_{qu} \;\; = \;\; \frac{\text{Number of photons generated in the recombination zone}}{\text{Number of recombining carrier pairs in the recombination zone}}$$

We already know that, it could be expressed as,

$$\eta_{qu} \;=\; \frac{1}{1 \;+\; \eta_{rad}/\eta_{non\text{-}rad}}$$

In the high injection approximation the number of carriers is about equal to the number of carriers injected (across a junction) into the recombination zone. That part of the total recombination occurring via a radiative channel determines the quantum efficiency. However, the surplus carriers in the recombination zone have one more "channel", not considered so far, for disappearing from the recombination zone: They simply move out!. In other words: parts of the injected carriers will simply flow across the recombination zone and leave it at "the other end" . This effect can be described by the current efficiency η_{cu}; it is defined as

$$\eta_{cu} \;\; = \;\; \frac{\text{Number of recombining carrier pairs in the recombination zone}}{\text{Number of carrier pairs injected into the recombination zone}}$$

The optical efficiency takes care of the fact that in most devices a large part of the photons generated become reabsorbed or are otherwise lost and never leave the device. The total or external efficiency η_{ex} now simply is

$$\eta_{ex} = \eta_{opt} \cdot \eta_{cu} \cdot \eta_{qu}$$

If we want to optimize the external efficiency, we must work on all three factor - none of them is negligible. We already "know" how to optimize the quantum efficiency η_{qu} by looking at the equation above. We must look for the best combination of materials producing radiation at the desired wavelength, and then dope it in such a way as to maximize the radiative channel(s) by minimizing the corresponding lifetimes. While this is not easy to do in practice, it is clear in principle.

2.9 Quantum well structures and its properties - Superlattices

A quantum well is a particular kind of heterostructure in which one thin "well" layer is surrounded by two "barrier" layers. This layer, in which both electrons and holes are confined, is so thin (typically about 100 Å or about 40 atomic layers) that we cannot neglect the fact that the electron and hole are both waves. In fact, the allowed states in this structure correspond to standing waves in the direction perpendicular to the layers. Because only particular waves are standing waves, the system is quantized, hence the name "quantum well (QW) ". One-dimensional quantum wells are formed through epitaxial growth of alternating layers of semiconductor materials with different band gaps. A single quantum well is formed from one semiconductor sandwiched between two layers of a second semiconductor having a larger band gap. The centre layer with the smaller band gap semiconductor forms the QW, while the two layers sandwiching the centre layer create the potential barriers as shown in Fig. 2.12. Two potential wells are actually formed in the QW structure; one well is for conduction-band electrons, the other for valence-band holes. The well depth for electrons is the difference (*i.e.* the offset) between the conduction-band edges of the well and barrier semiconductors, while the well depth for holes is the corresponding valence-band offset. Multiple quantum well structures consist of a series of QWs (*i.e.* a series of alternating layers of wells and barriers). If the barrier thickness between adjacent wells is sufficient to prevent significant electronic coupling between the wells, then each well is electronically isolated; this type of structure is termed as *multiple quantum well*.
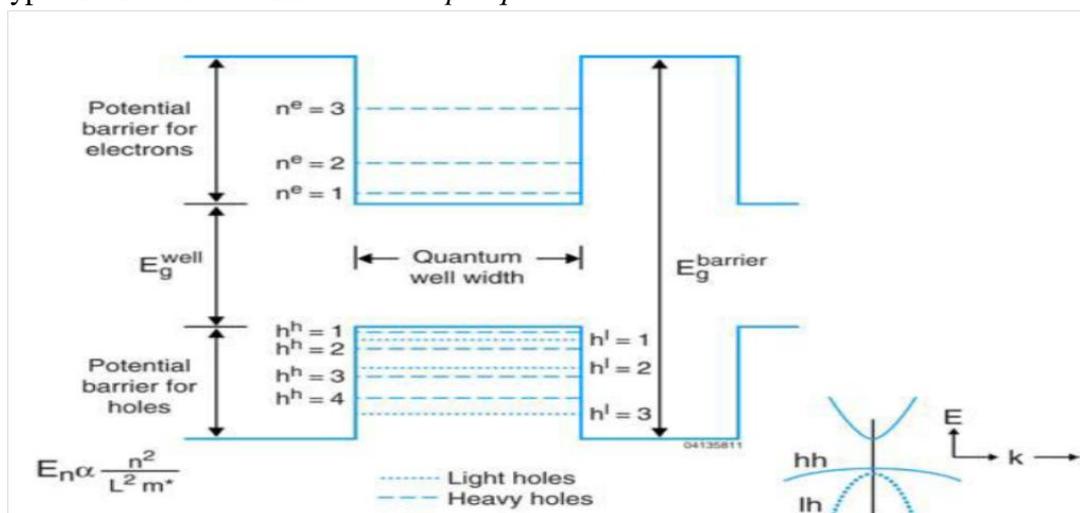

Fig.2.12: One-dimensionally confined quantum well created by a thin small-band gap semiconductor layer sandwiched between two larger band gap semiconductor layers. Eg ^{Well} is the band gap of the well material and Eg ^{barrier} that of the barrier material.

Quantum wells are thin layered semiconductor structures in which we can observe and control many quantum mechanical effects. They derive most of their special properties from the quantum confinement of charge carriers (electrons and "holes") in thin layers (e.g 40 atomic layers thick) of one semiconductor "well" material sandwiched between other semiconductor "barrier" layers.

We can understand the basic properties of a quantum well through the simple "particle in a box" model. Here we consider Schrödinger's equation in one dimension for the particle of interest (e.g., electron or hole),

$$\frac{\hbar^2}{2m}\frac{d^2\phi_n}{d_z^2} + V(z)\phi_n = E_n\phi_n$$

(2.8)

where V(z) is the structural potential (i.e., the "quantum well" potential) seen by the particle along the direction of interest (z), m is the particle's (effective) mass, and En and ϕn are the Eigen energy and Eigen function associated with the nth solution to the equation. The simplest case is shown in Fig. 2.13. In this "infinite well" case, we presume for simplicity that the barriers on either side of the quantum well are infinitely high. Then the wave function must be zero at the walls of the quantum well. The solution is then particularly simple:

$$E_n = \frac{\pi^2\hbar^2 n^2}{2m^* L_z^2} \quad n = 1,2..... \quad \phi_n = A\sin(\frac{n\pi z}{L_z})$$
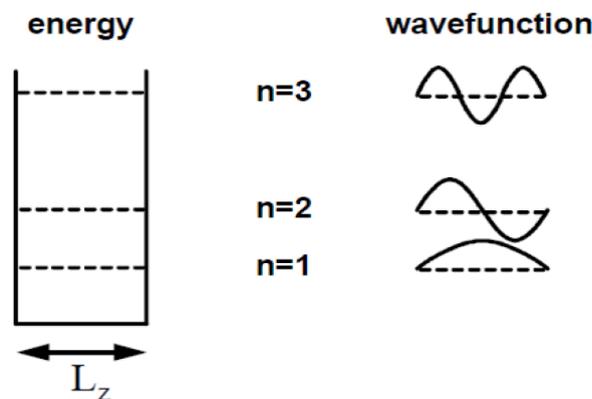
(2.9)

Fig. 2.13: Infinite quantum well and associated wave functions.

The energy levels (or "confinement energies") are quadratically spaced, and the wave functions are sine waves. In this formula, the energy is referred to the energy of the bottom of the well. Note that the first allowed energy (corresponding to n=1) is above the bottom of the well. We see that the energy level spacing becomes large for narrow wells (small Lz) and small effective mass m. The actual energy of the first allowed electron energy level in a typical 100 Å GaAs quantum well is about 40 meV, which is close to the value that would be calculated by this simple formula. This scale of energy is easily seen, even at room temperature. The solution of the problem of an actual quantum well with finite height of

barriers is a straightforward mathematical exercise. It does, however, require that we choose boundary conditions to match the solutions in the well and the barriers. One boundary condition is obvious, which is that the wave function must be continuous.
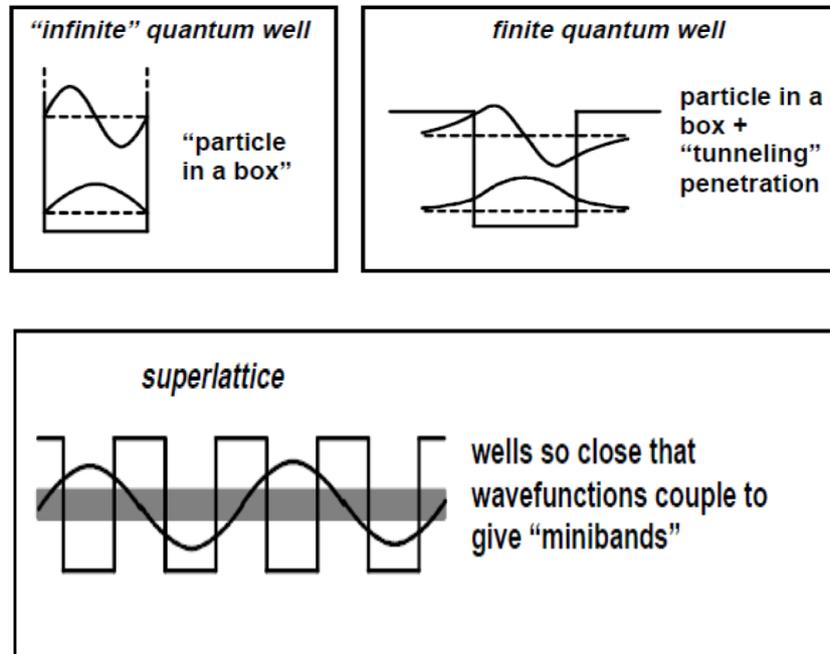

Fig. 2.14 Comparison of "infinite" quantum well, "finite" quantum well, and superlattice behavior. For the superlattice, a wavefunction for one of the possible superlattice miniband states is shown (actually the state at the top of the miniband).

Since the Schrödinger equation is a second order equation, we need a second boundary condition, and it is not actually obvious what it should be. Fig. 2.14 illustrates the differences between the idealized "infinite" quantum well, the actual "finite" well.

In contrast to bulk semiconductors, excitonic effects are very clear in quantum wells at room temperature, and have a significant influence on device performance. The simplest model for absorption between the valence and conduction bands in a bulk semiconductor is to say that we can raise an electron from the valence band to a state of essentially the same momentum in the conduction band (a "vertical" transition) by absorbing a photon.

(i) Superlattices:

Also in Fig. 2.14, we have illustrated a **superlattice**. It will be useful here to define the difference between quantum wells and superlattices. The simplest, crystallographic, definition of *a superlattice is a "lattice of lattices"*. With that definition, any regular sequence of well and barrier layers would be a superlattice. A more useful definition here is the "electronic" definition; in this definition, we call such a regular structure a superlattice only if there is significant wavefunction penetration between the adjacent wells. Otherwise, the physics of the multiple layer structure is essentially the same as a set of independent wells, and it is more useful to call the structure a multiple quantum well (MQW). If

there is significant wavefunction penetration between the wells, we will see phenomena such as "minibands", and the structure is then usefully described as a superlattice. The "minibands" arise when quantum wells are put very close together in a regular way, just as "bands" arise in crystalline materials as atoms are put together. Just as with quantum wells, simple models for superlattices can be constructed using envelope functions and effective masses, and such models are also good first approximations. As a rule of thumb, for well and barrier layers thicker than about 50 Å in the GaAs/AlGaAs system, with a typical Al concentration of about 30 % in the barriers, the structure will probably be best described as a multiple quantum well.
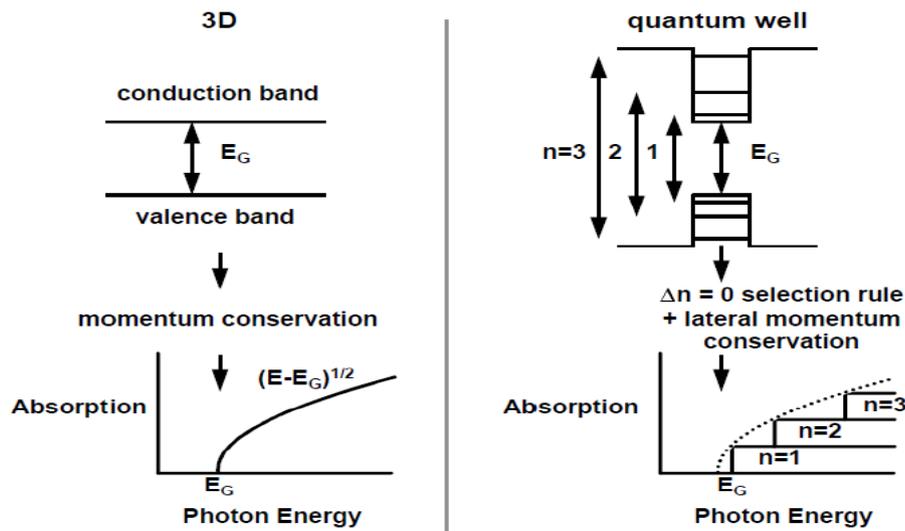
Fig. 2.15: Optical absorption in bulk (i.e., 3D) semiconductors and in quantum wells.

The state in the conduction band has to have essentially the same momentum because the photon has essentially no momentum on the scale usually of interest in semiconductors. In this simple model, we also presume that all such transitions have identical strength, although they will have different energies corresponding to the different energies for such vertical transitions. The optical absorption spectrum therefore has a form that follows directly from the density of states in energy, and in bulk semiconductors the result is an absorption edge that rises as the square root of energy, as shown in Fig. 2.15 In a quantum well, the electrons and holes are still free to move in the directions parallel to the layers; hence, we do not really have discrete energy states for electrons and holes in quantum wells; we have instead "sub-bands" that start at the energies calculated for the confined states. The electron in a given confined state can in addition have any amount of kinetic energy for its in-plane motion in the quantum well, and so can have any energy greater than or equal to the simple confined-state energy for that sub-band. The density of states for motion in the plane of the quantum well layers turns out to be constant with energy, so the density of states for a given sub-band really is a "step" that starts at the appropriate confinement energy. Optical transitions must still conserve momentum in this direction and just as for bulk semiconductors; the optical absorption must still therefore follow the density of states. Hence, in this simple model, the optical absorption in a quantum well is a series of steps, with one step for each quantum

number, n. It is easily shown, from the known densities of states, that the corners of the steps "touch" the square root bulk absorption curve (when that curve is scaled to the thickness of this infinite quantum well). Thus, as we imagine increasing the quantum well thickness, we will make a smooth transition to the bulk behaviour, with the steps becoming increasingly close until they merge into the continuous absorption edge of the bulk material.

(ii) Fabrication: Quantum wells are formed in semiconductors by having a material, like gallium arsenide, sandwiched between two layers of a material with a wider bandgap, like aluminium arsenide. (Other example: layer of indium gallium nitride sandwiched between two layers of gallium nitride.) These structures can be grown by molecular beam epitaxy or chemical vapor deposition with control of the layer thickness down to monolayers. Thin metal films can also support quantum well states, in particular, metallic thin overlayers grown in metal and semiconductor surfaces. The electron (or hole) is confined by the vacuum-metal interface in one side, and in general, by an absolute gap with semiconductor substrates, or by a projected band gap with metal substrates.

(iii) Applications: Because of their quasi-two dimensional nature, electrons in quantum wells have a density of states as a function of energy that has distinct steps, versus a smooth square root dependence that is found in bulk materials. Additionally, the effective mass of holes in the valence band is changed to more closely match that of electrons in the conduction band. These two factors, together with the reduced amount of active material in quantum wells, leads to better performance in optical devices such as laser diodes. As a result quantum wells are in wide use in diode lasers, including red lasers for DVDs and laser pointers, infra-red lasers in fiber optic transmitters, or in blue lasers. They are also used to make HEMTs (High Electron Mobility Transistors), which are used in low-noise electronics. Quantum well infrared photodetectors are also based on quantum wells, and are used for infrared imaging.

By doping either the well itself, or preferably, the barrier of a quantum well with donor impurities, a two-dimensional electron gas (2DEG) may be formed. Such a structure forms the conducting channel of a HEMT, and has interesting properties at low temperature. One such property is the quantum Hall effect, seen at high magnetic fields. Acceptor dopants can also lead to a two-dimensional hole gas (2DHG).

Unit – III

Optoelectronic devices

3.1 Introduction:

A large number of optoelectronic devices consist of a p-type and n-type region, just like a regular p-n diode. The key difference is that there is an additional interaction between the electrons and holes in the semiconductor and light. This interaction is not restricted to optoelectronic devices. Regular diodes are also known to be light sensitive and in some cases also emit light. The key difference is that optoelectronic devices such as photodiodes, solar cells, LEDs and laser diodes are specifically designed to optimize the light absorption and emission, resulting in a high conversion efficiency.

3.2 Modulation method and Modulators

Figure 3.1 illustrates two alternative ways to generate a modulated optical signal. In Fig. 3.1 (a), the laser is turned on and off by modulating its current; this method is known as *direct modulation*. In Fig. 3.l(b), the laser is on at all times, a so-called continuous wave (CW) laser, and the light beam is modulated with a kind of optoelectronic shutter, a so-called *modulato*r; this method is known as *external modulation*. Direct modulation has the advantages of simplicity, compactness, and cost effectiveness, whereas external modulation can produce higher-quality optical pulses, permitting extended reach and higher bit rates.
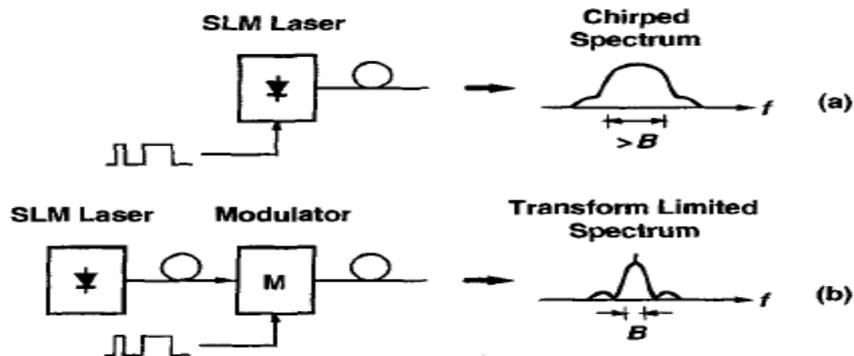

Fig. 3.1 Optical transmitters: (a) direct modulation vs. (b) external modulation

Direct as well as external modulation can be used to produce non-return-to-zero (NRZ) or return-to-zero (RZ) modulated optical signals. However, to produce very high-speed RZ-modulated signals, a cascade of two optical modulators, known as a tandem modulator, frequently is used. In this arrangement, the first optical modulator modulates the light from the CW laser with an NRZ signal and the second modulator, which is driven by a clock signal, coniverts the NRZ signal to an RZ signal in the optical domain.

3.2 Transmitter and its specifications : The role of the optical transmitter is to: convert the electrical signal into optical form, and launch the resulting optical signal into the optical fiber. The optical transmitter consists of the following components: optical source, electrical

pulse generator and optical modulator. Two important specifications of the optical transmitter:

(i)   the spectral linewidth and (ii) the extinction ratio.

The values that can be achieved for these parameters depends on whether direct or external modulation is used.

(i) Spectral Linewidth. For a perfectly monochromatic light source followed by a perfect intensity modulator, the optical spectrum of the modulated output signal looks like that of an amplitude-modulated (AM) transmitter: a carrier and two sidebands corresponding to the spectrum of the baseband signal. In the case of an NRZ modulation, the spectrum looks as shown in Fig. 3.l(b). The 3-dB bandwidth of one NRZ sideband is about half the bit rate, B /2, and thus the full bandwidth, which covers both sidebands, is about equal to the bit rate.' If we convert this bandwidth or frequency linewidth to the commonly used wavelength linewidth, we get

$$\Delta\lambda = \frac{\lambda^2}{c}\Delta f \approx \frac{\lambda^2}{c}B.$$

(3.1)

where λ is the wavelength and c is the speed of light in vacuum (c = 3 x 10^8 m/s). For example, at 10 Gb/s, the frequency linewidth is about 10 GHz, corresponding to a wavelength linewidth of 0.08nm for A = 1.55 pm. In practice, it is difficult to build a transmitter with a linewidth as narrow as this; only some types of external modulators can come close to this ideal. Optical pulses that do have this narrow spectrum are known as transform limited pulses. For most transmitters, the modulation process not only changes the light's amplitude but also its phase or frequency. This unwanted frequency modulation (FM) is called *chirp* and causes the spectral linewidth to broaden as shown in Fig. 3.l(a). The directly modulated laser is a good example for a transmitter with a significant amount of chirp. Mathematically, the effect of chirp on the transmitter linewidth can be approximated by

$$\Delta\lambda \approx \frac{\lambda^2}{c}\sqrt{\alpha^2 + 1} \cdot B.$$

(3.2)

where α is known as the chirp parameter or linewidth enhancement factor . With the typical value $\alpha = 4$ for a directly modulated laser, the linewidth of a 10-Gb/s transmitter broadens to about 41 GHz or 0.33 nm. External modulators also exhibit a small amount of chirp, but virtually all types of modulators can provide $\alpha < 1$ and some achieve α < 0.1, thus approaching the transform limited case So far, we assumed that the unmodulated source is perfectly monochromatic (zero linewidth), or at least that the unmodulated linewidth is much smaller than those given in Eqs. (3.1) and (3.2). However, many sources have a much larger linewidth. For example, a Fabry-Perot laser has a typical unmodulated linewidth of about 3 nm, a light-emitting diode (LED) has an even wider linewidth in the range of 50 to 60 nm. For such wide-linewidth sources, the spectrum of the modulation signal and the chirp mostly are irrelevant, and the transmitter linewidth is simply given by

$$\Delta\lambda = \Delta\lambda_s \qquad\qquad (3.3)$$

where $\Delta\lambda_S$ is the linewidth of the unmodulated source.

(ii) Extinction Ratio. Optical transmitters, no matter if directly or externally modulated, do not shut off completely when a zero is transmitted. This undesired effect quantified by the extinction ratio (ER), which is defined as follows:

$$ER = \frac{P_1}{P_0}, \qquad\qquad (3.4)$$

where P_O is the optical power emitted for a zero and P_1 the power for a one. Thus, an ideal transmitter would have an infinite ER. The ER usually is expressed in dBs using the conversion rule 10 log ER. Typically, ERs for directly modulated lasers range from 9 to 14 dB, whereas ERs for externally modulated lasers can exceed 15 dB . SONET / KDH transmitters typically are required to have an ER in the range of 8.2 to 10 dB, depending on the application. It doesn't come as a surprise that a finite ER causes a power penalty. Figure 3.2(a) and (b) illustrates how decreasing the ER reduces the optical signal swing, P_1 - P_O, even if the average power = $(P_I + P_0)/2$ is kept constant. To restore the original signal swing, we have to increase the average transmitted power, as shown in Fig. 3.2(c). The power penalty PP due to a finite extinction ratio can easily be derived as

$$PP = \frac{ER + 1}{ER - 1}. \qquad\qquad (3.5)$$

For example, an extinction ratio of 10 dB (ER = 10) causes a power penalty of 0.87dB (PP = 1.22).
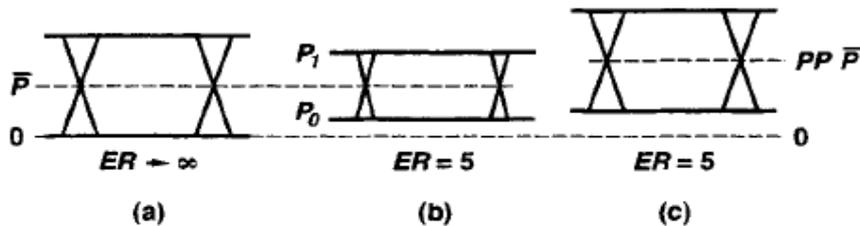
Fjg, 3.2 Eye diagram (a) with infinite ER, (b) with ER = 5, and (c) with ER = 5 and increased average power (1.5 x) to restore the original signal swing.

In deriving Eq. (3.5), it was assumed that the ER does not affect the amount of noise at the receiver. This is the case for unamplified p-i-n receivers; however, in systems with an avalanche photodetector (APD) or optical amplifiers, the noise increases when the ER is reduced: (i) the nonzero value of PO adds noise on the zeros and (ii) the increase in power to compensate for the finite ER adds noise on the zeros and ones, necessitating an even larger power increase to compensate for this noise. As a result of these two mechanisms, the power penalty becomes larger than given in Eq. (3.5). If we take the extreme case where the: receiver noise is dominated by the detector (or optical amplifier) noise such that the electrical noise power is proportional to the received signal current, we find that

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$$PP = \frac{\sqrt{ER}+1}{\sqrt{ER}-1} \cdot \frac{ER+1}{ER-1} \qquad (3.6)$$

For example, an extinction ratio of 10 clB (ER = 10) causes a power penalty of up to 3.72dB (PP = 2.35) in an amplified lightwave systems. In regulatory standards, the receiver sensitivity usually is specified for the worst- case extinction ratio. Therefore, the corresponding power penalty must be deducted from the sensitivity based on ER + 00. Typically, 2.2 dB (for ER = 6 dB) must be deducted in short-haul applications, and 0.87 dB (for ER = 10 dB) must be deducted in long-haul applications. Instead of specifying the average transmitter power, the optical modulation amplitude (OMA), which is defined as P_J - P_O and measured in dBm, can be used to measure the transmitter power. The OMA measure is used, for example, in 10-GbE systems. If the transmitter power and the receiver sensitivity are specified in terms of OMA rather than average power, a finite extinction ratio causes much less of a power penalty (no power penalty in the case of constant noise).

3.3 Light Emitting Diode:

A light-emitting diode (LED) is a semiconductor device that emits visible light when an electric current passes through it. The light is not particularly bright, but in most LEDs it is monochromatic, occurring at a single wavelength. The output from an LED can range from red (at a wavelength of approximately 700 nanometers) to blue-violet (about 400 nanometers). Some LEDs emit infrared (IR) energy (830 nanometers or longer); such a device is known as an infrared-emitting diode (IRED). An LED or IRED consists of two elements of processed material called P-type semiconductors and N-type semiconductors. These two elements are placed in direct contact, forming a region called the P-N junction. In this respect, the LED or IRED resembles most other diode types, but there are important differences. The LED or IRED has a transparent package, allowing visible or IR energy to pass through. Also, the LED or IRED has a large PN-junction area whose shape is tailored to the application.

3.4 Advantages and Disadvantages of LEDs

The light emitting diodes (LEDs) are very simple devices as compared to laser diodes. The advantages and disadvantages of LEDs are following:

Advantages:

Simple device. It is a simple device like *p-n* junction diode without any resonator mirrors and complicated striped structure.

Low cost. It is an inexpensive optical source due to simple *p-n* junction device and is ideally used with multimode fibres.

Reliability. The LEDs are reliable in performance and it does not degrade abruptly. It is free from modal noise and is easy to handle.

Temperature dependence. It is just like a *p-n* junction diode and the variation of temperature with current is linear. If the temperature of device is increased, its output may decrease but it will not stop working. Thus, no cooling is required as compared to laser diode where temperature rise an degrade laser power drastically.

Simple electronics. It uses simple device circuits for its working and no temperature compensation circuits are needed. So, overall cost of electronics is also low.

Linearity. The light output varies linearly with the device current so it is a good device for modulation like a *p-n junction* diode.

Application areas. LEDs are used in LAN and WAN application with multimode fibre because multimode fibre can have large angle of acceptance of light.

Disadvantages :

Low output. The LEDs produce low output power and the coupled power in the fibre is in the range of microwatts.

Low bandwidth. The bandwidth for modulation is lower and hence these are used for transfer of data from computers, distributed process control system and also for data transfer in LAN.

Harmonic distortion. The harmonic distortion is more in LEDs..

Typical applications include*:*

  (i)   Indicator lights: These can be two-state (i.e., on/off), bar-graph, or alphabetic-numeric readouts.

  (ii)   LCD panel backlighting: Specialized white LEDs are used in flat-panel computer displays.

  (iii)   Fiber optic data transmission: Ease of modulation allows wide communications bandwidth with minimal noise, resulting in high speed and accuracy.

  (iv)   Remote control: Most home-entertainment "remotes" use IREDs to transmit data to the main unit.

  (v)   Optoisolator: Stages in an electronic system can be connected together without unwanted interaction.

3.5 . Types of Homojunction LEDs

(i) Planar LED

As the name indicates LEDs are the diodes which emit light when the current is applied across the diode. Initially, simple *p-n* junction diode made out of GaAs was used to produce light. It is called planar LED and is the simplest of the structure fabricated from. GaAs substrate . Figure 3.3 shows its structure. It is not used for optical fibre communication.
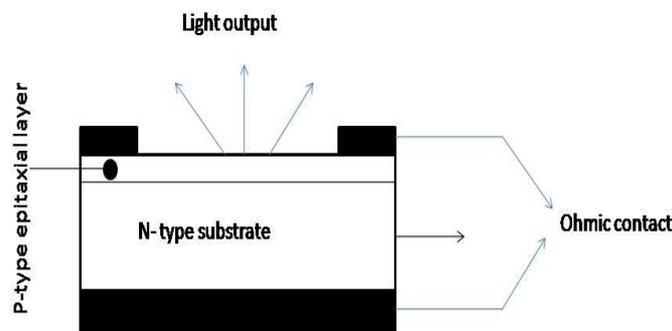

Fig3.3 Planar light emitting diode

An *n*-type GaAs substrate is diffused by *p*-type dopings by liquid or vapour phase epitaxial process so that a thin layer of *p*-GaAs is formed on *n*-type substrate. Ohmic contacts are formed on *n* and *p* surfaces. When current is injected into *p-n* GaAs device, light output

comes out from *p*-GaAs surfaces. Since light will be emitted out from GaAs device in all directions, only a part of light will come out from *p*-GaAs surface which will further reduce at the boundary of *p*-GaAs and air due to internal reflection and variation of refractive index. Hence low light output will emerge. These diodes are used as cheap plastic encapsulated visible light sources and in various electronic produces like TV, audio products and electronic toys.

(ii) Hemispheric LED

The planer LED is improved by the development of hemispheric LED. In this LED, a hemisphere of *n*-type GaAs is formed, around a diffused *p*-type region. The diameter of hemisphere is optimized so that the maximum about of internal light emission reaches the surface within the critical angle *n*-GaAs and air interface. Hence, this LED has higher radiance output as compared to planar LED. The geometry of such type of hemisphere is large enough to overcome internal losses and thus, the overall emission area is very large resulting into reduction of radiance in the direction of fibre. Figure 3.4 shows the shape of hemispheric LED. These diodes do not produce high radiance for use in optical fibre communication.
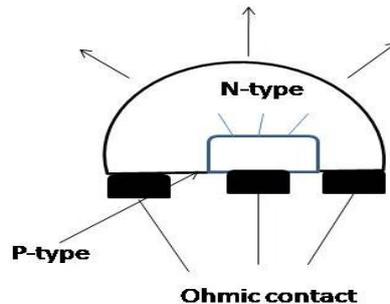
Fig.3.4 The structure of a hemispheric LED

(iii) **Truncated ellipsoid LED**

The light emitted out of LED is to be coupled with fibre and mostly, it is lost either in LED or LED-fibre interface and only a fraction of power is delivered into the fibre from LED.

Truncated ellipsoid LED couples with a truncated spherical microlens made from oxides of silica and titanium with the InGaAsP surface emitting LED (Burrus diode). This is shown in Figure 3.5. Such type of LED provides a very small emission region diameter of light for efficient coupling with optical fibre. During various experiments conducted on truncated ellipsoid LED at wavelength of 1-3 nm, it was found that 9-14nm active diameter of refractive index n_1 and 85 mm core diameter step index fibre of refractive index n_2 gave best result for NA = 0.16. The coupling efficiency was increased by 15 times as compared to the theoretical prediction of 30 times.

The power conversion efficiency η_{pc} is given by

$$\eta_{pc} = P_c / P \qquad (3.7)$$

Where P_c is power launched into the fibre and P is electric power applied (in watts).

The overall electrical to light conversion efficiency in fibre varies from 0.5% to 1% only. A diagram of truncated ellipsoid LED is shown in Figure 3.5. The overall power conversion efficiency in LED is 0.5%.
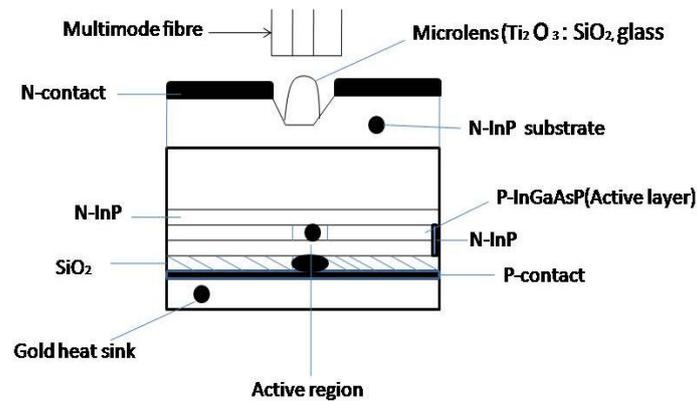

Fig.3.5 The use of truncated spherical microlens for coupling the emission from an InGaAsP surface emitting LED to the fibre.

3.5 Double heterostructure LEDs

The convention LED has simple *p-n* junction in which light is emitted out in all directions so its output is very less in forward direction. In order to increase light output from a LED, special devices are fabricated based on surface emitting structure and edge emitting LED using *n*-doped GaAs materials. These LEDs are found to give more than 50 microwatts of power in forward direction which is coupled with the fibre cable.

Here two types of LEDs are described :
(i) Burrus type double heterostructure surface emitting LED (DH-SLED)
(ii) The stripe geometry edge emitting LED (ELED).

(i)   Burrus LEDs

This type of LED is a three-layered device consisting of *n*-GaAs as substrate, *p*-GaAs as active region and SiO_2 as an insulating layer. This is mounted in back arrangements as shown in Figure 3.6 so that it provides a small emission area and high radiance from its surface. The active region which produce light is behind the GaAs substrate. The emitting radiation passes through the substrate whereas active region material is mounted on heat sink which provides efficient cooling. So, flow of current is restricted to thin region of active *p*-GaAs material. These LEDs can work satisfactorily and instantly due to closeness of active region to the heat sink. This indicates that the thermal cooling efficiency is higher and so high current densities can be used to produce continuous light output even at higher temperature. If the temperature risesto 90-100°C from the room temperature, the output power of the light decreases by 50%.

After successful working of GaAs Burrus device in the surface emitting mode, a five layered double heterojunction Burrus type LED is made using GaAs and GaA1As layers. The two outer layers 1 and 5, as given in Figure 3.7, are called contact layers. These prodice low resistance contact between electrodes and confining layers 2 and 4. One of the *n*-GaAs contact layers will be a substrate layers on which other layers are formed an 1grown

epitaxially. The layer 3 in an active layer sandwiched between two confining layers made from GaA1As material.
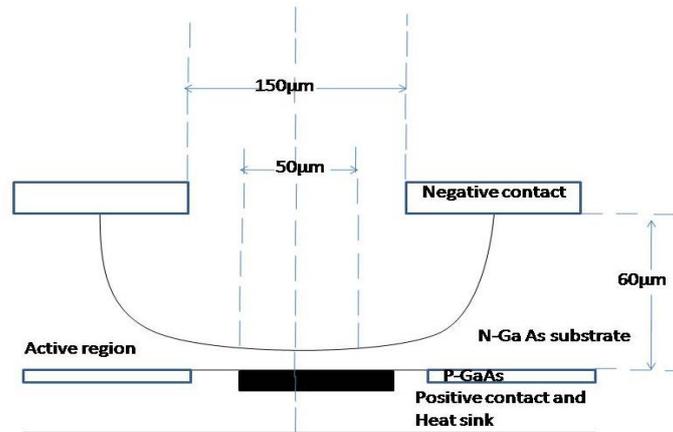

Fig.3.6 Axial cross-section through a Burrus-type surface –emitting LED
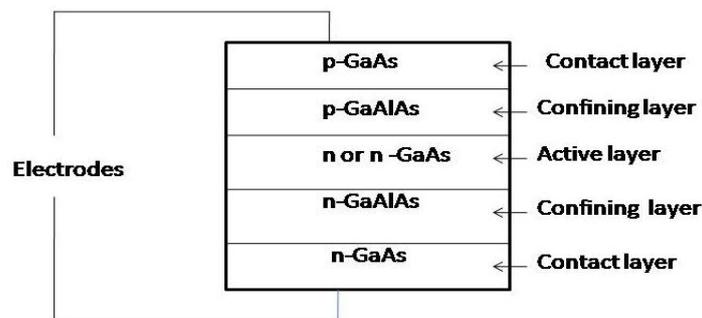

Fig.3.7 Shows 5 layers structure

In the Burrus type–double heterostructure junction LED, active layer is either *p*-GaAs or *n*-GaAs and confining layers are *n*-GaA1As and *p*-GaA1As, whereas *p*-GaAs is contact layer and *n*-GaAs is substrate layer on 40 mm wide. The layers are epitaxially grown on substrate material of *n*-GaAs. The adjacent confining layers in 10mm and rest of the three layers are 1 mm wide. The active layers produces and emits photon which passes through GaAs layer without any absorption because band gap of GaA1As is more than GaAs. But, the thermal resistivity of GaA1As is more than GaAs and hence, there is some heating in the confining layer as current density increases. The bottom confining layer and the adjacent contact layer are bombarded by sufficient does of protons at $3x10^{19}$ proton/m^2 which raises the resistivity by 100 times. The proton bombardment increases the heat dissipation and then reduces the temperature rise for a given current density. The other advantages is that the depletion layer capacitance of *p-n* junction is not charged and discharged during high frequency operations and thus decreases the losses due to depletion layer capacitances. These devices offer distinct advantages as shown in Figure 3.8.

1. There are negligible degradation in their performance at room temperature even at high active area current densities (50 A/mm^2) and at higher temperature at relatively low current densities.
2. When LEDs are tested for life test, they are found to give quality output and found to be reliable too.
3. The power output is higher and the DHS-LED is able to inject about 65m mW of light power into a multimode fibre of dimater 50 mm at minimum NA (0.17).
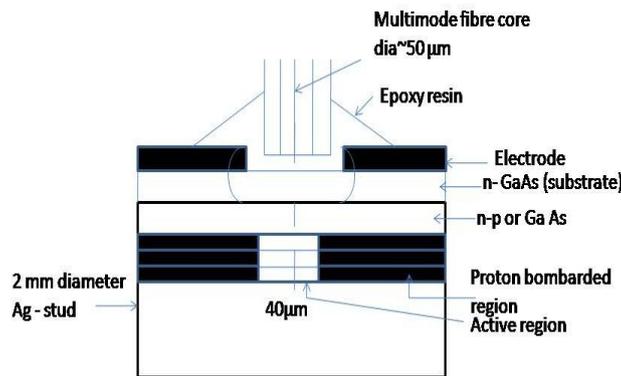

Fig. 3.8 Double heterostructure Burrus-type LED, shown bonded to fibre with index-matcing epoxy. The active region is bounded by material made insulating by proton bombardment.

 (ii) Edge Emitting LED (ELED)

This diode is based on double heterostructure LED. The important feature of this alternative design is that it provides an order-of-magnitude increase in radiome from a very small emission area. It consists of 5 layers of Gps III-V semiconductor materials. The LED is grown epitaxially on n-GaAs substrate of $50\,\mu m$ thick which is mounted on heat sink after mentallization. A layer of n-GaAs of thickness $3\,\mu m$ is grown epitaxially on GaAs substrate. On this layer, $n-Ga_{0.6}Al_{0.4}As$ is formed as confining layer of thickness $2\,\mu m$. An active layer of $0.05\,\mu m$ is formed from $n-Ga_{0.6}Al_{0.4}As$ semiconductor material on the confining layer, which generates light output at different current densities. This active layer is covered by another confining layer of $p-Ga_{0.6}Al_{0.4}As$ of $2\,\mu m$ thickness which is covered by $p^+ -GaAs\, 3\,\mu m$ grown epitaxially on the confining layer. A silica layer is formed on GaAs layer, which acts as an insulator and is connected to gold contact. The diode is found to give more output power from a small active area. The diode offers numerous advantages.

1. The active region is very thin so self –absorption of photon is considerably reduced.
2. The optical power is guided by internal reflections at the heterojunction and is directed towards end facet of LED.
3. The LED is similar in geometry to stripe edge type laser diode.
4. A slot is cut closed to the end of active layer and a strip contact is defined in active layer.

5. The photons moving towards other end facet are absorbed by the ELED (opposite side to emitting end) where no current is flowing in the device.

6. It gives narrow spectral line width as compared to a SLED. It is about 25 nm at 0.9 μm and 70 nm at 1.3 μm.

7. The beam emanating from the LED has narrow beam width in the direction perpendicular to the junction so its coupling with fibre using lens coupler is good. ELED can be used for both multimode and single mode fibres as light source for short distance communication (up to 20 km).

8. Coupling efficiency in fibre is 6 times more from ELED when NA is less than 0.30. In GaAsP/InP material has been used in ELED to give 1 μm output of 1.3 μm. The coupling power in fibre is 3 microwatt maximum.

9. A short strip long structure of 100 μm ELED can give high output power as compared to 150 μm long strip structure. Bandwidth of 600 Mb/s has been achieved in such ELED.

10. Light output has emerged in the lambertian pattern of elliptical shape having major axis of 120° and minor axis angle of 30° as shown in Figure 3.9(a).

Figure 3.9(b) shows be construction of truncated ELED. The LED is made on 100 micrometre substrate on which two micrometre layers of *n*-Inp and *p*-InP materials are grown as confinement layers which sandwich the thin active layer of InGaAsP. The silica isolation is provided on the confinement layer. Finally, the metallization is done on the top. A truncated area of 20 μm wide into 100 μm long is made as shown in Figure 3.9(b).
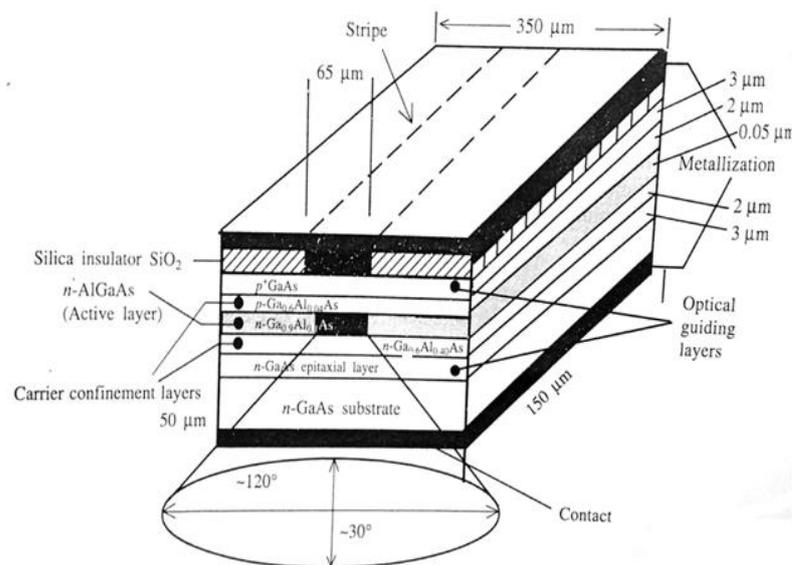

Fig.3.9(a) ELED

LED to fibre launch system : The LED power in the air is around 2.0mW. The LED and fibres are two different components and are to be coupled efficiently. Following techniques are used :

1. The LED emitting surface and multimode fibre of core diameter, greater than the active area of LED are coupled in index matching liquid so that all the emitting light output from the fibre is coupled into the fibre
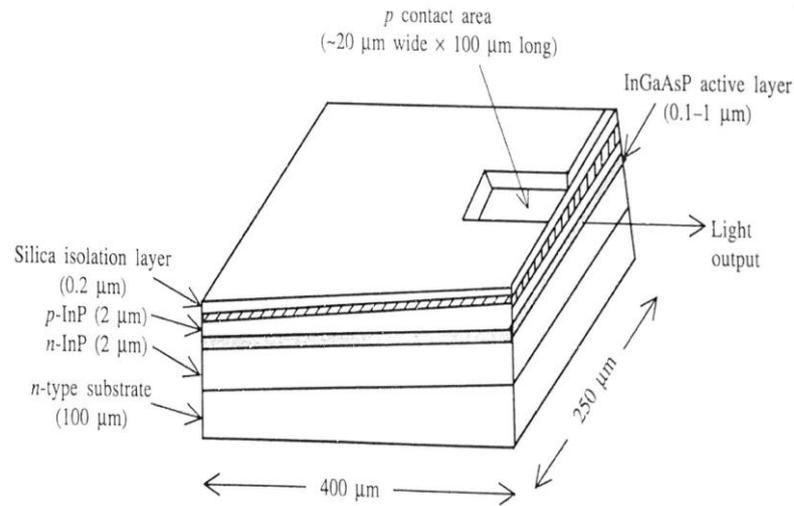

Fig.3.9 (b) Truncated stripe INGaAsP edge-emitting LED (ELED).

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2. The LED and fibre can also be coupled by making a lens shape in the end fibre. The LED active area is kept at the focal point of the fibre lens so that all the output light is collected by the lens of the fibre.
3. A spherical lens of higher refractive index is formed on the semiconductor emitting face, which helps to collimate the emitting radiations and finally light output is directed in to the fibre by cementing the spherical lens with the fibre.
4. A lens is formed on LED emitting surface and a spherical is formed in the fibre. The light from LED is collimated by LED lens and the fibre end collected this light and injected into the fibre.

Table 3.1 illustrates comparison of two-types of LED Sources.

TABLE 3.1 Comparison of SLED and ELED Devices

S.No	SLED	ELED
1.	Easy to fabricate.	Difficult to fabricate
2.	Easy to mount and handle.	Difficult to mount and handle mechanically.
3.	Require less critical tolerances.	Ned critical tolerances on fabrication.
4.	Cheaper in cost.	More expensive.
5.	Less reliable	Highly reliable
6.	Low system performance	High system performance.

3.6 LED Analog transmission
(i) LED Drive Circuits

The analog signal is basically a time varying voltage waveform in which both amplitude and phase are varying with time. Therefore, LED shall provide a linear region in

which output power of LED responds linealy to the variation of input voltage or current. Using the linear characteristics of LED, it is possible to do analog communication from LED source using transistor circuits when extremely low level distortions are not required. LED can be connected either in Darlington transistor pair configuration or in common emitter configuration.

Two possible high speed drive circuit configurations are illustrated in Figure 3.10(a) that shows a driver consisting of a common emitter transconductance amplifier which converts an input base voltage into a collector current. The circuit is based for a class A mode of operation with the quiescent collector current about half the peack value. A similar transconductance configuration which utilizes a Darlington transistor pair in order to reduce the impendence of the source is shown in Figure 3.10(b). A circuit of this type has been used to drive high radiance LEDs at frequencies of 70 MHz.
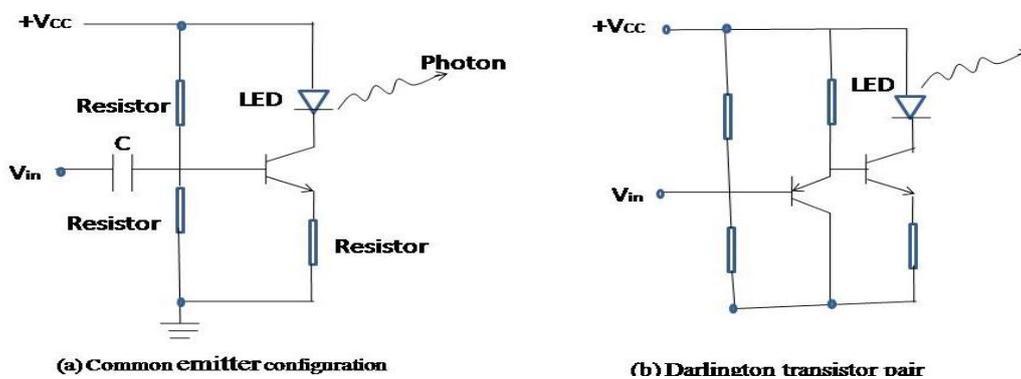

Fig.3.10 Transconductance drive circuits for analog transmission

Another simple driver circuit configurations is shown in Figure 3.11. It consists of a differential amplifier operated over its linear region which directly modulates the LED. The LED operating point is controlled by a reference voltage V_{ref} whilst the current generator provided by the transistor T_3 feeding the differential stage (T1 and T_2) limits the maximum
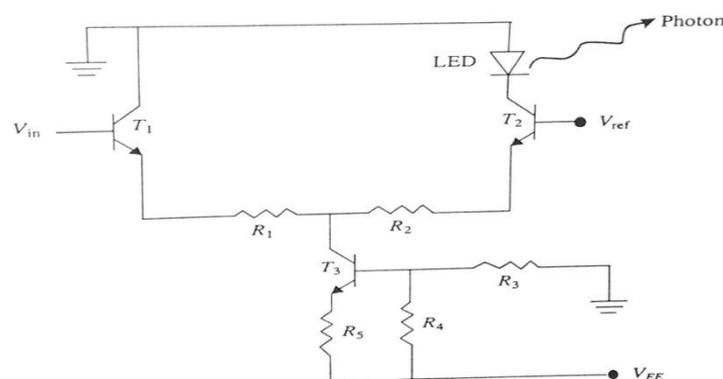

Fig.3.11 A differential amplifier drive circuit

current through the device. The transimpedance of the driver is reduced through current series feedback provided by the two resistors R_1 and R_2 which are normally assigned equal values.

Furthermore, variation between these feedback resistors can be used to compensate for the transfer function of both the drive circuit and the LED.

3.7 LED Digital transmission

LED digital transmitters deal with high speed switching of, on or off LED currents in response to logic circuit's coding. The switching speeds of several kilohertz to six hundred megahertz are used whereas current pulses may range from several tens of milliamperes to several hundreds of multiamperes. This switching is achieved by using bipolar transistor in common emitter mode which means, the collector current follows the pulse switching applied at the base. A common method of achieving this current switching operation of LED is shown in Figure 3.12. The illustrated circuit uses a bipolar transistor switch operated in the common emitter mode. This single stage circuit provides current gain with a small voltage drop across the switch when the transmitter is in saturation. (i.e., when the collector − base junction is forward biased, the emitter to collector voltage V_{CE} is around V).
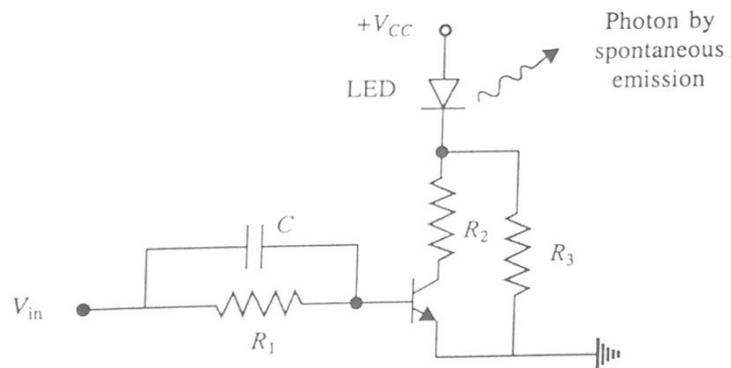

Fig. 3.12 A simple drive circuit for binary digital transmission consisting of a common emitter saturating switch.

The current flow through the LED is limited by the resistor R_2 whilst independent bias to the device may be provided by the incorporation of resistor R_3. However, the switching speed of the common emitter configuration is limited by space charge and diffusion capacitance, thus bandwidth is traded for current gain. This may, to a certain extent, be compensated by overdriving the base current when the switch is on. In the circuit extent, be compensated by overdriving the base current when the switch is one. In the circuit, shown in Figure 3.12 over driving at the base is accomplished by the use of the speed-up capacitor C.

The increased switching speed may be obtained from LED without a pulse shaping or speed-up element by the use of a low impedance driving circuit whereby charging of the space charge and diffusion capacitance occurs as rapidly as possible. This may be achieved by the emitter follower driver circuit shown in Figure 3.13. The use of this configuration with a compensating matching network [R_3C] provides fast direct modulation of LEDs with a relatively low drive power. Circuit, with optimum values for the matching network, is capable of giving optical rise time of 2.5 ns for LEDs with capacitance of 180pF, thus allowing 100 Mb/s. Another type of low impedance driver is the shunt configuration shown in Figure 3.14. The switching transistor in this circuit is placed in parallel with the LED, providing a low impedance path for switching off the LED by shunting current around it. The performance of the circuit in the ON state is determined
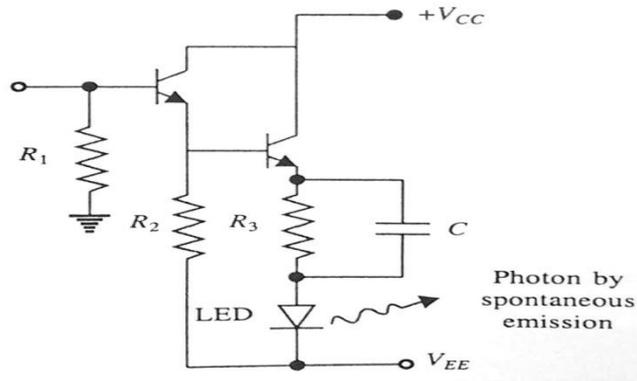
Fig.3.13 Low impedance drive circuit consisting of an emitter follower with compensating matching network
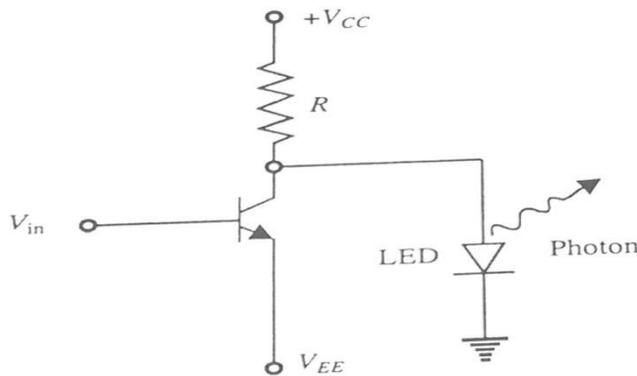

Fig. 3.14 Low impedance drive circuit consisting of a simple shunt configuration.

by the combination of resistor R and the LED capacitance. Stored space charge may be removed by slightly reverse biasing the LED when the device is switched off. This may be achieved by placing the transistor emitter potential V_{EE} below ground. In this case, Schottky clamp (shown dotted) may be incorporated to limit the extent of the reverse bias without introducing any extra minority carrier (stored charge) into the circuit.

A frequent requirement for digital transmission is the interfacing of the LED by drive circuit with a common logic family, as illustrated in the block schematic representation of Figure 3.15. In this case, the logic interface must be considered along with possible driver circuits. Compatibility with TTL may be achieved by the use of commercial integrate circuits, as shown in Figures 3.15(a), (b) and (c). The configuration shown in Figure 3.15

(a)

(b)
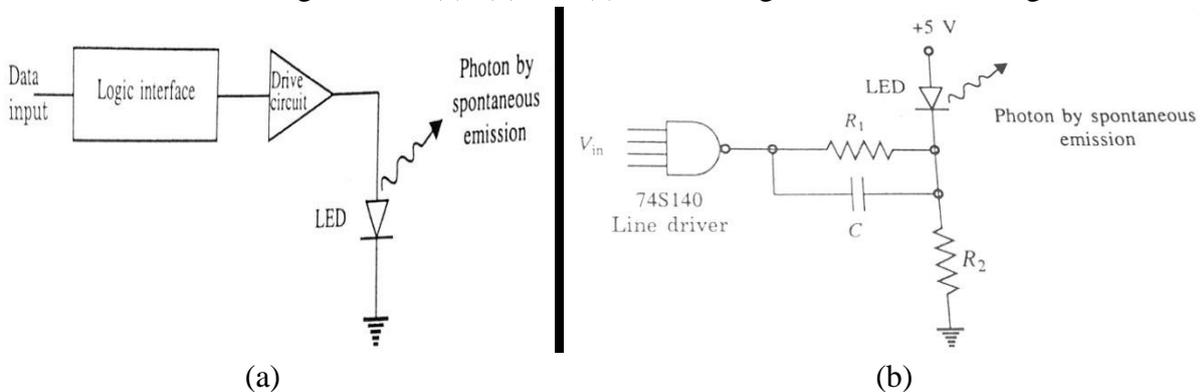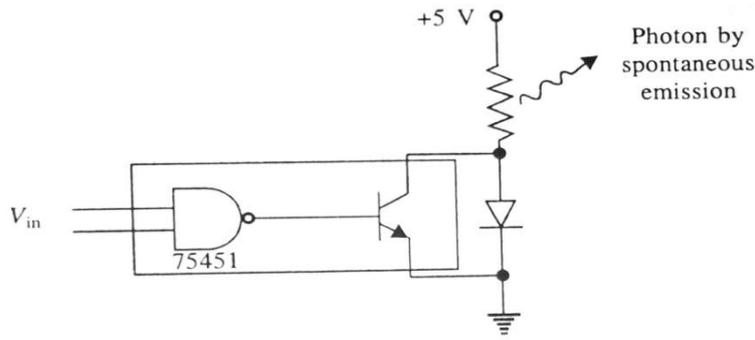
(c)

Fig.3.15 (a) Interfacing of the LED drive circuit with logic input levels (b) A simple TTL compatible LED drive circuit employing 74S140 line driver (c) A TTL shunt drive circuit using integrated circuit

uses of Texas Instrument 74S140 line driver which provides a drive current of around 60 mA to the LED when R_1 is 50W. Moreover, the package contains two sections which may be connected in parallel in order to obtain a drive current of 20 mA. The incorporation of a suitable speed-up capacitor (e.g C=47pF) gives optical rise time of around 5 ns when using LEDs with n 150 N 200 pF capacitance. Figure 3.15 illustrates the shunt configuration using a standard TTL 75451 integrated circuit. The rise time of this shunt circuit may be improved through maintenance of charge on the LED capacitance by placing a resistor between the shunt switch collector and the LED.

An alternative important drive circuit configuration is the emitter coupled circuit shown in Figure 3.16. The LED acts as a load in one collector so that the circuit provides current gain and hence a driver current for the device. Thus the circuit resembles a linear differential amplifier, but it is operated outside the linear range and in the switching mode. Fast switching speeds may be obtained due o the configuration's non– saturating characteristic which avoids switch-off time degradations caused by stored charge accumulation on the transistor base region. The lack of saturation also minimizes the base drive requirements for the transistors,.
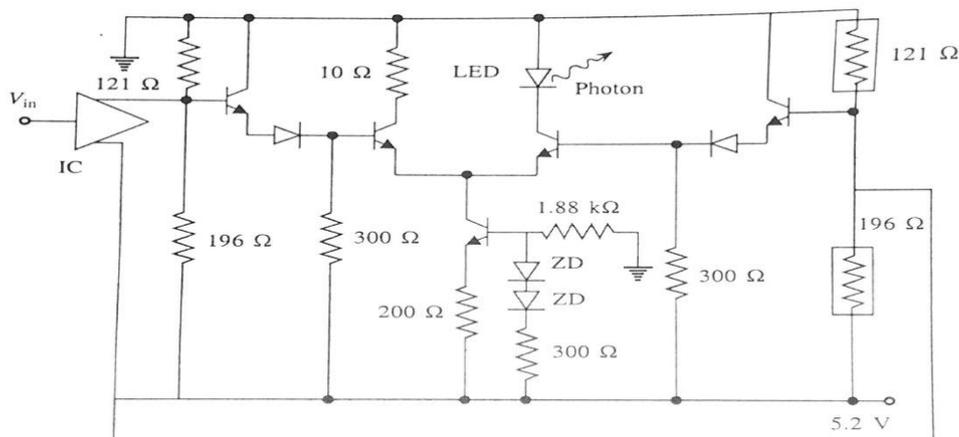

Fig.3.16 An emitter coupled drive circuit which is compatible with ECL

thus preserving their small signal current gain. The emitter coupled driver configuration shown in Figure 3.16 is compatible with commercial emitter coupled logic (ECL). However, to achieve this compatibility the circuit includes two level shifting transistors which give

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ECL levels (high -0.8 V, low 1.8 V) when the positive terminal of the LED is at earth potential. The response of this circuit is specified at up to 50 Mb/s, with a possible extension to 300 Mb/s when using a faster ECL logic family and high speed transistors. The emitter coupled driver circuit configuration may also be interfaced with other logic families

3.8 Laser Semiconuctor Transmitters
Laser drive circuit:

The laser, being a threshold device, has somewhat different drive current requirements from the LED. For instance, when digital transmission is considered, the laser is usually given a substantial applied bias, often referred to as prebias, in the OFF state. Reasons for biasing, the laser near but below threshold in the OFF state are as follows :

1. It reduces the switch-on delay and minimizes any relaxation oscillations.
2. It allows easy compensation for changes in ambient temperature and device ageing.
3. It reduces the junction heating caused by the digital driver current since the ON and OFF currents are not widely different for most lasers.

Although biasing near threshold causes spontaneous emission of light in the OFF state, this is not normally a problem for digital transmission because the stimulated emission in the ON state is generally greater by, at least a factor of 10.

A simple laser drive circuit for digital transmission is shown in Figure 3.17. This circuit is a shunt driver utilizing a field effect transistor (FET) to provided high speed laser operation. Sufficient voltage is maintained in series with the laser using the resistor R_2 and the compensating capacitor C such that the FET is biased into its active or pinch-off region. Hence for a particular input voltage V_{in} (i.e. V_{GS}) a specific amount of the total current flowing through R_1 is diverted around the laser leaving the balance of the current to flow through R2 and provide the OFF state for the device.
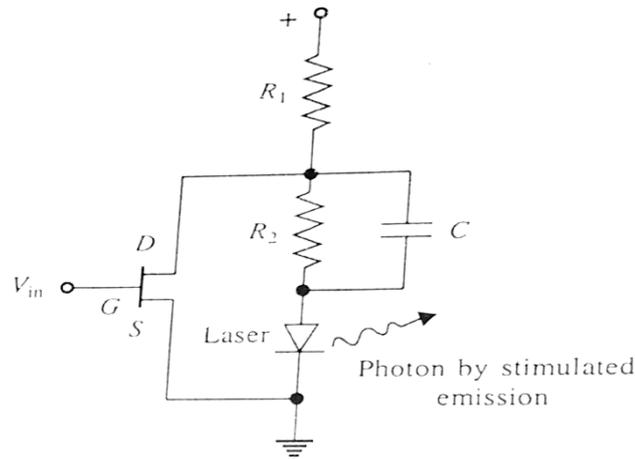

Fig.3.17 A shunt drive circuit for use with an injection laser

An alternative high speed laser drive circuit employing bipolar transistors is shown in Figure 3.18. This circuit configuration, again for digital transmission, consists of two differential amplifiers connected in parallel. The input stage, which is ECL compatible, exhibits a 50 W
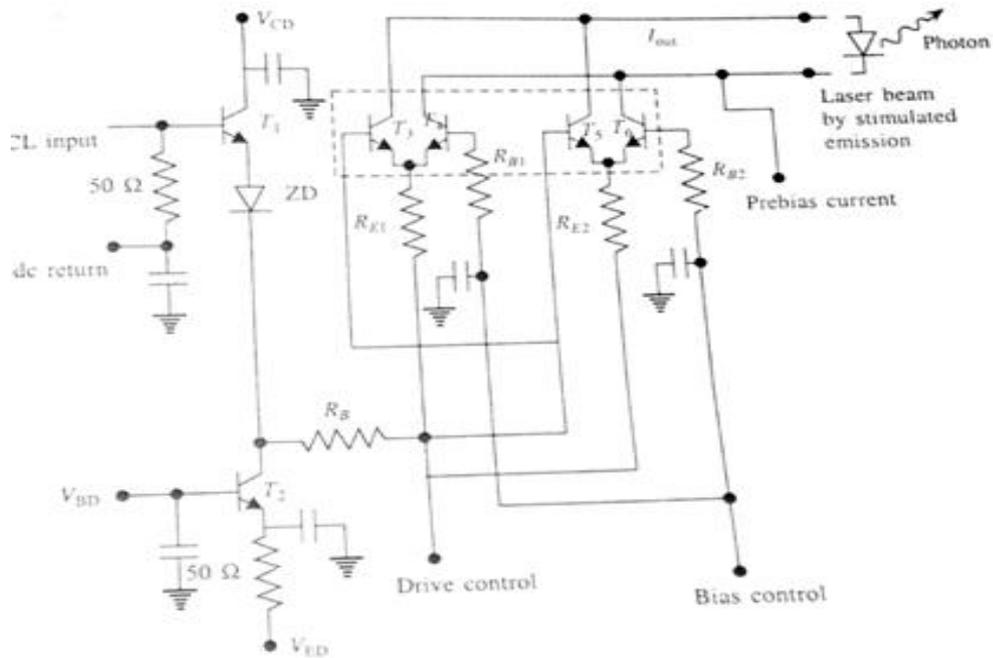
Fig.3.18 An ECL compatible high speed laser drive circuit

input impedance by the use of an emitter follower T_1 and a 50 W resistor in parallel with the input. The transistor T_2 acts as a current amplitude for the laser under a dc control current I_E thorough the two emitter resistors RE_1 and RE_2. I_E is provided by an optical feedback control circuit which will be discussed shortly. Finally, a prebias current is applied to the laser from a separate current source. The circuit utilizing microwave transistors was operated with a return to zero digital format at 1 Gb/s. A major difference between the drive circuits of Figure 3.17 and Figure 3.18 is the absence and presence, respectively, of feedback control for adjustment of the laser output level. For this reason, shunt drive circuit of Figure 3.17 could not be used for a system application. Some form of feedback control is generally required to ensure continuous laser operation because the device lasing threshold is a sensitive function of temperature. Also, the threshold levels tends to increase as the laser ages following an increase in internal device losses.

3.9 Semiconductor laser diode

It is made from *p* and *n*-type materials of Group III-V such as GaAs, GaAlAs, AgA1AsP where substrate material can be either GaAs, InP or InSb. In 1964, simple *p-n* junction was used to produce laser beam. It was cooled by liquid N_2 due to heating of the device when high current densities were injected and conversion efficiency was very poor. GaAs material was taken and a Fabry-Perot diode laser structure was made. The GaAs laser diode is a rectangular parallelepiped and *p-n* junction is parallel to the largest surface. The smallest faces are cleaved perpendicular to the junction as shown in Figure 3.19.

The laser beam emerges from the junction plane normal to the cleaved surface. The *p and n* regions are heavily doped for the purpose of population inversion. At high currents, the conversion efficiency becomes constant and then decreases because of laser diode heating effects.
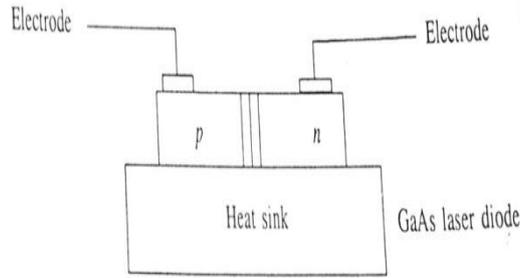
Fig. 3.19 A simple *p-n* junction diode

If r is the semiconductor resistivity, A is the chip area and t is the thickness of the chip, the resistance R is given by,

$$R = rt / A$$

Let J is the current density then the power is

$$P = I^2 R = J^2 rtA$$

Therefore, joule heat generate per unit junction area is :

$$P / A = J^2 rt \qquad (3.8)$$

The typical values of 77 K were $J = 10^3$ A/cm^2, $r = 10^{-3}$ ohm cm, $t = 10^2$ mm and P/A = 10 watt/cm^2 which is very high. Laser diode can work at 4 K, 20 K and 77 K but not at room temperature so further research was done and three-layered laser diodes were invented. They are successfully developed based on heterostructure in which active layer is sandwiched between two confining layers of *p* and *n* –types layers, made from two different semiconductor materials as shown in Figure 3.20. In this device, InGaAsP is the active layer. *n*- InGaAsP and *p*- InGaAsP are bottom and top layers. It is used as distributed feedback diode laser which has given laser operation at room temperature with single frequency operation. Subsequent to three-layered laser diodes, double heterostructure laser diodes are developed which can produce large output of power in a single mode. It consists of five layers of various p and n-type p/n heterojunction materials of different thickness varying from 1 to 5 mm which are grown on a substrate of GaAs or InP as shown in Figure 3.21
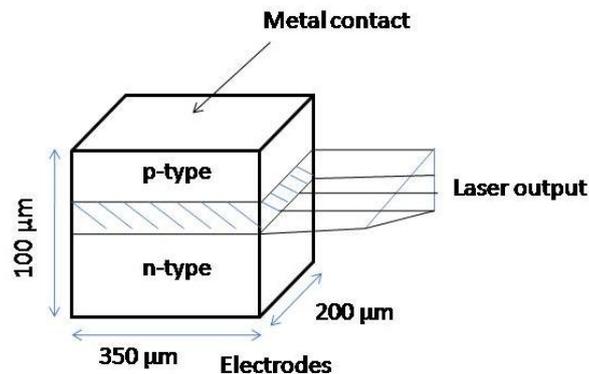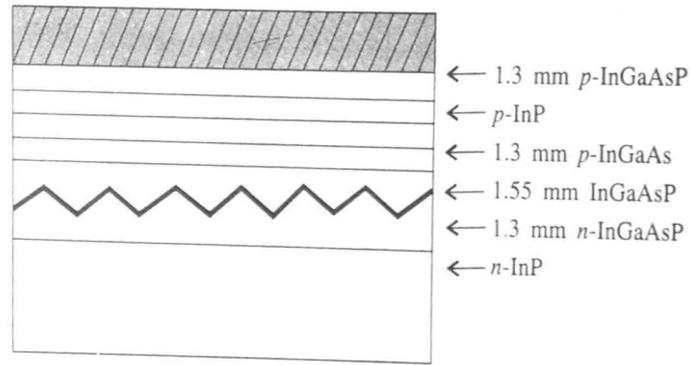

Fig. 3.20 Three-layered laser diode.

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Fig.3.21 DFB InGaAsP laser showing thickness and composition of various layers

(i) Heterostructure Semiconductor Lasers

A junction of two dissimilar semiconductors is called a heterojunction and devices employing such junctions are referred to as the heterostructure semiconductor lasers. Figure 3.22 shows schematically a heterostructure semiconductor laser. Typical dimensions of the device are also indicated to emphasize that the physical size of a semiconductor laser is comparable to that of a grain of salt. Stimulated recombination occurs only inside the thin active layer of thickness ~ 0.2 mm. Its band gap is slightly lower as compared to the p-type and n-type cladding layers. The physics behind the simultaneous confinement of charge carriers and photons by the heterostructure scheme can be understood by referring to Figure 3.22. Since the narrow central regional has a lower band gap, electrons from the n-region and holes from the p- region can move freely to the active layer.
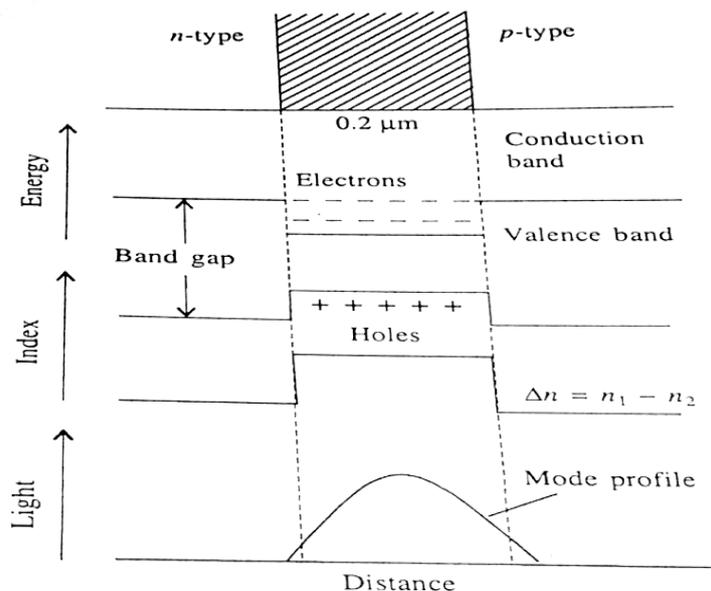

Fig.3.22 Schematic illustration of the simultaneous confinement of the charge carriers and photons offered by the heterostructure scheme

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However, their crossing over to the other side is restricted by the potential barrier arising from the band gap difference of two semiconductors. This allows for the build – up of electron and hole populations in the conduction and valence bands, respectively. The light confinement occus because of a fortunate coincidence. A semiconductor with a smaller band gap also has a higher refractive index, thereby allowing the total internal reflection to occur at the heterostructure interfaces. The active layers acts as a dielectric waveguide and the refractive index difference Δn helps to confine the optical mode within the gain region.

The use of a heterostructure for the semiconductor laser of Figure 3.22 solves the confinement problem only in the direction perpendicular to the junction plane. Such a laser is often referred to as a broad –area laser since both the current and the optical field spread over a wide region (~100mm) along the junction plane. Relatively high (~1A) values of the current are required to operate as a broad area laser. The heterostructure concept can be generalized to confine the charge carriers and photons in the lateral direction as well, at least at the expense of considerable fabrication complexity. The active region is in the form of a rectangular cylinder and is buried on all sides in a higher band gap semiconductor materials. Such lasers are called buried heterostructure semiconductor lasers. Several designs have been proposed and Figure 3.23 shows one of such design. The active region (hatched area) is typically 2 mm wide and 0.2 mm thick. The surrounding layers are either n-type or p-type and are judiciously chosen so as to force the current flow through the active region.
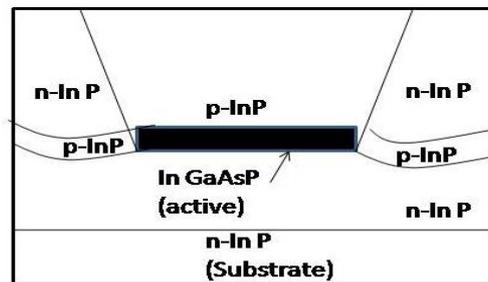

Fig.3.23 Cross-section of a buried heterostructure semiconductor laser

To understand the region of the laser threshold, it is helpful to reconsider the process of spontaneous and stimulated emissions discussed earlier. As the current is progressively increase, the density of electrons and holes injected into the active layer builds up and eventually population inversion occurs. Because of the feedback provided by the cleaved facets, the number of photons travelling perpendicular to the facets increases. However, some photons are lost through the partially transmitting facets and some get scattered or absorbed inside the cavity. If the loss exceeds the gain, stimulated emission cannot sustain a steady supply of photons. This is precisely what happens below threshold and the output consists, of mainly spontaneously emitted photons with power levels of a few microwatts. At threshold, gain equals loss and stimulated emission begins to dominate.

In a narrow current range in the vicinity of the threshold current, the output power jumps by several orders of magnitude and the spectral width of the emitted radiation becomes narrow considerably because of the coherent nature of stimulated emission. At that point, the

laser has reached threshold and the injected carrier density is pinned to its threshold value. With further increase in the current, the internal quantum efficiency becomes nearly 100% and almost all electrons and holes injected into the active region recombine through stimulated emission. However, not all generated photons constitute the output power, since some of them are internally absorbed or scattered. A useful measure of efficiency is the differential quantum efficiency which is the ratio of the rate of emitted photons to the rate of generated photons. It is related to the slope of the L-1 curve by the simple relation:

$$\eta_d = 2q/h\nu . \, dL/dI \qquad\qquad (3.9)$$

where q is the magnitude of the electron's charge. The differential quantum efficiency is typically 50%. The corresponding value of the slope dL/dI at 13 mm is about 0.24 mW/mA/facet.

It is evident that the performance of a semiconductor laser degrades with an increase in the device temperature. The threshold current that is fairly low (~15 mA) around room temperature increases almost exponentially with the temperature rise. This behaviour can be understood by recalling that electrons and holes in a semiconductor can recombine either radiatively or non-radiatively. For long-wavelength semiconductor laser ($\lambda > 1\mu m$), the non-radiative recombination is dominated by the Auger process. The rate of Auger recombination increases exponentially with temperature leading to the observed increase in the threshold current. The differential quantum efficiency decreases with the temperature rise and the L-1 curves roll off at much lower output powers. Several factors may contribute to this behaviour. One possible factor is the increase in the leakage current when the total device current is increased. To understand its origin, note in Figure 3.23 that all the current does not pass through the active region.

The part of the current that flows around the active region is the leakage. An attempt is made to minimize the leakage current through the use of current – blocking junctions. However, these junctions becomes less effective at high currents and lead to the roll-off.

ii). The Semiconductor Injection Laser

These lasers produce light radiations by stimulated emission when semiconductor is placed within the optical cavity. The stimulated emission of photon is achieved by injected carriers which on recombination produce photons of constant phase and frequency. These injection lasers offer the following advantages :

1. The stimulated emission after amplification gives high radiance in terms of milliwatts of laser power.
2. The injection laser produces narrow linewidth of the order of 1 nm or less.
3. The modulation bandwidth can be increased up to terabits / sec from gigabits/sec.
4. The single mode systems produce high temporal coherence for detection of low power signals.
5. The focusing of laser gives narrow spot size due to moderate spatial coherence resulting into greater intensity in focused beam.

The advantage of single-frequency laser is that it is best suitable for single mode fibre and hence, it is possible to attain long distance comunicaiton.

The injection lasers of small threshold current densities ($< 10^3$ A/cm^2) are made by using double heterojunction injection laser fabricated from semiconductor alloys of Group

III-V, which gives better optical amplification, confinement and results in enhanced performance. Thus due to this feature, injection lasers are used for continuous wave operation when mounted on heat sink. The design is shown in Figure 3.24.
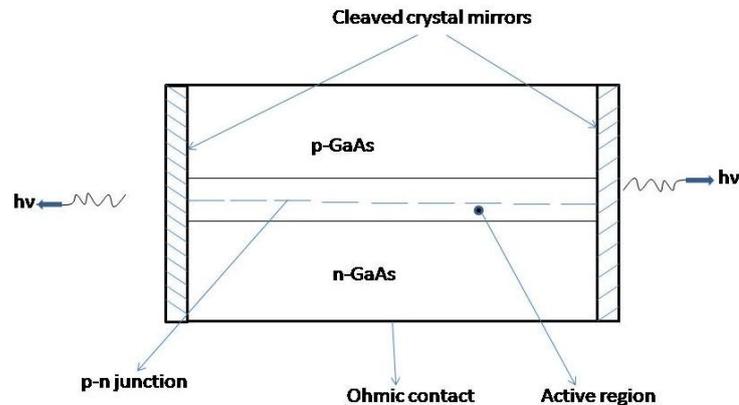

Fig.3.24 Schematic diagram of a GaAs heterojunction injection laser with a Fabry-Perot cavity

The performance of injection laser can be further enhanced by using stripe geometry double heterostructure laser design which gives more carrier and optical confinement in active region.

(a) Stripe geometry laser design

Laser device emits photon in all directions and two edges are roughened to stop leakage of photons and two longitudinal edges are cleaved and provided with Fabry-Perot cavity. If we reduce generation of stimulated photon in a stripe region rather than in complete surface, it is possible to produce laser beam at less threshold current because active region does not extend to all four edges. The stripe is formed by creating high resistance region on both side of stripe by proton bombardment or by oxide isolation. Due to guiding mechanism in stripe and isotropic emission, diffraction of laser beam takes place in semiconductor structure resulting into a laser output of 40° span in vertical plane and 9° span in horizontal plane. The gain profiles of these lasers are studied by varying the stripe width from 2 to 65 mm. The optical mode distribution along the junction plane is determined from optical gain and these devices are said to be gain guided laser structures.

There are several longitudinal and transverse modes in a laser beam. Single mode laser means that its beam will have one longitudinal mode and one transverse mode. This may be possible by reducing the stripe size in vertical and horizontal planes besides controlling hte length of the laser dioed. The vertical width shall be less than 0.4 mm and length should be such that only one longitudinal mode is amplified and other dies down due to losses.

We shall now consider some injection laser structures.

(b) Gain Guided injection laser

The stripe geometry is formed in the diode structure by implanting the stripe with protons (proton isolated stripe) to make it highly resistive or by silicon oxide isolation or by *p-n* junction isolation. It is shown in Figure 3.25.

In this laser diode, *n* –GaAs is substrate and *p*-GaAs is active layer. In the *p*-A1GaAs layer, highly resistive regions at both the ends is formed by proton bombardment which gives

better current confinement in stripe region as compared to oxide insulation. It has excellent temperature properties. The *p-n* junction isolation involves a selective diffusion through *n*-type region to ultimately reach *p*-type layers as shown in Figure 3.25.
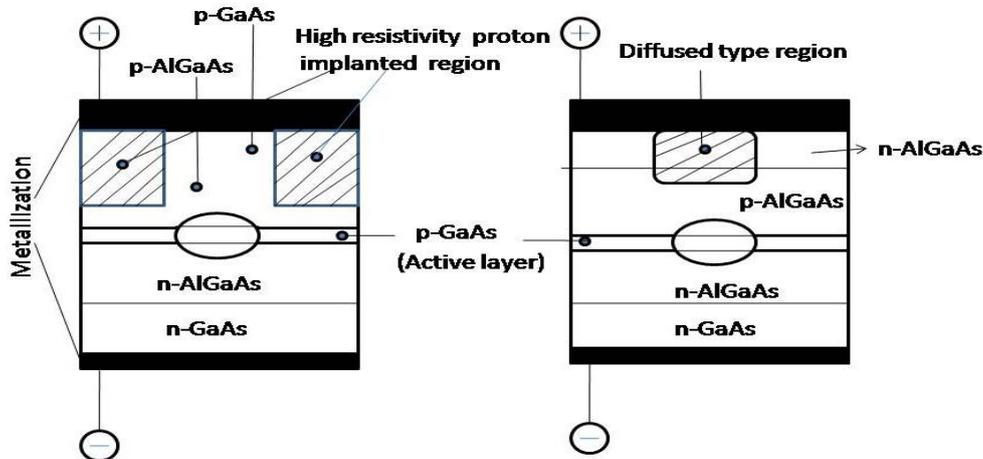

Fig.3.25 Gain guided injection laser

This *p-n* junction does not confine all the current and radiations in stripe region and spreading occurs out of stripe region. Such laser gives highly efficient coupling in multicode fibres but poor coupling efficiency in single mode fibres. The gain guided injection laser have relatively large threshold current 9100 to 150 mA) as well as low quantum efficiency. We may now consider output of two laser devices I and II as shown as Figure 3.26.
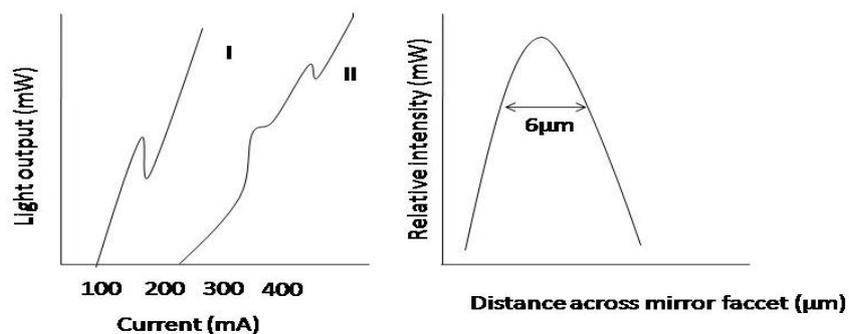

Fig.3.26 Output of laser devices

There are two kinks in the light output. First type of kink results from changes in the dominant mode lateral of the laser at the current changes. The lower order mode changes to higher order lateral modes due to increase in the current and thus changes the slope of curve II. The second type of kink involves a spike as seen in the characteristic of laser I. The sudden jurk and kink in the characteristic of laser I is due to filamentary behaviour within the active region when the current increase the filaments are formed in the active region due to increase in current from the defects within the crystal structure. It is thus necessary to reduce stripe width to less than 10 mm. In general, the stripe size of 6 mm, formed by a plannar process, allow the fundamental lateral mode to grow. However, it has been notice in gain guided laser that as the current increase, the non-linearties in the light output are seen.

(iii) Quantum Well Lasers

The size and thickness of active layer in double heterostructure laser is continuously decreased to attain better performance. The thickness of active layer is reduced from 0.1 to 0.3 mm to 10 nm. As a result of this reduction, dhe motion of carrier, normal to dhe active layer is thus restricted or we can say continuous kinetic energy is quantized into discrete energy levels for the carrier moving in that direction. In fact, a quantum well is created by the stripe of 10 ns which allows high gain at low carrier density due to above one-dimensional potential well and thus, it is possible to operate laser at lower threshold currents. This is called single quantum well laser (SQW) (Fig.3.27(a)). Similarl6y, many narrow stripes of 10 ns can be formed in the active layer which results into multiquantum well (MQW) laser device(Fig.3.27(b)).
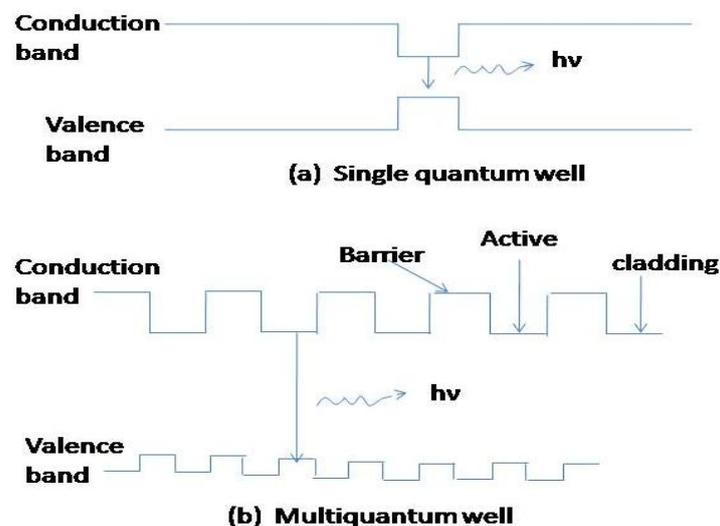

Fig.3.27 Energy band diagrams showing various types of quantum well structure

This has multiple active regions in a single laser device. The barrier layers separate these active narrow stripes. The end layer is called cladding layer which may have equal energy or higher energy. The higher cladding energy devices are called modified multiquantum well. It has been observed that due to multible active regions in MQW devices, there are better confinement of laser action besides operation of device at lower threshold current density. In A1GaAs/GaAs materials, the superior performance of MQW device is observed with respect to normal DH lasers, that is, lower threshold currents, narrow line widths, higher modulation speeds, lower temperature dependence and less frequency instability have been observed in MQW devices. Other materials like ZnGaAsP/InP are under investigation so that the wavelength range of quantum well laser increases to higher side in the infrared region as shown in Figure 3.27.

(iv) Index Guided Lasers

The disadvantages in terms of non-linearities, higher threshold current for laser action and kinks in laser output are overcome by the fabrication of index guided injection lasers. In the weak type index guiding structure, thickness of the active region waveguide is varied by

growing it over a channel or ridge in the substrate. The ridge acts as a narrow current confining stripe. These devices perform at low threshold current not provide stable power at low current besides producing single lateral mode at various wavelengths.

Development of strong index guiding injection lasers can provide improved transverse mode control. This can be achieved by using a buried heterostructure (BH) device in which the active volume is completely buried in a material of wider band gap and lower refractive index as shown in Figure 3.28
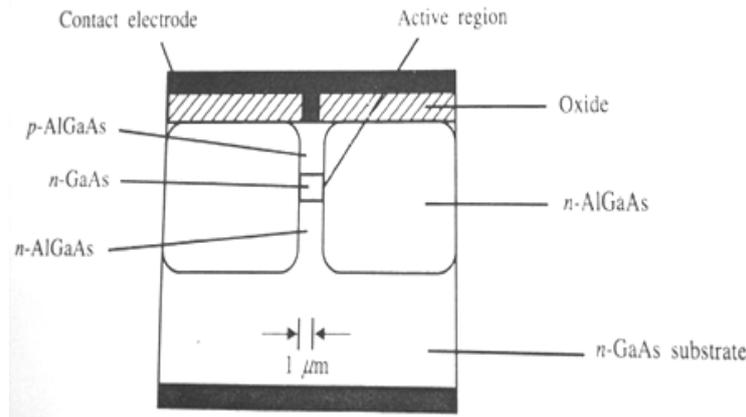

Fig.3.28 GaAs / AlGaAs buried heterostructure device

This device provides good carrier confinement besides strong index guiding of optical modes. The confinement of the injected current in the active laser layer is obtained through the reverse biased junction of the higher band gap materials. AlGaAs is used as low refractive index confinement material with GaAs for lasers at wavelength of 0.8 to 9 mm whereas InGaAsP along with InP is used in devices operating from 1.1 to 1.6 mm wavelength range.

Both multimode and single mode operation from large number of BH laser devices are made available commercially. In general, the lower threshold currents of 10 to 15 mA is possible due to lateral current confinement in the active layer which is much lower as compared to gain guided laser or weak index guided laser. A more complex device which is called double channel planar buried heterostructure laser is shown in Figure 3.29 .

In laser diode, narrow path regions for laser action are created either by zinc or cadmium diffusion into the *p*-type layer or proton bombardment or proton implantation can produce high resistance region and only small area in *p*-type material allows passage of current and produces small lasing region in the active layer. This small active lasing region can also be formed by inner stripe confinement. Alternately, bent layer structure may be formed by etching into the substrate by the technique of regrowth of back biased *p-n* junction which restricts the current on both sides of the channel.

In refractive index variation device, that is, index guided lasers, D_n-0.08 and active layer thickness <1 micron, it is possible to generate only one mode, that is, fundamental transverse mode. This laser provides very high power operation using InGaAsP active region with continuous wave (CW) output powers of up to 50 mW in the longer wavelength region whereas threshold currents at room temperature are very low in the range of 15 mA for wavelength of 1.3 mm and 1.5 mm
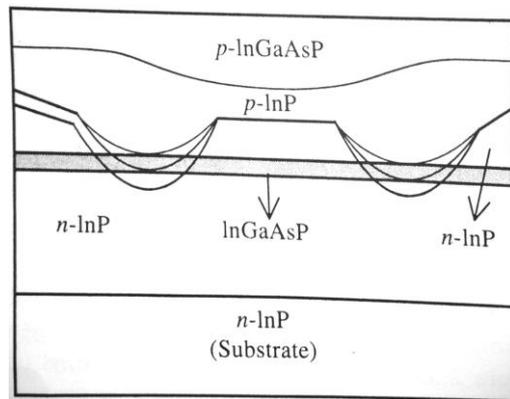
Fig.3.29 InGaAsP / InP double channel planar buried heterostructure device

(v) Single – frequency Injection Lasers

On the basic of mechanism used for controlling the longigudinal modes of a semiconductor laser, single-frequency injection lasers are categorized into following two categories :

(a). Distributed feedback lasers

(b). Coupled – cavity lasers

(a) Distributed Feedback lasers

These lasers are constructed using distributed Bragg diffraction grating which is fabricated inside the laser diode structure. These lasers have found widespread applications in single-frequency operation.

In the laser heterostructure waveguide, the diffraction grating provides periodic variation in refractive index along the direction of propagation of wave so that the feedback of optical energy is obtained through Bragg reflection and not by resonator cleaved mirrors. Figure 3.30 shows corrugated grating close to active layer which produces wavelength of longitudinal mode emission. When the period of corrugation is equal to $l\lambda B / 2ne$, where l is order of grating, λB is Bragg wavelength and n_e is the effective refractive index of waveguide, only wavelength equal to $B\lambda$ will interfere constructively and amplified. This particular mode will lase and higher order modes will suffer losses and do not oscillate. Thus, only single frequency wavelength will be emitted out.

There are two categories which use the mechanism of distributed feedback. These are:

1. Distributed feedback (DFB) laser
2. Distributed Bragg reflector (DBR) laser

In the DFB laser [see Figure 3.30(a)], the optical grating is usually applied over the entire active region which is pumped but in the DBR laser [Figure 3.30(b)], grating is constructed beyond the active layer, that is, towards both ends of the material due to which feedback does not occur in the central region where laser action is taking place. The advantage of keeping corrugated grating outside the active region is due to the fact that perturbed regions in the laser medium is separated out but is has proved lossy to some extent due to optical absorption in the distributed grating regions. The distributed grating at both the ends of active region acts as mirrors due to reflections at the selected wavelength. The grating

in the DFB laser is fabricated after etching into an appropriate cladding layer adjacent to the active layer and the grating period can be selected by desired emission frequency from the structure following the Bragg condition.
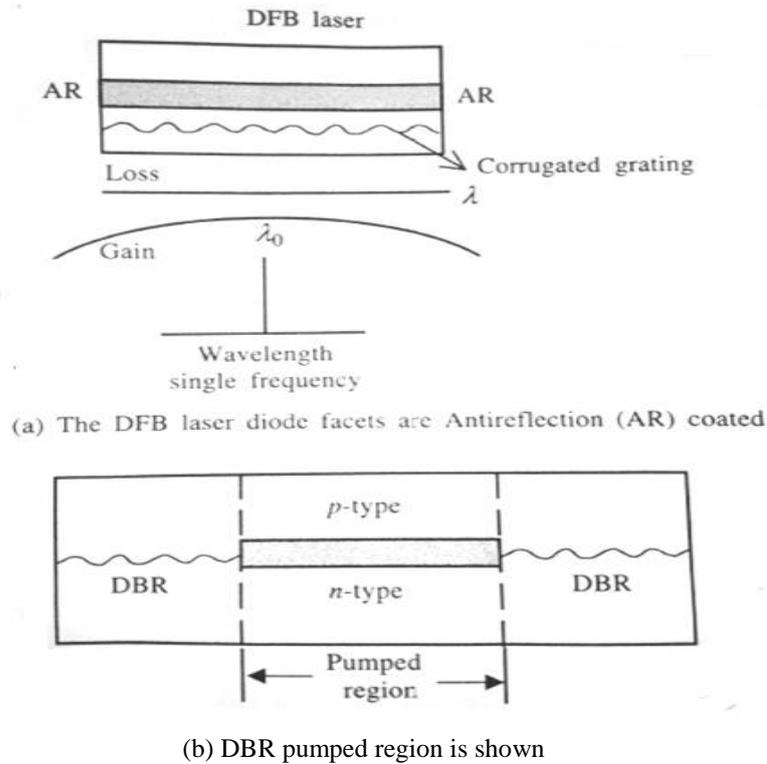

(a) The DFB laser diode facets are Antireflection (AR) coated

(b) DBR pumped region is shown

Fig.3.30 DFB laser diode

In view of extensive research work on DFB layers, buried heterostructure DFB lasers have been constructed with low threshold currents (10-20 mA), high modulation speeds (>100 Gb/s) and output power comparable with Fabry-Pero diode devices at the wavelength of 1.55 mm. High output is found to reduce as the temperature varies from 20°C to 110°C which shows that more input current is needed to produce light output at high temperature.

The facet asymmetry can be increased by placing a light reflection coating on one end facet and a low reflection coating on the other facet (known as high-low mirror structure). It improves the power output for single – frequency operation. Another technique to improve the performance of the DFB laser is to modify the grating at a central point to introduce an additional optical phase shift of $\lambda/4$ or less as shown in Figure 3.31. This is called buried heterostructrue DFB laser. This laser provides stable single frequency operation with $\lambda/4$ (quarter wavelength change) shift at the centre of laser cavity with both end facet coated with AR coating. Thus the phase shift will vary from $0 - \lambda/2$ and the lowest threshold gain is obtained at Bragg wavelength when phase shift is $\lambda/2$ and other wavelengths deviate maximum at this phase shift. The performance of quarter wavelength shifted DFB laser is superior to the conventional DFB structure.

It has been observed that the use of reverse biased current can give rise to parasitic capacitances at the junctions and thus restricting the high speed modulation capabilities of
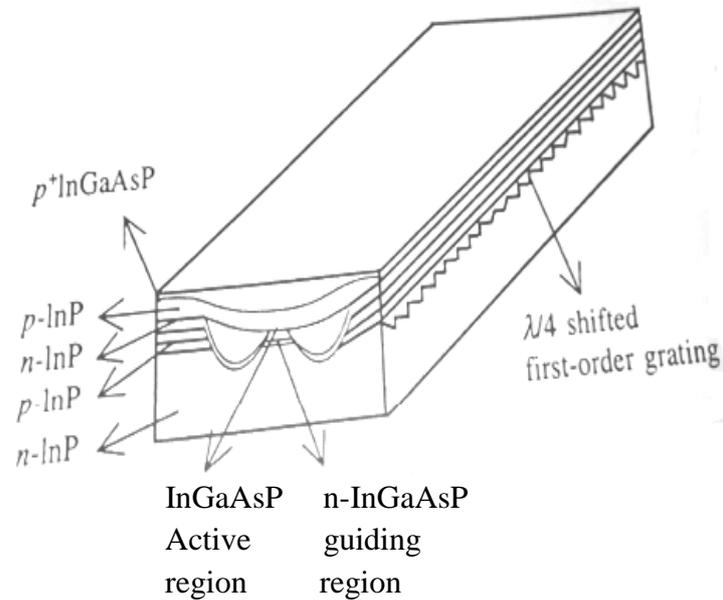
Fig.3.31   Quarter wavelength shifted double channel planar BH-DFB laser

BH lasers. However, this problem has been subsequently overcome either by the regrowth of semi-insulating material or the deposition of a dielectric material. Using these techniques, modulation speed in excess of 20 GHz have been achieved which are limited by the active region rather than the parasitic capacitances. Hence these laser diodes are frequently used in various guided laser communication over long distances

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Unit-IV

Optical Modulators and Detectors

4.1. Modulation of Light:

Modulation is the addition of information to an electronic or optical carrier signal. A carrier signal is one with a steady waveform -- constant height (amplitude) and frequency. Information can be added to the carrier by varying its amplitude, frequency, phase, polarization (for optical signals), and even quantum-level phenomena like spin. Modulation is usually applied to electromagnetic signals -- radio, lasers/optics and computer networks. Modulation can even be applied to direct current (which can be treated as a degenerate carrier wave with amplitude 0 and frequency 0) mainly by turning it on and off (as in Morse code telegraphy), or applied to alternating current (as with power-line networking).

Common modulation methods include the following:

Amplitude modulation (AM), in which the height (i.e., the strength or intensity) of the signal carrier is varied to represent the data being added to the signal. Frequency modulation (FM), in which the frequency of the carrier waveform is varied to reflect the frequency of the data. Phase modulation (PM), in which the frequency of the carrier waveform is varied to reflect changes in the frequency of the data (similar but not the same as FM). Polarization modulation, in which the angle of rotation of an optical carrier signal is varied to reflect transmitted data. Pulse-code modulation, in which an analog signal is sampled to derive a data stream that is used to modulate a digital carrier signal. Radio and television broadcasts and satellite radio typically use AM or FM. Most two-way radios use FM, although some employ a mode known as single sideband (SSB). More complex forms of modulation include phase-shift keying (PSK) and Quadrature Amplitude Modulation (QAM).

4.2. Anisotropy and Birefringence:

(i) **Anisotropy**: A difference in a physical property (absorbance, refractive index, density, etc) for a given material when measured along different axes. (As opposed to Isotropy, or homogeneity in all directions).

(ii) Birefringence: Property of some crystalline materials (e.g., calcite) where the anisotropy is exhibited as a change of refractive index between light rays vibrating in different planes. Another name for this is "Double Refraction". A subset of birefringence, when the anisotropy is wavelength dependent (a measure of dispersion), is called Dichroism. Literally "Two Colors", a dichroic material emits a plane polarized beam of light of a specific wavelength when impinged upon by a beam of white light. An example is the mineral Tourmaline that absorbs all wavelengths but green.

(iii) *Birefringence number(Δn)*: The numerical difference between the two refractive indices of a birefringent substance. For example Calcite has a Refractive index (o-ray) = 1.658 and RI (e-ray) = 1.486, so the birefringence number = 0.172. Birefringence numbers are diagnostic tools for identifying unknown substances.
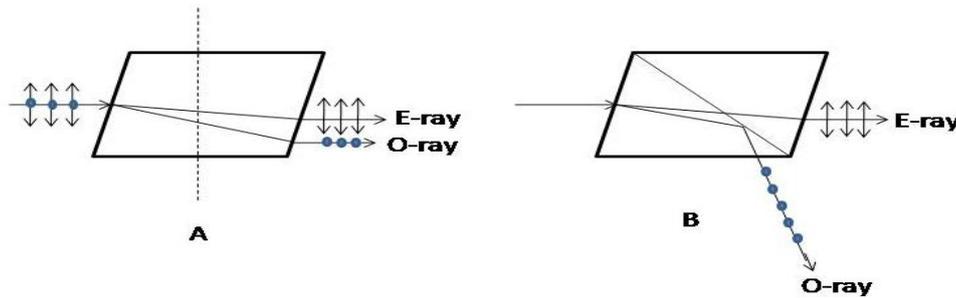

Fig.4.1 Birefringent crystal

A: When a beam of non-polarized light passes into a crystal of calcite the vibrational plane determines its velocity. Since refraction is a function of velocity, a beam of light will be decomposed into two beams that refract at different angles (Fig.4.1(A)). One plane of vibration will realize a higher refractive index and refract according to Snell's law. This is called the "Ordinary-Ray". Another beam, vibrating at right angles to the O-Ray, will realize an lower refractive index and bend at a lower angle. This beam is called the "Extraordinary-Ray", or E-Ray. Thus, two spatially separated rays will exit the birefringent object. The rays will be Plane Polarized, and will be vibrating orthogonal to each other. In addition, the slow ray will lag in phase relative to the fast ray. When they emerge from the birefringent crystal, they may interact via wave interference which results in the production of Interference Colors (depending on the optical path of the material). The colors directly relate to the wave Retardation. Below are refractive indices of the O- and E-rays of common birefringent materials.

Material	n_o	n_e	Δn
beryl $Be_3Al_2(SiO_3)_6$	1.602	1.557	-0.045
calcite $CaCO_3$	1.658	1.486	-0.172
calomel Hg_2Cl_2	1.973	2.656	+0.683
ice H_2O	1.309	1.313	+0.014
lithium niobate $LiNbO_3$	2.272	2.187	-0.085
magnesium fluoride MgF_2	1.380	1.385	+0.006
quartz SiO_2	1.544	1.553	+0.009
ruby Al_2O_3	1.770	1.762	-0.008
rutile TiO_2	2.616	2.903	+0.287
peridot $(Mg, Fe)2SiO4$	1.690	1.654	-0.036
sapphire Al_2O_3	1.768	1.760	-0.008
sodium nitrate $NaNO_3$	1.587	1.336	-0.251
tourmaline (complex silicate)	1.669	1.638	-0.031
zircon, high $ZrSiO_4$	1.960	2.015	+0.055
zircon, low $ZrSiO_4$	1.920	1.967	+0.047

B: Creating a beam of plane polarized light- The Nicol Prism. The first device used to produce a beam of polarized light was invented by William Nicol (1770–1851). It consists of a piece of calcite, rhombohedral in shape, and cut at 68° (a, above). The crystal is then bisected, one half inverted and glued back onto the first half. Canada Balsam (n=1.555) was used originally to glue the two halves together. When non-polarized light impinges on the crystal, the resulting slow, or O-Ray bends at an angle that results in total reflection at the interface between the two halves. The faster, less refracted E-ray passes through the interface and exits the opposite end of the crystal as a beam of plane polarized light. Modern polarizers are made of iodine crystals embedded in a plastic (PVA) sheet ("H-Sheet"). When the sheet is stretched, the crystals align. This Polaroid Filter produces plane polarized light in a manner similar to the Nicol prism. Light that vibrates perpendicular to the crystal orientation pass through the sheet. Light that vibrates parallel to the crystals interacts with the atomic structure of the crystals and is absorbed(Fig.4.1(b)).

(iv) Common birefringent materials: The best-characterized birefringent materials are crystals. Due to their specific crystal structures their refractive indices are well defined. Depending on the symmetry of a crystal structure, crystals in that group may be forced to be isotropic (not birefringent), to have uniaxial symmetry, or neither in which case it is a biaxial crystal.

Many plastics are birefringent, because their molecules are 'frozen' in a stretched conformation when the plastic is molded or extruded. For example, ordinary cellophane is birefringent.

Polarizers are routinely used to detect stress in plastics such as polystyrene and polycarbonate.

Cotton fiber is birefringent because of high levels of cellulosic material in the fiber's secondary cell wall.

Polarized light microscopy is commonly used in biological tissue, as many biological materials are birefringent. Collagen, found in cartilage, tendon, bone, corneas, and several other areas in the body, is birefringent and commonly studied with polarized light microscopy. Some proteins are also birefringent, exhibiting form birefringence.

Inevitable manufacturing imperfections in optical fiber leads to birefringence which is one cause of pulse broadening in fiber-optic communications. Such imperfections can be geometrical (lack of circular symmetry), due to stress applied to the optical fiber, and/or due to bending of the fiber. Birefringence is intentionally introduced (for instance, by making the cross-section elliptical) in order to produce polarization-maintaining optical fibers.

In addition to anisotropy in the electric polarizability (electric susceptibility), anisotropy in the magnetic polarizability (magnetic permeability) can also cause birefringence. However at optical frequencies, values of magnetic permeability for natural materials are not measurably different from μ_0 so this is not a source of optical birefringence in practice.

(v) Applications: Birefringence is used in many optical devices. Liquid crystal displays, the most common sort of flat panel display, cause their pixels to become lighter or darker through rotation of the polarization (circular birefringence) of linearly polarized light as viewed

through a sheet polarizer at the screen's surface. Similarly, light modulators modulate the intensity of light through electrically induced birefringence of polarized light followed by a polarizer. The Lyot filter is a specialized narrowband spectral filter employing the wavelength dependence of birefringence. Wave plates are thin birefringent sheets widely used in certain optical equipment for modifying the polarization state of light passing through it.

Birefringence also plays an important role in second harmonic generation and other nonlinear optical components, as the crystals used for this purpose are almost always birefringent. By adjusting the angle of incidence, the effective refractive index of the extraordinary ray can be tuned in order to achieve phase matching which is required for efficient operation of these devices.

Medicine: Birefringence is utilized in medical diagnostics. One powerful accessory used with optical microscopes is a pair of crossed polarizing filters. Light from the source is polarized in the X direction after passing through the first polarizer, but above the specimen is a polarizer (a so-called analyzer) oriented in the Y direction. Therefore, no light from the source will be accepted by the analyzer, and the field will appear dark. However areas of the sample possessing birefringence will generally couple some of the X polarized light into the Y polarization; these areas will then appear bright against the dark background. Modifications to this basic principle can differentiate between positive and negative birefringence. Urate crystals, with the crystals with their long axis seen as horizontal in this view being parallel to that of a red compensator filter. These appear as yellow, and are thereby of negative birefringence.

In ophthalmology, binocular retinal birefringence screening of the Henle fibers provides a reliable detection of strabismus and possibly also of anisometropic amblyopia. Furthermore, scanning laser polarimetry utilises the birefringence of the optic nerve fibre layer to indirectly quantify its thickness, which is of use in the assessment and monitoring of glaucoma.

Birefringence characteristics in sperm heads allow for the selection of spermatozoa for intracytoplasmic sperm injection. Likewise, zona imaging uses birefringence on oocytes to select the ones with highest chances of successful pregnancy. Birefringence of particles biopsied from pulmonary nodules indicates silicosis. Dermatologists use dermatascopes to view pigmented lesions and nevi. Dermatascopes use cross-polarized light, allowing the user to view chrystaline structures corresponding to dermal collagen in the skin. These structures may appear as shiny white lines or rosette shapes, and are only visible under polarized dermoscopy.

Stress induced birefringence:

Isotropic solids do not exhibit birefringence. However, when they are under mechanical stress, birefringence results. The stress can be applied externally or is "frozen in" after a birefringent plastic ware is cooled after it is manufactured using injection molding. When such a sample is placed between two crossed polarizers, colour patterns can be observed, because polarization of a light ray is rotated after passing through a birefingent material and

the amount of rotation is dependent on wavelength. The experimental method called photoelasticity used for analyzing stress distribution in solids is based on the same principle.

Other cases of birefringence:

Birefringence is observed in anisotropic elastic materials. In these materials, the two polarizations split according to their effective refractive indices which are also sensitive to stress. The study of birefringence in shear waves traveling through the solid earth (the earth's liquid core does not support shear waves) is widely used in seismology. Birefringence is widely used in mineralogy to identify rocks, minerals, and gemstones.

4.3 Electro-optic effect:

An electro-optic (EO) effect is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light. The term encompasses a number of distinct phenomena, which can be subdivided into

a) change of the absorption:

(i) . *Electroabsorption:* general change of the absorption constants

(ii) *Franz-Keldysh effect*: change in the absorption shown in some bulk semiconductors

(iii) *Quantum-confined Stark effect*: change in the absorption in some semiconductor quantum wells

(iv) *Electrochromic effect*: creation of an absorption band at some wavelengths, which gives rise to a change in colour

(b) change of the refractive index and permittivity:

(i) *Pockels effect* (or linear electro-optic effect): change in the refractive index linearly proportional to the electric field. Only certain crystalline solids show the Pockels effect, as it requires lack of inversion symmetry

(ii) *Kerr effect* (or quadratic electro-optic effect, QEO effect): change in the refractive index proportional to the square of the electric field. All materials display the Kerr effect, with varying magnitudes, but it is generally much weaker than the Pockels effect

(iii).*electro-gyration*: change in the optical activity.

(iv) Electron-refractive effect or EIPM

4.4 EO Material:

An important criterion for an electro-optic material is the half-wave voltage which, as its name implies is the voltage necessary to produce a retardation of half wavelength between the ordinary and extraordinary rays. Table 4.1 tabulates the half-wave voltages for a number of materials.

TABLE 4.1 Some Electro-optic Materials

Materials	Chemical formula	Electro–optic const. $(\mu m/V)$	Half-wave voltage
Ammonium dihydrogen phosphate (ADP)	$NH_4H_2PO_4$	24.5×10^{-6}	10600
Potassium dihydrogen phosphate (KDP)	KH_2PO_4	10.5×10^{-6}	8000
Potassium dideuterium phosphate (KDP)	KD_2PO_4	26.4×10^{-6}	3000
Quartz	SiO_2	0.2×10^{-6}	30000
Lithium tantalite	$LiTaO_3$	21.7×10^{-6}	2500
Lithium niobate	$LiNbO_3$	18.0×10^{-6}	2900
Barium strontium niobate	$Sr_{0.75}Ba_{0.25}Nb_2O_6$	1380	50
Barium sodium niobate	$Ba_2NaNb_5O_{15}$	-	1500
Lithium potassium niobate	$K_6Li_4NbO_3$	-	930
Strontium potassium niobate	$KSr_2Nb_5O_{15}$	130	400
Hexamine	$(CH_2)_6N_4$	4.18×10^{-6}	14900
Potassium tantalum niobate (KTN)	$KTa_{0.65}NB_{0.35}O_3$		300
Zinc telluride	ZnTe		2700
Cuprous chloride	CuC1	6.1×10^{-6}	7200
Zinc sulphide	ZnS	$2 \text{ x} \times 10^{-6}$	10400
Zinc selenide	ZnSe	1.6×10^{-6}	7100
Barium titanate	$BaTio_3$	10^{-4}	7160

4.5 The Kerr Effect

When a material is under the action of an electric field, an optic axis may be induced parallel to the direction of the field. This effect is known as the Kerr effect an occurs in all of the 32 types of crystal classes. An optic axis may be defined as *the direction in a crystal in which when light is propagated in the same direction, the refractive index is independent of the direction of polarization of the light.*

Some crystals are naturally birefringent, i.e., they have a naturally occurring optic axis. In fact most naturally birefringent crystals have two optic axes and, are therefore, called biaxial.

In the Kerr effect, the applied electric field produces an optic axis, or an additional optic axis in the case of crystals which are already uniaxial or biaxial. The amount of phase retardation between the ordinary and extraordinary components is, among other things, proportional to the square of the applied voltage. Consequently the Kerr effect is also known as the quardratic electro-optic effect

Figure 4.2 shows a voltage V being applied to electrodes of separation d fixed to the faces of a crystal. The length of the crystal through which the light propagates is l. The phase retardation produced is given by

$$\Delta\phi = \frac{2\pi k l V^2 \lambda}{d^2}$$
(4.1)

Where k is the Kerr coefficient and λ is the wavelength of light used. V is in esu volts (1 esu volt = 300 volts).

The Kerr constant for most crystals is very small. However, for nitrobenzene the coefficient has a value of 220 which is sufficiently high to be utilized for electro-optic devices. Nitrobenzene must be extremely pure to maintain a high Kerr coefficient. As it is also toxic and unstable most electro-optic devices used in conjunction with laser make use of the Pockels effect which occurs in sufficient magnitude in more satisfactory materials.
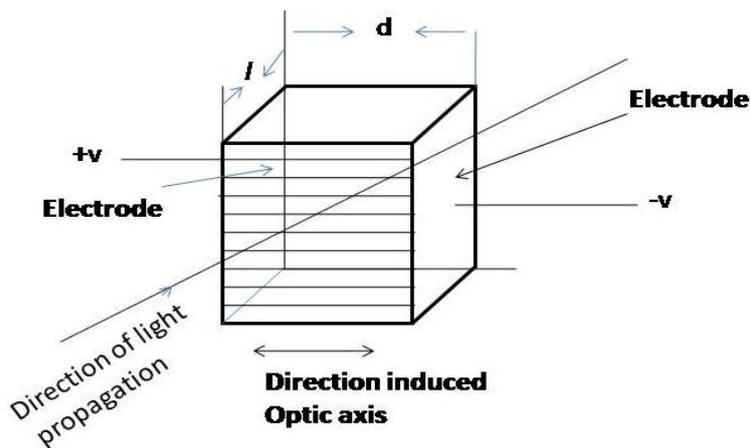

Fig.4.2 The Kerr effect

4.6 Kerr Modulators

Many isotropic media, both solids and liquids, when placed in an electric field behave as uniaxial crystal with the optic axis parallel to the electric field. In this opto-electric effect, which was discovered in glass by J.Kerr (1875), the change in refractive index is proportional to the square of the applied field. The difference in refractive indices for light polarized parallel to and perpendicular to the induced optic axis is given by

$$\Delta n = n_p - n_s = K\lambda E^2$$
(4.2)

Where K is the Kerr constant and λ is the vacuum wavelength.

The electric field induces and electric moment in non-polar molecules and changes the moment of polar molecules. There is then a reorientation of the molecules by the field which

causes the medium as a whole to become anisotropic. This explains the delay that occurs between the application of the field and the appearance of the maximum effect. The delay can be several seconds but for non-polar liquids the delay is very small and probably less than 10^{-11} Hz has been obtained.

Although liquid Kerr cells containing nitrobenzene have been used extensively for many years, for example, in the accurate measurement of the velocity of light, they suffer from the disadvantages of requiring a large power to operate them. A more promising approach is to use mixed ferroelectric crystals operating at a temperature near to the Curie points where a greatly enhanced opto-electric effect is observed. (Ferroelectric of ferromagnetic materials, below a certain temperature. This is the Curie point, above with the crystal structure changes and the ferroelectricity disappears), Potassium tantalite niobate (KTN), which is used in Kerr-effect devices, is a mixture of two crystals with high and low Curie points giving a Curie point for the mixture near to room temperature. The crystal has to be 'poled' by the application of a large bias voltage. This has the effect of causing the ferroelectric domains with electric polarization in the direction of the applied field to grow at the expense of the other domains until the whole crystal is polarized in one direction. This then reduces the ac voltage required for 100% modulation to about 50 V peak and the half-wave voltage is very much less than for other materials, being about 250 V in KTN and barium titanate ($BaTiO_3$). Nevertheless, most practical electro-optic modulators make used of the Pockels effect.

4.7 Scaning and Switching : We saw that the application of a voltage V_π to a Pockels cell with in effect rotate the plane of polarization of the transmitted optical beam through 90°. Thus if a block of birefringent material is placed after the cell, the beam can be switched from one position to another as shows in Fig. 4.3. An array of m such combinations in sequence can obviously be used to address 2^m different locations. Such a system may be used, for example, in bit-oriented optical memories.
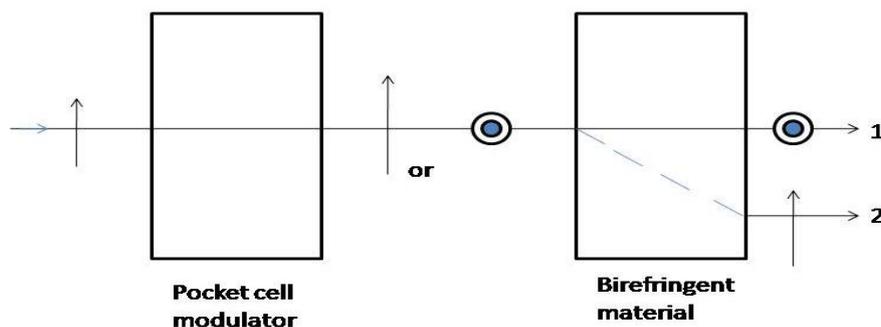

Fig. 4.3 Beam switching using a Pockels cell modulator. As the applied voltage is changed from zero to V_π the beam is switched from position 1 to position 2.

Alternatively the arrangement shown in Figure (4.4(a)) can be used for beam switching. Here we have two similar prisms of KDP, for example, but with opposite orientations. Thus, if an electric field is applied in the z-direction and the optical beam travels in the direction of one of the induced principal axes with its polarization parallel to the other principal axis then the beam will 'see' different refractive indices in the two prisms. The difference in refractive

indices will be $n_0^3 r E_z$, we see that a ray entirely in the upper prism travels in a medium of refractive index.

$$n_2 =_0 - \frac{n_0^3}{2} r E_z,$$ (4.3)

While a ray entirely in the lower prism travels in a medium where the effect of the applied field is reversed so that

$$n_2 =_0 + \frac{n_0^3}{2} r E_z,$$ (4.4)

We can see that this arrangement leads to a deflection of the beam by considering Fig. (4.4(b)). Here we show a crystal whose refractive index and hence optical path length varies with the transverse distance x across the crystal. If we assume that the variation of n with x is uniform then ray 1 'sees' a refractive index x while ray 2 'sees' a refractive index n while ray 'sees' an index $n+\Delta n$. The rays 1 and 2 will traverse the crystal in time t_1 and t_2 where

$$t_1 = L_n / c \text{ and } t_2 = L(n + \Delta n) / c$$ (4.5)

The difference is transit time results in ray 2 lagging behind ray 1 by a distance $\Delta y = L\Delta n / n$; this is equivalent to a deflection of the wavefront by an angle θ' measured inside the crystal just before the beam emerges. We can see from Fgiure (4.4(b)) that $\theta' = \Delta y / W$, where W is the width of the crystal.
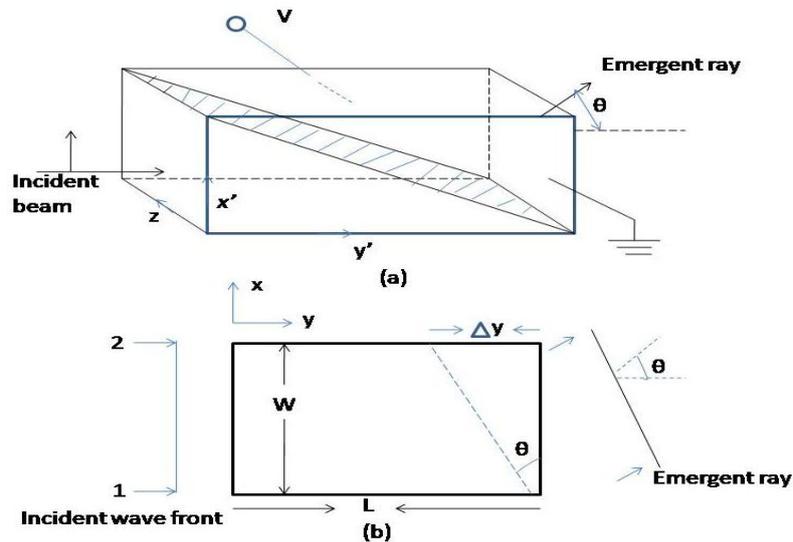

Fig 4.4 Schematic diagram of a beam deflector : (a) the double –prism KDP beam deflector and (b) the principle of defelction beam in a medium where the refractive index varies linearly in a direction normal to the direction of propagation.

Using Snell's law, the angle of beam direction θ measured outside the crystal is given by

(assuming θ issmall)

$$\theta = n\theta' = n\frac{\Delta y}{W}, \qquad \text{Where} \quad \theta' = \frac{\Delta y}{W}, \qquad \text{from Figure (4.3)}$$

(Or) $$\theta = \frac{L\Delta n}{W}, \qquad as \quad \frac{n}{\Delta n} = \frac{L}{\Delta y}$$

Thus, using the arrangement shown in Figure (4.4(a)) the deflection θ is given by

$$\theta = (L/W)n_0^3 r\, E_z, \tag{4.6}$$

Light beams can also be deflected by means of diffraction gratings which are electro-optically induced in a crystal by evaporating a periodic metallic grating electrode onto the crystal. A voltage applied to this electrode induces a periodic variation in the refractive index thereby creating an efficient phase diffraction grating. This technique is especially usefull in the integrated optical devices. Beam deflectors and scanners are used in laser displays, printers and scribers, for optical data storage systems and in optical character recognition.

4.8 Magneto – Optic (MO) devices :

The presence of magnetic field may also effect the optical properties of some substances thereby giving rise to a number of useful devices. In general, however, as electric fields are easier to generate than magnetic fields, electro-optic devices are usually preferred to magneto-optic devices.

(i) Faraday Effect

This is the simplest magneto-optic effect and the only one of real interest for optical modulators; it concerns the change in refractive index of a material subjected to a steady magnetic field. Faraday (1845) found that when a beam of plane polarized light passes through a substance subjected to a magnetic field, its plane of polarization is observed to rotate by an amount proportional to the magnetic field components parallel to the direction of propagation. This is very similar to optical activity which results from certain materials having different refractive indices n_r and n_l for light and left circularly polarized light. There is one important difference in the two effects. In the Faraday effect the sense of rotation of the plane of polarization is independent of the direction of propagation. This is in contrast to optical activity where the sense of rotation is related to the direction of propagation. Thus, in the case under discussion, the rotation can be doubled by reflecting the light back through the Faraday effect device.

The rotation of the plane of polarization is given by

$$\theta = VBL \tag{4.6}$$

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Where V is the Verdet constant, B is the magnetic flux parallel to the direction of propagation and L is the path length in the material. The Faraday effect is small and wavelength dependent: the rotation for dense flint glass is $\theta \approx 1.6° \, mm^{-1} \, T^{-1}$ at $\lambda = 589.3nm$. We can also express θ in terms of the refractive indices n_r and n_1 i.e.,

$$\theta = \frac{2\pi}{\lambda}(n_r - n_1)L$$

(4.7)

A Faraday rotator used in conjunction with a pair of polarizers acts as an optical isolator which allows a light beam to travel through it in one direction but not in the opposite one. It may therefore be used in laser amplifying chains to eliminate reflected, backward travelling waves, which are potentially damaging. The construction of a typical isolator is shown in Fig.4.5. Light passing from left to right is polarized in the vertical plane by polarizer P_1. The Faraday rotator is adjusted to produce a rotation of 45° in the clockwise sense. The second Polarizer P_2 is set at 45° to P_1 so that it will transmit light emerging from the rotator. However, a beam entering from the right will be plane polarized at 45° to the vertical by P_2 and then have its plane rotated by 45° in the clockwise sense by the rotator. It will therefore be incident on P_1 with its plane of polarization at right angles to the plane of transmission and be eliminated. The device thus isolates the components on its left from light incident from the light.
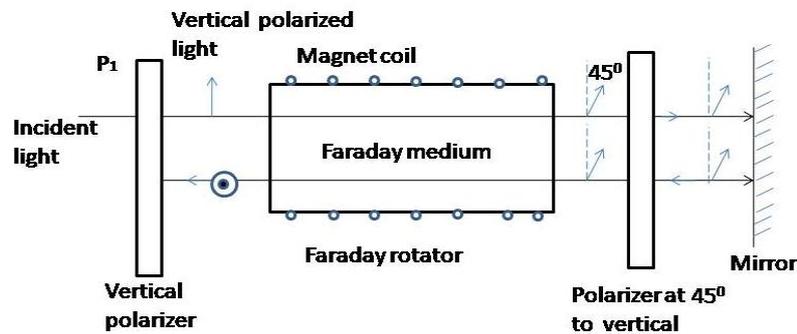

Fig. 4.5: Optical isolator based on the Faraday effect. The reflected ray is shown displaced for clarity.

One potential application of magneto-optics currently receiving attention is large capacity computer memories. Such memories must be capable of storing very large amounts of information in a relatively small area and permit very rapid readout and, preferably, random access. The usual magnetic memories have a number of limitations of size and reading speed. Optical techniques can overcome both these constraints.

The magneto-optic memories developed so far are read via the Faraday effect or the magnetic Kerr effect, which relates to the rotation of a beam of plane polarized light reflected from the surface of a material subjected to a magnetic field. In either case a magnetized ferro- or ferromagnetic material rotates the plane of polarization of laser light incident on it.

4.9 Acousto – Optic (AO) effect

The acousto – optic effect is the change in the refractive index of a medium caused by the mechanical strains accompanying the passage of an acoustic (strain) wave through the medium. The strain and hence the refractive index varies periodically with a wavelength λ equal to that of the acoustic wave. The refractive index changes are caused by the photoelastic effect which occurs in all materials on the application of a mechanical stress. It can be shown that the change in refractive index is proportional to the square root of the total acoustic power.

In general, the relationships between changes of refractive index and mechanical strain, and between the strain and stress are rather complicated. However, for simplicity we can consider the case of a monochromatic light wave, wavelength λ, incident upon a medium in which an acoustic wave has produced sinusoidal variations of wavelength Λ in the refractive index. The situation is shown in Figure 4.5 where the solid horizontal lines represent acoustic wave peaks (pressure maxima) and the dashed horizontal lines represent acoustic wave peaks (pressure maxima). As the light enters the medium, the portions of the wavefront near to a pressure peak will encounter a higher refractive index and, therefore, advance with a lower velocity than those portions of the wavefront which encounter pressure minima. The wavefront in the midum therefore soon acquires the wavy appearance shown by the dashed curve in Fig. 4.6. The acoustic wave velocity is very much less than the light wave velocity, so we may ignore it and consider the variation in refractice index to be stationary in the medium.As elements of the light wave propagate in a direction normal to the local wavefront, almost all the wave elements will suffer a change in direction leading to a re-distribution of the light flux, which tends to concentrate near regions of compression. In effect, the acoustic wave sets up a diffraction grating within the medium so that the optical energy is diffracted out of the incident beam into the various orders. There are two main cases of interest, namely (a) the Raman-Nath regime and (b) the Bragg regime.
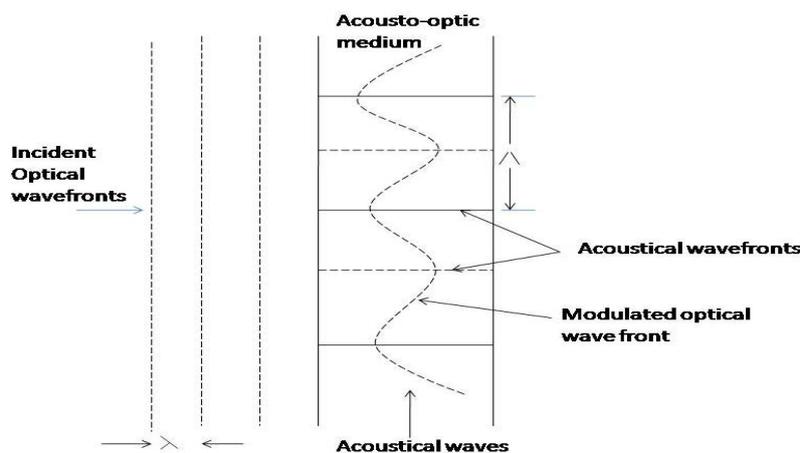

Fig. 4.6 Schematic illustration of acousto – optic modulation. The acoustic waves change the refractive index of the medium in a periodic way so that the plane optical wavefronts take on the 'wavy' appearance shown (very much exaggerated) as they propagate through the medium.

In the Raman-Nath regime, the acoustic diffraction grating is so 'thin' that the diffracted light suffer no further redistribution before leaving the modulator. The light is diffracted as from a simple place grating such that

$$m\lambda_0 = \Lambda \sin\theta_m \qquad (4.8)$$

where $m = 0, \pm 1, \pm 2, ...,$ is the order and θ_m is the corresponding angle of diffraction, as illustrated in Figure 4.7.

The irradiance I of the light in these orders depends on the 'ruling depth' of the acoustic grating, which is related to the amplitude of the acoustic grating. This, in turn, is related to the amplitude of the acoustic modulating wave (that is, the stress produced). The fraction of light removed from the zero order beam is $\eta = (I_0 - I)/I_0$, where I_0 is the transmitted irradiance in the absence of the acoustic wave. Thus amplitude variations of the acoustic wave are transformed into irradiance variations of the optical beam.
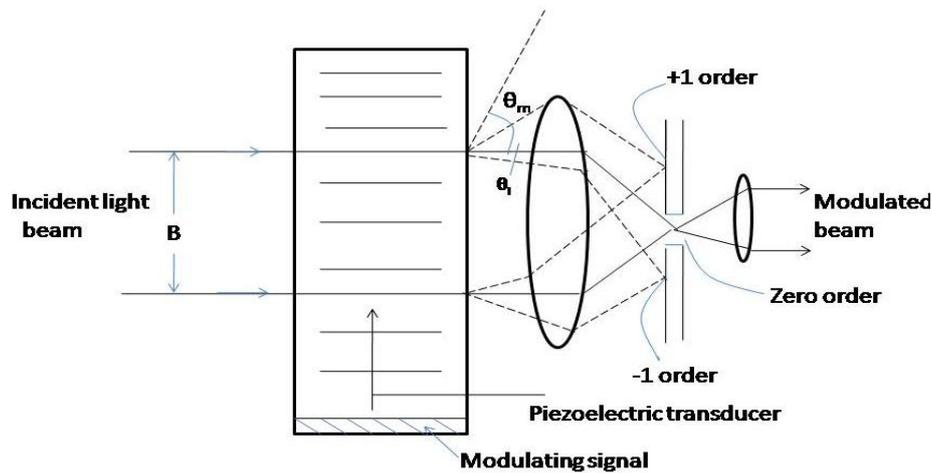

Fig 4.7 Geometry for Raman-Nath (or transmission-type) acousto-optic diffraction grating modulation. The amount of light diffracted into the orders $m \geq 1$ from the incident beam, and hence the modulation of the transmitted beam, depends on the amplitude of the modulating signal.

The physical basis of the Bragg regime is that the light diffracted from the incident beam is extensively re-diffracted before leaving the acoustic field. Under these conditions, the acoustic field acts very much like a 'thick' diffraction grating, that is, a grating made up of planes rather than lines. The situation is then very similar so that of Bragg diffraction (or ' reflection') of X-rays from planes of atoms in a crystal. Consider a plane wavefront incident on the grating planes at an angle of incidence θ_i as shown in Figure 4.8(a); significant amounts of light will emerge only in those directions in which constructive occurs. The conditions to be satisfied are : (a) light scattered from a given grating plane must arrive in phase at the new wavefront and (b) light scattered from successive grating planes must also arrive in phase at the new wavefront, implying that the path difference must be an integral

number of wavelengths. The first of these conditions is satisfied when $\theta_d = \theta_i$, where θ_d is the angle of diffraction. The second condition requires that

$$\sin\theta_i + \sin\theta_d = \frac{m\lambda}{\Lambda}$$

with $m = 0,1,2,........$, the two conditions are simultaneously fulfilled when

$$\sin\theta_i + \sin\theta_d = \frac{m\lambda}{2\Lambda} \tag{4.9}$$

The diffraction is similar to that obtained with a plane grating but only for special angles of incidence; the angle of incidence must equal the angle of diffraction.

Although in the simplified theory given above, strong scattering can take place when m is equal to any positive integer, a more rigorous treatment, taking into account the fact that scattering is not from discrete planes but from a continuous medium, shows that scattering only takes place when $m = 1$. This is shown in Figure 4.8(b), the equation for the so-called Bragg angle θ_B then becomes $\sin\theta_B = \lambda/2\Lambda$. The modulation depth $(I_0 - I)/I_0$ (or diffraction efficiency, η) in this.
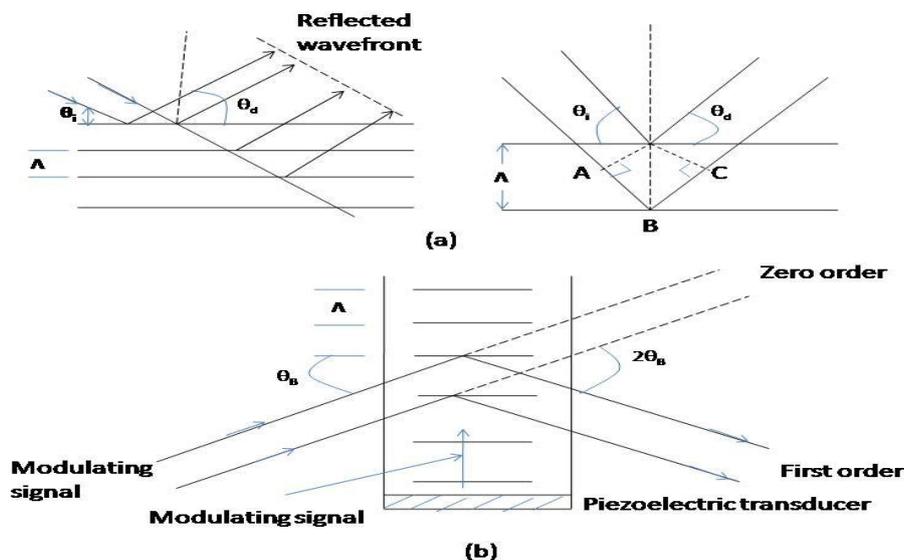
Fig. 4.8. Geometry for Bragg (or reflection-type) acousto-optic diffraction grating modulation : (a) incident rays being scattered from successive layers – for constructive interference the path difference AB + BC must equal an integral number of wavelengths $m\lambda$ and (b) the amount of light 'reflected' into the first order depends on the amplitude of the modulation signal.

case can theoretically equal 100% in contrast to about 34% for the Raman-Nath case. At the Bragg angle, it is given by $\eta = \sin^2\varphi 2$, where $\varphi = (2\pi/\lambda)X(\Delta L/\cos\theta_B)\Delta n$ being the amplitude of the refractive index fluctuation and L the length of the modulator

The acoustic waves, which create the diffraction grating, are of course moving through the medium and, as a consequence, the diffracted wave behaves as if it had been reflected from a 'mirror' moving with the same velocity as the grating and, therefore, appears to originate from a source moving at twice the mirror (or grating) velocity. Thus the frequency of the reflected beam is changed by the Doppler effect and is given by

$$v' = v_0 \left[1 \pm 2\upsilon_a (c/n) \right]$$

where $\pm v_a$ is the component of the velocity of the acoustic wave along (or a way from) the original beam direction and n is the medium refractive index. The frequency shift is :

$$\Delta v = v' - v_0 = \frac{\pm 2 v_0 \upsilon_a n}{c}$$

If the light is incident at an angle $\theta_i = \theta_D$ to the acoustic wave as shown in Figure 4.7(a) then is the acoustic wave velocity. The frequency shift is then

$$\Delta v = \frac{\pm 2 v_0 \upsilon_a \sin\theta_d n}{c} \tag{4.10}$$

Combining Eqs. (4.9) and (4.10) and taking $m = 1$ gives a frequency shift of $\pm \upsilon_a / \Lambda \, or \pm f_0$, where f_0 is the acoustic wave frequency. This change in frequency can be used as the basis of a frequency modulator.

The minimum time required to move from a condition where the acoustic wave interacts with the light beam and 'turns off' the undiffracted light to a condition where there is no diffraction is the transit time of the acoustic wave across the optical beam. This is simply, from Figure 4.8, $t_{min} = B/\upsilon_a$, where B is the optical beamwidth. Hence, the bandwidth of the modulator is limited about υ_a / B. Commercial modulators have bandwidths of up to 50 MHz. This limitation is partly due to the frequency dependence of the acoustic losses of available acousto-optic materials. At the present time only $LiNbO_3$ and $PbMoO_4$ appear to have sufficiently low loss to have a reasonable prospect of being operated at appreciably higher frequencies.

Acousto-optic modulators can in general be used for similar applications to electro-optic modulators, though they are not so fast. On the other hand, because the electro-optic effect usually requires voltages in the kilovolt range, the drive circuitry for modulators based on this effect is much more expensive than for acousto-optic modulators, which operate with a few volts.

4.10 Photodetector:

Photosensors or photodetectors are sensors of light or other electromagnetic energy. A photo detector converts light signals that hit the junction into voltage or current. The connection uses an illumination window with an anti-reflect coating to absorb the light

photons. This results in creation of electron-hole pairs in the depletion region. Photodiodes and photo transistors are few examples of photo detectors. Solar cells are also similar to photo detectors as they absorb light and turn it into energy.

(i) Types: Photodetectors may be classified by their mechanism for detection:

   (i) Photoemission: Photons cause electrons to transition from the conduction band of a material to free electrons in a vacuum or gas.

   (ii)   *Photoelectric*: Photons cause electrons to transition from the valence band to the conduction band of a semiconductor.

   (iii) *Photovoltaic:* Photons cause a voltage to develop across a depletion region of a photovoltaic cell.

   (iv) Thermal: Photons cause electrons to transition to mid-gap states then decay back to lower bands, inducing phonon generation and thus heat.

   (v) *Polarization:* Photons induce changes in polarization states of suitable materials, which may lead to change in index of refraction or other polarization effects.

   (vi) Photochemical: Photons induce a chemical change in a material.

   (vii) *Weak interaction effects*: photons induce secondary effects such as in photon drag detectors or gas pressure changes in Golay cells.

   Photodetectors may be used in different configurations. Single sensors may detect overall light levels. A 1-D array of photodetectors, as in a spectrophotometer or a Line scanner, may be used to measure the distribution of light along a line. A 2-D array of photodetectors may be used as an image sensor to form images from the pattern of light before it.

(ii) Properties: There are a number of performance metrics, also called figures of merit, by which photodetectors are characterized and compared

   (i) Spectral response: The response of a photodetector as a function of photon frequency.

   (ii) Quantum efficiency: The number of carriers (electrons or holes) generated per photon.

   (iii)Responsivity: The output current divided by total light power falling upon the photodetector.

   (iv) Noise-equivalent power: The amount of light power needed to generate a signal comparable in size to the noise of the device.

   (v) Detectivity: The square root of the detector area divided by the noise equivalent power.

   (vi) Gain: The output current of a photodetector divided by the current directly produced by the photons incident on the detectors, i.e., the built-in current gain.

   (vii) Dark current: The current flowing through a photodetector even in the absence of light.

   (viii) Response time: The time needed for a photodetector to go from 10% to 90% of final output.

(ix) Noise spectrum: The intrinsic noise voltage or current as a function of frequency. This can be represented in the form of a noise spectral density.

4.11 Thermal Detectors: A thermal detector absorbs radiation and changes temperature. Because the power in absorbed radiation is typically rather small ($<10^{-7}$ W), the detector itself should be small so that it has a low heat capacity.

A *thermocoupl*e is the joining of two dissimilar-metal or metal alloy wires or films. When this occurs, a potential difference is formed between the other ends of the metals. Since potential differences are temperature-dependent (called the Seebeck effect), temperature values or changes in temperatures can be determined by calibration

A *bolometer* is a semiconductor or thin metal strip whose resistance decreases with temperature. They are small, and typically painted black to better absorb radiation.

A *Golay detector* is a small pneumatic chamber filled with gas and covered with a thin membrane. When radiation strikes the detector, the gas warms, increasing the internal pressure and deforming the membrane. Deflection of the membrane can be measured mechanically or optically.

A pyroelectric detector uses a crystal of a pyroelectric material, which has a strong temperature-dependent electric polarization. The change in electric polarization causes a measurable current, which changes fast enough to respond to the output of an interferometer. The most common material used is deuterated triglycine sulfate, (dTGS). Lithium tantalate (LiTaO3) and lead zinc titanate (PZT) are also used.

4.12 Photoconductor: The photoconductive device (Fig.4.9) is based on the decrease in the resistance of certain semiconductor materials when they are exposed to both infrared and visible radiation. The photoconductivity is the result of carrier excitation due to light absorption and the figure of merit depends on the light absorption efficiency. The increase in conductivity is due to an increase in the number of mobile charge carriers in the material.
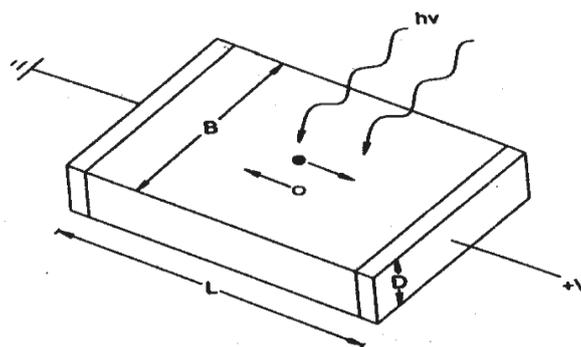

Fig.4.9 Sketch of photoconductive device

Theory: Let us consider a photo conducting slab. It is simply a light sensitive semiconductor material with ohmic contacts on both ends. When the material is illuminated with photons of energy $E \geq E_g$ electron hole pairs are generated and the electrical conductivity of the material increases. Where Eg is the bandgap energy of the semiconductor material given by

$$E_g = hc / \lambda$$

Where λ is the wavelength of the incident photon.

Let I_0 be the intensity of monochromatic light falling normally onto the slab. Then the intensity of transmitted light I is given by

$$I = I_0 \exp(-\alpha D).$$

Where α is the absorption coefficient of the material and D is the thickness of the slab. Let L and B be the length and breadth of the photoconductive slab respectively. Also let us assume that the slab absorbs the entire light falling on it. Now the light energy falls on the sample per sec is given by I_0 BL, where I_0 is the light energy falling per second on unit area of the slab. Therefore the number of photons falling on the photoconductor per second

$$= \frac{I_0 BL}{hv}$$

Let η- be the quantum efficiency of the absorption process. It is nothing but the fraction of incident energy absorbed. Therefore the number of photons absorbed per second

$$= \eta \frac{I_0 BL}{hv}$$

Now the average generation rate of charge carriers is given by

$$r_g = \frac{\eta I_0 BL}{hv BLD} \quad , \quad r_g = \frac{\eta I_0}{hv D}$$

Let Δn and ΔP be the excess electron and hole density per unit volume in the device. If τ_c is the life time of charge carriers, Then the recombination rate

$$r_r = \frac{\Delta n}{\tau_c} = \frac{\Delta p}{\tau_c}$$

At equilibrium, the recombination rate = generation rate. Therefore $\Delta p = \Delta n = r_g \tau_c$. We know the conductivity of a semi conducting material is $\sigma = ne\mu_e + p.e\mu_h$. Under illumination the conductivity will increase by an amount is

$$\Delta \sigma = \Delta ne\mu_e + \Delta p.e\mu_h$$
$$= \Delta ne(\mu_e + \mu_h)$$
$$= r_g \tau_c e(\mu_e + \mu_h)$$

When a voltage is applied to the contacts, electrons and holes move in opposite directions resulting in a photocurrent given by $\Delta i = \frac{BD}{L} \Delta \sigma V$, $\Delta i = \frac{BD}{L} r_g \tau_c e(\mu_e + \mu_h)V$

The quantum efficiency of a photoconductor device is defined by the term photoconductor gain G. Photoconductive gain is defined as the ratio of rate of flow of electrons per second to the rate of generation of electron hole pairs within the device.

$$G = \frac{Rate\ of\ flow\ of\ electrons\ /\sec}{Rate\ of\ generation\ of\ electron - hole\ pairs}$$

But rate of flow of electrons per sec = $\Delta i/e$.

Rate of generation of electron hole pairs = r_g BLD

$$G = \frac{(\Delta i/e)}{r_g BLD} \qquad G = \frac{\tau_c(\mu_e + \mu_h)V}{L^2},$$

The photoconductive gain G can be increased by increasing the voltage V and decreasing the length, L of the device. The photoconductive gain can also be defined as the ratio of the minority carriers life time and the transit time t.

i.e., $\qquad G = \frac{\tau_c}{t}$

Construction of photoconductive device: The four materials normally employed in photoconductive devices are: Cadmium Sulphide (CdS), Cadmium Selenide (CdSe), lead sulphide (PbS) and Thallium Sulphide (TlSIn a typical construction of photoconductive device, thin film is deposited on an insulating substrate. The electrodes are formed by evaporating metal such as gold through a mask to give comb -like pattern as shown in Fig 4.10. The geometry results in a relatively large area of sensitive surface and a small inter electrode spacing. This helps the device to provide high sensitivity.
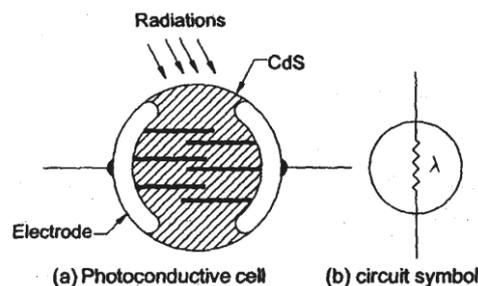

Fig. 4.10 Geometry of the photoconductive cell

When the device under forward bias is illuminated with light electron–hole pairs are generated. The electron-hole pairs generated move in opposite directions. This results in a photocurrent. The photoconductive cell has very high resistance in dark called dark resistance. When illuminated the resistance falls. The spectral response of CdS cell is similar to that of the human eye. The illumination characteristics of the cell is shown in Fig.4.11.
Desired characteristics of photoconductive materials.They are

    i) High spectral sensitivity in the wavelength region of interest
    ii) Higher quantum efficiency
    iii) Higher photoconductive gain
    iv) Higher speed of response and
    v) lesser noise
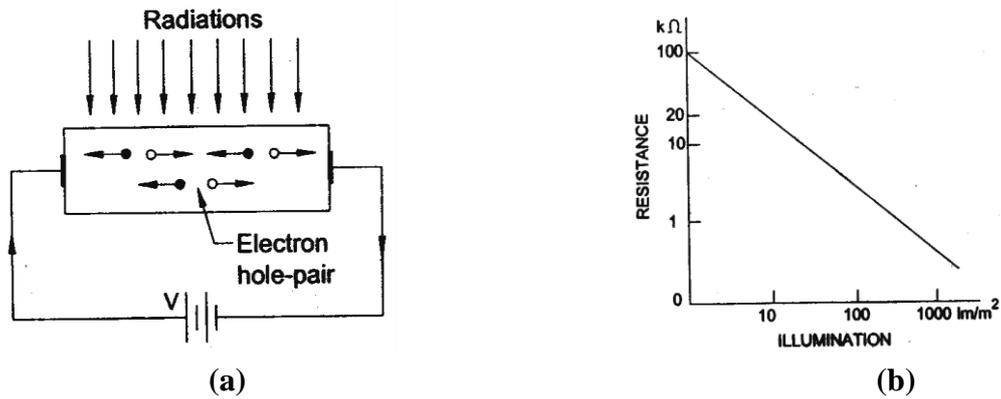
Fig.4.11 (a) Photoconductor in circuit (b) Spectral response of CdS cell

Materials:

(i) Cadmium sulfide (CdS) and Cadmium selenide (CdSe) :

These are highly sensitive in the visible region of radiation.They have high photoconductive gains (103 to 104) but poor response time (about 50 ms). The response gets reduced at higher illumination levels indicating the presence of traps.

(ii) Lead sulfide (PbS)

It has spectral responsitivity from 1 to 3.4 μm and hence very much suitable for fabricating near-infrared detectors. It has maximum sensitivity in the region of 2 μm with typical response time about 200 μs.

(iii) Indium antimonide (InSb)

These detectors have wavelength response extending out to 7 μm and exhibit response times of around 50 ns.

(iv) Mercury cadmium telluride (HgxCd1-x Te)

This is an alloy composed of the semi-metal HgTe and the semi-conductor CdTe. Semi-metals have overlapping valence and conduction bands. Depending on the composition of alloy, a semiconductor can be formed with a bandgap varying between zero and 1.6eV. Correspondingly the detector sensitivities lie in the range 5 to 14 μm. Photoconductive gains of up to 500 are possible

Applications of photoconductivity devices

They are,
- Light meters
- Infrared detectors
- TV cameras
- Voltage regulator
- Relays and
- Detecting ships and air crafts

4.13 Photodiode: A photodiode is a semiconductor device that converts light into current. Fig.4.12(a) shows the basic structure of a photodiode. The current is generated when photons are absorbed in the photodiode . A small amount of current is also produced when no light is present. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. Photodiodes usually have a slower response time as their surface area increases. The common, traditional solar cell used to generate electric solar power is a large area photodiode. Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p–n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.
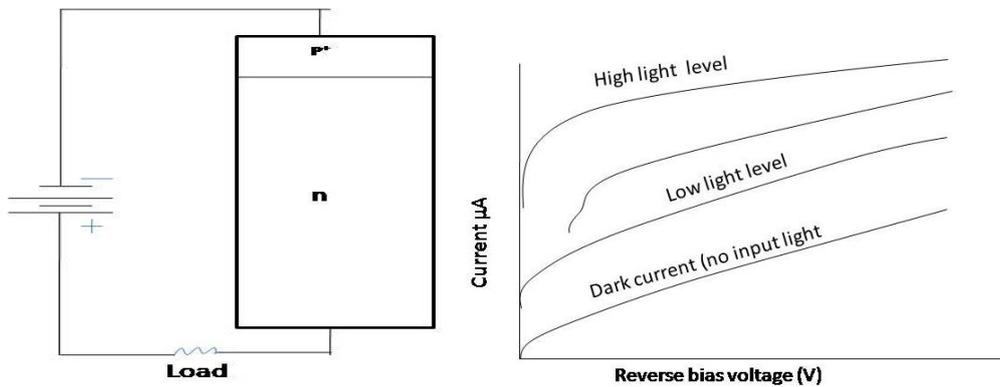

Fig.4.12(a) A typical p-n photodiode (b) characteristics curves

Principle of operation:

A photodiode is a p–n junction . When a photon of sufficient energy strikes the diode, it creates an electron-hole pair. This mechanism is also known as the inner photoelectric effect. If the absorption occurs in the junction's depletion region, or one diffusion length away from it, these carriers are swept from the junction by the built-in electric field of the depletion region. Thus holes move toward the anode, and electrons toward the cathode, and a photocurrent is produced. The total current through the photodiode is the sum of the dark current (current that is generated in the absence of light) and the photocurrent, so the dark current must be minimized to maximize the sensitivity of the device.

 Suppose a photon of light is incident in or near the depletion region and if the energy of the incident photon ($h\gamma$) is equal to or greater than the bandgap energy (E_g) of the semiconductor material of the p-n junction, the photon will excite an electron in valence band to the conduction band . The process will generate an electron-hole pair as shown in Fig.4.13(a) when

$$h\gamma > E_g \qquad\qquad\qquad (4.11)$$

99

The photogenerated carriers electron-hole pairs are separated in the depletion layer and are swept away by the electric field due to the applied reverse biased voltage and a leakage current flows in the external circuit (Fig.4.13(a-b)). The energy level diagram is shown in Fig.4.13(c). The operating characteristics of a p-n diode which are curves between the photocurrent versus biased voltage with light intensity as parameter is shown in Fig.4.12(b)
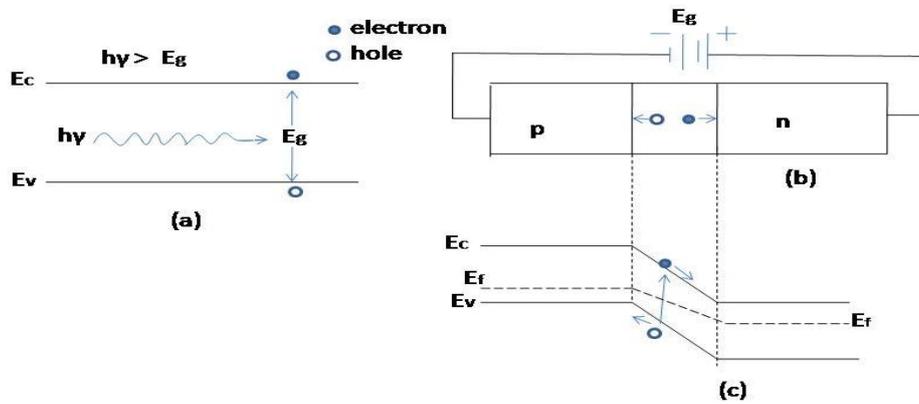

Fig.4.13(a) Operating principle of p-n photodiode (a) photogeneration of an electron hole pair in an intrinsic semiconductor (b) structure of a reverse biased photodiode (c) energy band diagram of the reverse biased p-n junction illustrating photogneration and subsequent of an electron-hole pair

4.14 PIN photodiode: A PIN diode is a diode with a wide, undoped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region. The p-type and n-type regions are typically heavily doped because they are used for ohmic contacts. The wide intrinsic region is in contrast to an ordinary p–n diode. The wide intrinsic region makes the PIN diode an inferior rectifier (one typical function of a diode), but it makes it suitable for attenuators, fast switches, photodetectors, and high voltage power electronics applications.

(i) PIN photodiode structure: Although an ordinary p-n junction can be used as the basis of a photodiode, the p-i-n junction provides a far more satisfactory photodiode structure. In the photodiode fabrication process a thick intrinsic layer is inserted between the p-type and n-type layers. The middle layer may be either completely instrinsic, or very lightly doped to make it and n- layer. In some instances it may be grown as an epitaxial layer onto the substrate, or alternatively it may be contained within the substrate itself (Fig.4.14).
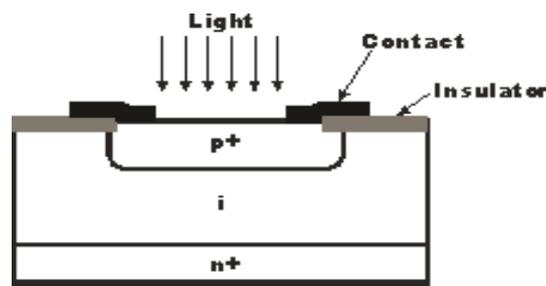

Fig.4.14 PIN photodiode structure

In some instances a heterojunction may be used. This form of structure has the additional flexibility that light can be received from the substrate and this has a larger energy gap which makes it transparent to light (Fig.4.15).
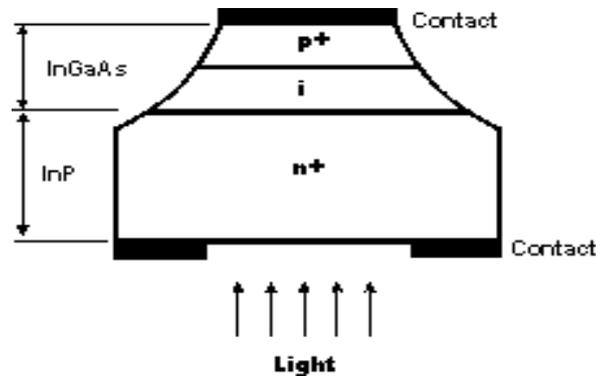

Fig.4.15 PIN photodiode heterojunction structure

The heterojunction format for a PIN photodiode uses less standard technology often using materials such as the InGaAs and InP depicted in the diagram. Being a less standard process, it is more expensive to implement and as a result tends to be used for more specialist products

(ii) PIN photodiode materials: The materials used within a photodiode determine many of its critical properties. The wavelength of light to which it responds and the level of noise are both critical parameters that are dependent upon the material used in the photodiode. The wavelength sensitivity of the different materials occurs because only photons with sufficient energy to excite an electron across the bandgap of the material will produce significant energy to develop the current from the photodiode.   Wavelength ranges for commonly used photodiode materials is given in table 4.2. While the wavelength sensitivity of the material is very important, another parameter that can have a major impact on the performance of the photodiode is the level of noise that is produced. Because of their greater bandgap, silicon photodiodes generate less noise than germanium photodiodes. However it is also necessary to consider the wavelengths for which the photodiode is required and germanium photodiodes must be used for wavelengths longer than approximately 1000 nm.

Material	Wavelength sensitivity (nm)
Germanium	800 - 1700
Indium gallium arsenide	800 - 2600
Lead sulphide	~1000 - 3500
Silicon	190 – 1100

Table 4.2

(iii) Principle of operation: A PIN diode operates under what is known as high-level injection. In other words, the intrinsic "i" region is flooded with charge carriers from the "p" and "n" regions. Its function can be likened to filling up a water bucket with a hole on the side. Once the water reaches the hole's level it will begin to pour out. Similarly, the diode will conduct current once the flooded electrons and holes reach an equilibrium point, where the number of electrons is equal to the number of holes in the intrinsic region. When the diode is

forward biased, the injected carrier concentration is typically several orders of magnitude higher than the intrinsic carrier concentration. Due to this high level injection, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from the P to the N region, which results in faster operation of the diode, making it a suitable device for high frequency operations.

(iv) Characteristics: A PIN diode obeys the standard diode equation for low frequency signals. At higher frequencies, the diode looks like an almost perfect (very linear, even for large signals) resistor. There is a lot of stored charge in the intrinsic region. At low frequencies, the charge can be removed and the diode turns off. At higher frequencies, there is not enough time to remove the charge, so the diode never turns off. The PIN diode has a poor reverse recovery time. The high-frequency resistance is inversely proportional to the DC bias current through the diode. A PIN diode, suitably biased, therefore acts as a variable resistor. This high-frequency resistance may vary over a wide range (from 0.1 Ω to 10 kΩ in some cases; the useful range is smaller, though).

The wide intrinsic region also means the diode will have a low capacitance when reverse-biased. In a PIN diode, the depletion region exists almost completely within the intrinsic region. This depletion region is much larger than in a PN diode, and almost constant-size, independent of the reverse bias applied to the diode. This increases the volume where electron-hole pairs can be generated by an incident photon. Some photodetector devices, such as PIN photodiodes and phototransistors (in which the base-collector junction is a PIN diode), use a PIN junction in their construction. The diode design has some design trade-offs. Increasing the dimensions of the intrinsic region (and its stored charge) allows the diode to look like a resistor at lower frequencies. It adversely affects the time needed to turn off the diode and its shunt capacitance. It is therefore necessary to select a device with the appropriate properties for a particular use.

(v) Applications: PIN diodes are useful as RF switches, attenuators, photodetectors, and phase shifters.

(a) RF and microwave switches: Under zero- or reverse-bias (the "off" state), a PIN diode has a low capacitance. The low capacitance will not pass much of an RF signal. Under a forward bias of 1 mA (the "on" state), a typical PIN diode will have an RF resistance of about 1 ohm, making it a good RF conductor. Consequently, the PIN diode makes a good RF switch. Although RF relays can be used as switches, they switch very slowly (on the order of 10 milliseconds). A PIN diode switch can switch much more quickly (e.g., 1 microsecond).

PIN diode switches are used not only for signal selection, but also component selection. For example, some low phase noise oscillators use them to range-switch inductors.

(b) RF and microwave variable attenuators: By changing the bias current through a PIN diode, it is possible to quickly change the RF resistance. At high frequencies, the PIN diode

appears as a resistor whose resistance is an inverse function of its forward current. Consequently, PIN diode can be used in some variable attenuator designs as amplitude modulators or output leveling circuits.

(c) Limiters: PIN diodes are sometimes used as input protection devices for high frequency test probes. If the input signal is within range, the PIN diode has little impact as a small capacitance. If the signal is large, then the PIN diode starts to conduct and becomes a resistor that shunts most of the signal to ground

4.15 Avalanche Photodiode:

Avalanche photodiode is biased at very high reverse voltage so that the internal multiplication of electrons takes place resulting into gain of 100 to 500. Once the incident photons generate electron-hole pair in the depletion layer of *p-n* junction, the carriers moving out of depletion layer, due to its internal electric field, will produce more electrons and an avalanching process will start. Then, the carriers are traversing a region of very high electric field will set in and large current gain is created by this process. The carrier multiplication mechanism is called as impact ionization. The original and newly generated carries are accelerated in the high reverse bias electron field and gain enough energy to sustain further impact ionization process resulting into avalanche process.

Figure 4.16 shows that as we increase the reverse bias up to 450 volts the internal gain of 900 may be achieved in some materials but noise effect may also increase at high current gain. Normally, current gain of 100 to 500 are used for stable output.

The multiplication factor M is defined as:

$$M = I_M / I_p \qquad (4.12)$$
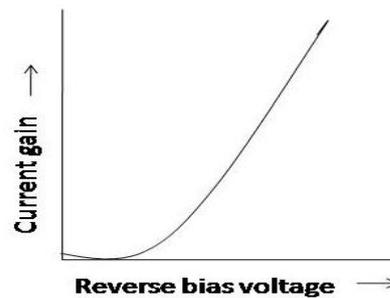
Fig.4.16 Variation of current gain with reverse bias voltage for an avalanche photodiode

where I_M is total average multiplied output current and I_P is primary unmultiplied photocurrent generated by incident photons of wavelength λ, energy hv and power P_0. If I_P is 0.20 mA and I_M is 25 mA, then

$$M = \frac{25\,\mu A}{0.20\,\mu A} = 125 \qquad (4.13)$$

This means that the incident photon current (primary current) is multiplied by 125 times inside the avalanche photodiode.

As explained earlier, most fast photodiodes are designed for use with a 50 W load impedance and the voltage output $i_{ext} R_L$ often requires considerable amplification. Useful internal amplification of the photocurrent is achieved in the avalanche photodiode. In this device, a basic *p-n* structure is operated under very high reverse bias. Carriers traversing through the depletion region, therefore, gain sufficient energy to enable further traversing the depletion region. The process is illustrated in Figure 4.17. Current gain in excess of 100 are readily obtainable and is very sensitive to the value of the bias voltage, as depicted in Figure 4.16. If the bias voltage is made to large then a self-sustaining avalanche current flows in the absence of any photoexcitation and sets an upper limit to the voltae that may be used. To ensure a uniformly high avalanche breakdown voltage and uniform gain throughout the diode, it is necessary to provide a highly uniform field profile across the device. Number of designs have been proposed, for example, one type uses the guard-ring structure as shown in Figure 4.18. The guard ring restricts the avalanche region to the central illuminated part of the cell.
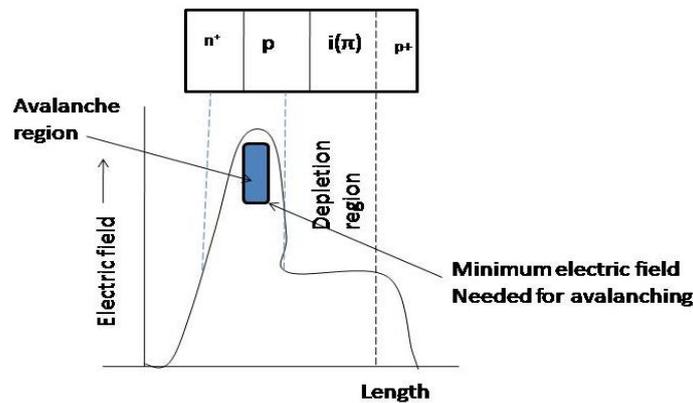
Fig.4.17 Avalanche photodiode in the avalanching mode.
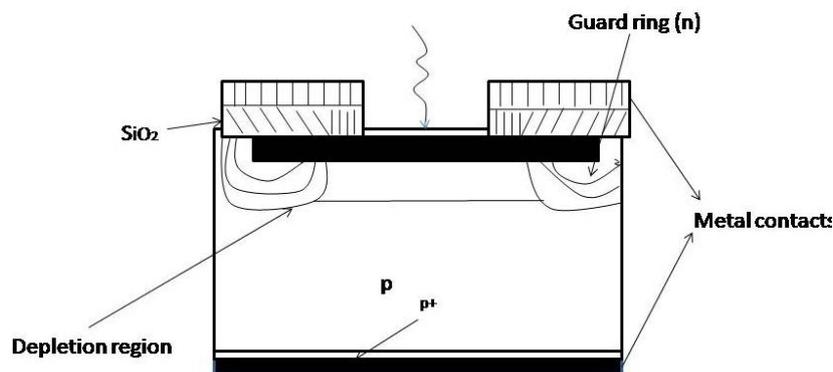
Fig.4.18 Silicon avalanche photodetector with guard –ring structure.

A number of precautions are necessary when using the avalanche photodiode. For example, the rapid variation of gain with bias voltage, shown in Figure 4.16, requires the use of a very stale power supply if constant gain is to be maintained.

The true rms noise current due to shot noise would be given by

$$\Delta_{if}(avalanche) = M[2ie\Delta f.F(M)]^{1/2} \qquad (4.14)$$

where Δ_{if} is rms noise current due to shot noise, M is multiplication factor (or number of secondary carriers), *i* is total current flowing in the diode, Δ_f is bandwith, and F(M) is excess noise factor in avalanche photodiode.

So the excess noise factor, F(M), is given by

$$F(M)=M\left[1-\left(1-\frac{1}{r}\right)\frac{(M-1)^2}{M}\right]$$

(4.15)

where *r* is the ratio of the electron to hole ionization probabilities. In silicon, *r* tends to have relatively large values (i.e. about 50) whereas for germanium *r* is about unity. This implies that avalanche photodiodes made from germanium are inherently more noisy than those made from silicon.

Avalanche photodiodes are very popular detectors for use in fibre optical communication systems. Suitable materials giving low noise performance in the region beyond 1.1 mm (the limit of silicon detectors) have been successfully developed and are working satisfactorily. The suitable PIN photodiode for the region of 1.3 and 1.55 micron are already developed and are being used for long distance communication with high reliability and satisfactory performance.

4.16 Photomultiplier tube: Photomultiplier tubes (photomultipliers or PMTs for short), members of the class of vacuum tubes, and more specifically vacuum phototubes, are extremely sensitive detectors of light in the ultraviolet, visible, and near-infrared ranges of the electromagnetic spectrum. These detectors multiply the current produced by incident light by as much as 100 million times (i.e., 160 dB), in multiple dynode stages, enabling (for example) individual photons to be detected when the incident flux of light is very low. Unlike most vacuum tubes, they are not obsolete. The combination of high gain, low noise, high frequency response or, equivalently, ultra-fast response, and large area of collection has maintained photomultipliers an essential place in nuclear and particle physics, astronomy, medical diagnostics including blood tests, medical imaging, motion picture film scanning (telecine), radar jamming, and high-end image scanners known as drum scanners. Semiconductor devices, particularly avalanche photodiodes, are alternatives to photomultipliers; however, photomultipliers are uniquely well-suited for applications requiring low-noise, high-sensitivity detection of light that is imperfectly collimated.

(i) Structure and operating principles: Photomultipliers are typically constructed with an evacuated glass housing, containing a photocathode, several dynodes, and an anode. Incident photons strike the photocathode material, which is usually a thin vapor-deposited conducting layer on the inside of the entry window of the device. Electrons are ejected from the surface as a consequence of the photoelectric effect. These electrons are directed by the focusing electrode toward the electron multiplier, where electrons are multiplied by the process of secondary emission (Fig.4.19). The electron multiplier consists of a number of electrodes called *dynodes*. Each dynode is held at a more positive potential, by ≈100 Volts, than the preceding one. A primary electron leaves the photocathode with the energy of the incoming photon, or about 3 eV for "blue" photons, minus the work function of the photocathode. A small group of primary electrons is created by the arrival of a group of initial photons. (In

Figure 4.19, the number of primary electrons in the initial group is proportional to the energy of the incident high energy gamma ray.) The primary electrons move toward the first dynode because they are accelerated by the electric field. They each arrive with ≈100 eV kinetic energy imparted by the potential difference. Upon striking the first dynode, more low energy electrons are emitted, and these electrons are in turn accelerated toward the second dynode. The geometry of the dynode chain is such that a cascade occurs with an exponentially-increasing number of electrons being produced at each stage. For example, if at each stage an average of 5 new electrons are produced for each incoming electron, and if there are 12 dynode stages, then at the last stage one expects for each primary electron about $5^{12} \approx 10^8$ electrons. This last stage is called the anode. This large number of electrons reaching the anode results in a sharp current pulse that is easily detectable, for example on an oscilloscope, signaling the arrival of the photon(s) at the photocathode ≈50 nanoseconds earlier.
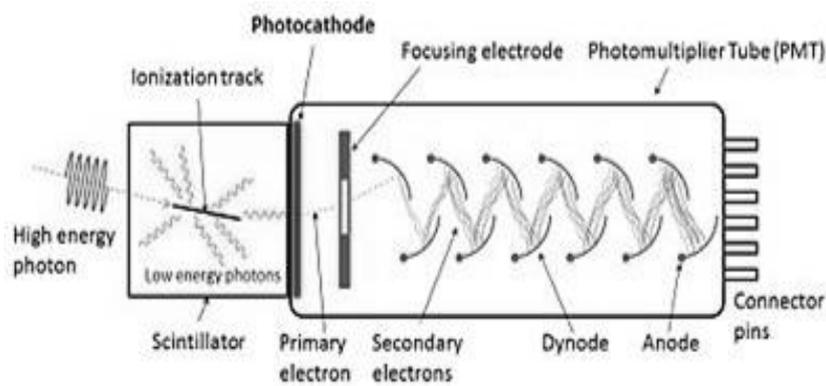

Fig.4.19 Schematic of a photomultiplier tube coupled to a scintillator. This arrangement is for detection of gamma rays.

The necessary distribution of voltage along the series of dynodes is created by a voltage divider chain, as illustrated in the Figure 4.20. In Fig.4.20, the photocathode is held at a negative high voltage of order 1000V, while the anode is very close to ground potential. The capacitors across the final few dynodes act as local reservoirs of charge to help maintain the voltage on the dynodes while electron avalanches propagate through the tube. Many variations of design are used in practice; the design shown is merely illustrative. There are two common photomultiplier orientations, the head-on or end-on (transmission mode) design, as shown above, where light enters the flat, circular top of the tube and passes the photocathode, and the side-on design (reflection mode), where light enters at a particular spot on the side of the tube, and impacts on an opaque photocathode. The side-on design is used, for instance, in the type 931, the first mass-produced PMT. Besides the different photocathode materials, performance is also affected by the transmission of the window material that the light passes through, and by the arrangement of the dynodes. A large number of photomultiplier models are available having various combinations of these, and other, design variables. Either of the manuals mentioned will provide the information needed to choose an appropriate design for a particular application.
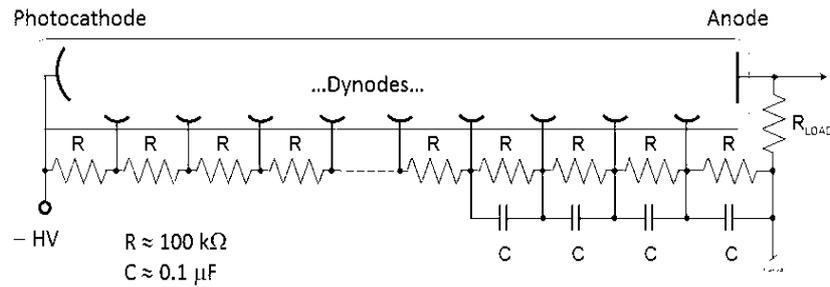
Fig.4.20 Typical photomultiplier voltage divider circuit using negative high voltage.

(ii) Typical applications:

Photomultipliers were the first electric eye devices, being used to measure interruptions in beams of light.

Photomultipliers are used in conjunction with scintillators to detect Ionizing radiation by means of hand held and fixed radiation protection instruments, and particle radiation in physics experiments.

Photomultipliers are used in research laboratories to measure the intensity and spectrum of light-emitting materials such as compound semiconductors and quantum dots. Photomultipliers are used as the detector in many spectrophotometers. This allows an instrument design that escapes the thermal noise limit on sensitivity, and which can therefore substantially increase the dynamic range of the instrument.

Photomultipliers are used in numerous medical equipment designs. For example: blood analysis devices used by clinical medical laboratories, such as flow cytometers, utilize photomultipliers to determine the relative concentration of various components in blood samples , in combination with optical filters and incandescent lamps. An array of photomultipliers is used in a Gamma camera. Photomultipliers are typically used as the detectors in Flying-spot scanners.

4.17 Phototransistor:

A phototransistor is a device that converts light energy into electric energy. Phototransistors are similar to photoresistors but produce both current and voltage, while photoresistors only produce current. This is because a phototransistor is made of a bipolar semiconductor and focuses the energy that is passed through it. Photons (light particles) activate phototransistors and are used in virtually all electronic devices that depend on light in some way. The basic structure of homojunction phototransistor is shown in Fig.4.21(a). The structure of an n-p-n heterojunction phototransistor is shown in the Fig.4.21(b). It consists of n-type collector (Indium phosphate) followed by a thin layer of p-type base (GaAsP) of thickness of about 0.1 X 10^{-6} m. The emitter layer is of n-type (Indium phosphate) material of wide band gap. The substrate and AuSn are meant for metallic contact with the transistor.

(i) How a Phototransistor Works:
A phototransistor is a bipolar device that is completely made of silicon or another semi-conductive material and is dependent on light energy. Phototransistors are generally encased in an opaque or clear container in order to enhance

light as it travels through it and allow the light to reach the phototransistor's sensitive parts. A phototransistor generally has an exposed base that amplifies the light that it comes in contact with. This causes a relatively high current to pass through the phototransistor. As the current spreads from the base to the emitter, the current is concentrated and converted into voltage. The circuit symbol and equivalent circuit of a phototransistor are shown in Fig.4.22
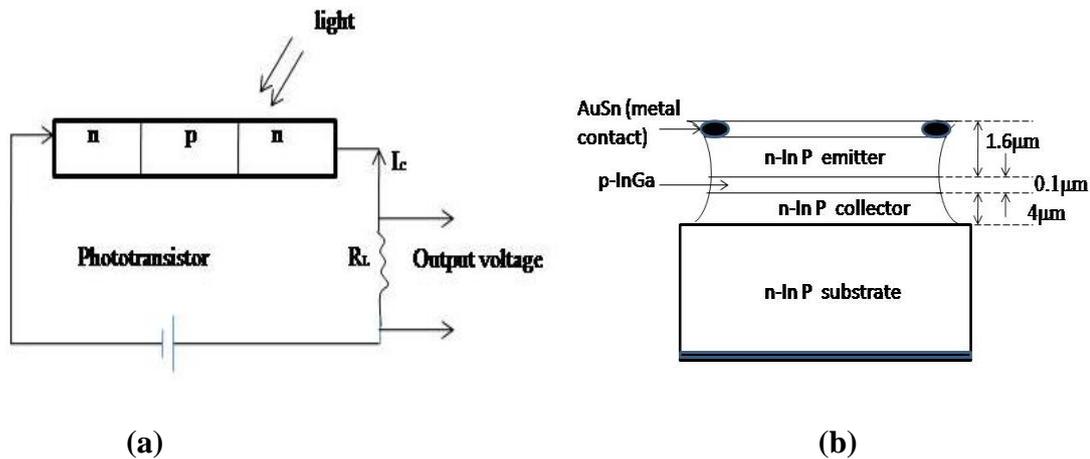

<p style="text-align:center">(a)</p>
<p style="text-align:center">(b)</p>

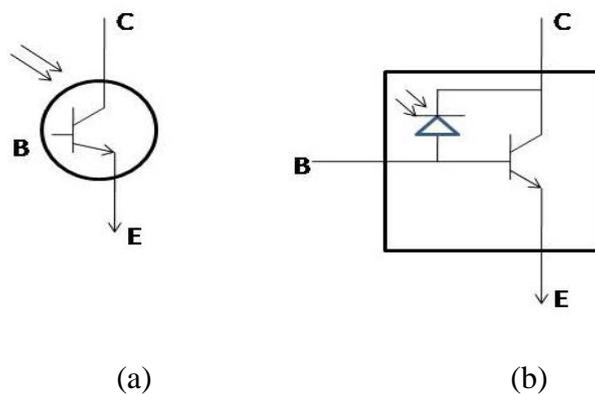**Fig.4.21 (a) Structure of homojunction phototransistor (b) heterojunction phototransistor**

<p style="text-align:center">(a)</p>
<p style="text-align:center">(b)</p>

Fig.4.22 (a) Circuit symbol (b) Equivalent circuit of Phototransistor

(ii) Applications: Phototransistors are used for a wide variety of applications. In fact, phototransistors can be used in any electronic device that senses light. For example, phototransistors are often used in smoke detectors, infrared receivers, and CD players. Phototransistors can also be used in astronomy, night vision, and laser range-finding.

(iii) Advantages: Phototransistors have several important advantages that separate them from other optical sensors. They produce a higher current than photodiodes and also produce a voltage, something that photoresistors cannot do. Phototransistors are very fast and their output is practically instantaneous. They are relatively inexpensive, simple, and so small that several of them can fit onto a single integrated computer chip.

(iv) Disadvantages: While phototransistors can be advantageous, they also have several disadvantages. Phototransistors made of silicon cannot handle voltages over 1,000 Volts. They do not allow electrons to move as freely as other devices, such as electron tubes, do. Also, phototransistors are also more vulnerable to electrical surges/spikes and electromagnetic energy.

(v) Characteristics of Phototransistors : An equivalent circuit for a phototransistor consists of a photodiode feeding its output photocurrent into the base of a small signal transistor. Based on this model it is not surprising that phototransistors display some of the characteristics of both types of devices.

Spectral Response: The output of a phototransistor is dependent upon the wavelength of incident light. These devices respond to light over a broad range of wavelengths from the near UV, through the visible and into the near IR part of the spectrum. Unless optical filters are used, the peak spectral response is in the near IR at approximately 840 nm.

Sensitivity: For a given light source illumination level, the output of a phototransistor is defined by the area of the exposed collector-base junction and the dc current gain of the transistor (Fig.4.23) . The collector-base junction of the phototransistor functions as a photodiode generating a photocurrent which is fed into the base of the transistor section. Thus, like the case for a photodiode, doubling the size of the base region doubles the amount of generated base photocurrent. This photocurrent (I_P) then gets amplified by the dc current gain of the transistor. For the case where no external base drive current is applied:

$$I_C = h_{FE} (I_P), \quad \text{where:} \quad I_C = \text{collector current}, \quad h_{FE} = \text{DC current}$$
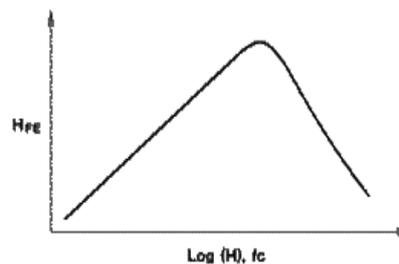gain, I_P = photocurrent.

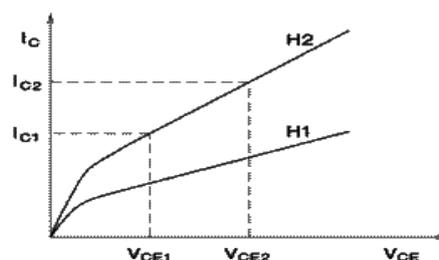**Fig.4.23 Transistor Gain vs Light Intensity**

Fig.4.24   Current vs Voltage Curves

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H_{FE} will also increase with increasing values for V_{CE}. The current -voltage characteristics of a typical transistor will demonstrate this effect (Fig.4.24). For a constant base drive the curve shows a positive slope with increasing voltage. It is clear that the current gain at collector-emitter voltage V_{CE2} is greater than the current gain at V_{CE1}. The current gain will also increase with increasing temperature

Linearity: Unlike a photodiode whose output is linear with respect to incident light over 7 to 9 decades of light intensity, the collector current (I_C) of a phototransistor is linear for only 3 to 4 decades of illumination. The prime reason for this limitation is that the dc gain (h_{FE}) of the phototransistor is a function of collector current (I_C) which in turn is determined by the base drive. The base drive may be in the form of a base drive current of incident light.

Collector-Emitter Saturation Voltage - $V_{CE}(SAT)$: By definition, saturation is the condition in which both the emitter-base and the collector-base junctions of a phototransistor become forward biased. From a practical standpoint the collector-emitter saturation voltage, $V_{CE}(SAT)$, is the parameter which indicates how closely the photodetector approximates a closed switch. This is because $V_{CE}(SAT)$ is the voltage dropped across the detector when it is in its "on" state. $V_{CE}(SAT)$ is usually given as the maximum collector-emitter voltage allowed at a given light intensity and for a specified value of collector current.

Dark Current - (I_D): When the phototransistor is placed in the dark and a voltage is applied from collector to emitter, a certain amount of current will flow. This current is called the dark current (I_D). This current consists of the leakage current of the collector-base junction multiplied by the dc current gain of the transistor. The presence of this current prevents the phototransistor from being considered completely "off", or being an ideal "open" switch. The dark current is specified as the maximum collector current permitted to flow at a given collector-emitter test voltage. The dark current is a function of the value of the applied collector-emitter voltage and ambient temperature.

Breakdown Voltages - (V_{BR}): Phototransistors must be properly biased in order to operate. However, when voltages are applied to the phototransistor, care must be taken not to exceed the collector-emitter breakdown voltage (VBRCEO) or the emitter-collector breakdown voltage (VBRECO). Exceeding the breakdown voltages cause permanent damage to the phototransistor. Typical values for VBRCEO range from 20 V to 50 V. Typical values for VBRECO range from 4 V to 6 V. The breakdown voltages are 100% screened parameters.

Speed of Response: The speed of response of a phototransistor is dominated almost totally by the capacitance of the collector-base junction and the value of the load resistance. These dominate due to the Miller Effect which multiplies the value of the RC time constant by the current gain of the phototransistor. This leads to the general rule that for devices with the same active area, the higher the gain of the photodetector, the slower will be its speed of response.A phototransistor takes a certain amount of time to respond to sudden changes in light intensity. This response time is usually expressed by the rise time (t_R) and fall time (t_F) of the detector where:

t_R - The time required for the output to rise from 10% to 90% of its on-state value.

t_F - The time required for the output to fall from 90% to 10% of its on-state value.

4.18 Charge-coupled device (CCD):

A charge-coupled device (CCD) is a device for the movement of electrical charge, usually from within the device to an area where the charge can be manipulated, for example conversion into a digital value. This is achieved by "shifting" the signals between stages within the device one at a time. CCDs move charge between capacitive bins in the device, with the shift allowing for the transfer of charge between bins.

The CCD is a major piece of technology in digital imaging. In a CCD image sensor, pixels are represented by p-doped MOS capacitors. These capacitors are biased above the threshold for inversion when image acquisition begins, allowing the conversion of incoming photons into electron charges at the semiconductor-oxide interface; the CCD is then used to read out these charges. Although CCDs are not the only technology to allow for light detection, CCD image sensors are widely used in professional, medical, and scientific applications where high-quality image data is required. In applications with less exacting quality demands, such as consumer and professional digital cameras, active pixel sensors (CMOS) are generally used; the large quality advantage CCDs enjoyed early on has narrowed over time.

(i) Basics of operation: A CCD for capturing images, there is a photoactive region (an epitaxial layer of silicon), and a transmission region made out of a shift register. Fig.4.25 illustrates the electrode structure defining an individual element.
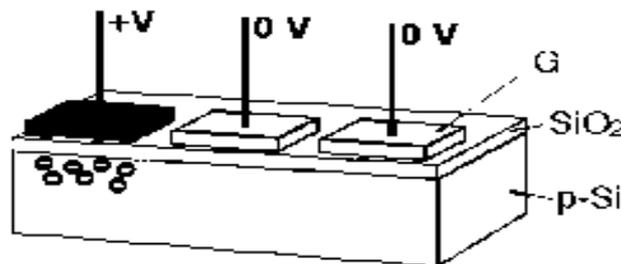

Fig. 4.25 The charge packets are collected in potential wells created by applying positive voltage at the gate electrodes (G). Applying positive voltage to the gate electrode in the correct sequence transfers the charge packets.

An image is projected through a lens onto the capacitor array (the photoactive region), causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. A one-dimensional array, used in line-scan cameras, captures a single slice of the image, whereas a two-dimensional array, used in video and still cameras, captures a two-dimensional picture corresponding to the scene projected onto the focal plane of the sensor. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor (operating as a shift register). The last capacitor in the array dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire contents of the array in the

semiconductor to a sequence of voltages. In a digital device, these voltages are then sampled, digitized, and usually stored in memory; in an analog device (such as an analog video camera), they are processed into a continuous analog signal (e.g. by feeding the output of the charge amplifier into a low-pass filter), which is then processed and fed out to other circuits for transmission, recording, or other processing.

(ii) Architecture: The CCD image sensors can be implemented in several different architectures. The most common are full-frame, frame-transfer, and interline. The distinguishing characteristic of each of these architectures is their approach to the problem of shuttering. In a full-frame device, all of the image area is active, and there is no electronic shutter. A mechanical shutter must be added to this type of sensor or the image smears as the device is clocked or read out. With a frame-transfer CCD, half of the silicon area is covered by an opaque mask (typically aluminum). The image can be quickly transferred from the image area to the opaque area or storage region with acceptable smear of a few percent. That image can then be read out slowly from the storage region while a new image is integrating or exposing in the active area. Frame-transfer devices typically do not require a mechanical shutter and were a common architecture for early solid-state broadcast cameras. The downside to the frame-transfer architecture is that it requires twice the silicon real estate of an equivalent full-frame device; hence, it costs roughly twice as much. The interline architecture extends this concept one step further and masks every other column of the image sensor for storage. In this device, only one pixel shift has to occur to transfer from image area to storage area; thus, shutter times can be less than a microsecond and smear is essentially eliminated.

(iii) Use in astronomy:

Due to the high quantum efficiencies of CCDs (for a quantum efficiency of 100%, one count equals one photon), linearity of their outputs, ease of use compared to photographic plates, and a variety of other reasons, CCDs were very rapidly adopted by astronomers for nearly all UV-to-infrared applications.

Thermal noise and cosmic rays may alter the pixels in the CCD array. To counter such effects, astronomers take several exposures with the CCD shutter closed and opened. The average of images taken with the shutter closed is necessary to lower the random noise. Once developed, the dark frame average image is then subtracted from the open-shutter image to remove the dark current and other systematic defects (dead pixels, hot pixels, etc.) in the CCD.

The Hubble Space Telescope, in particular, has a highly developed series of steps ("data reduction pipeline") to convert the raw CCD data to useful images. CCD cameras used in astrophotography often require sturdy mounts to cope with vibrations from wind and other sources, along with the tremendous weight of most imaging platforms. Array of 30 CCDs used on Sloan Digital Sky Survey telescope imaging camera, an example of "drift-scanning." An interesting unusual astronomical application of CCDs, called drift-scanning, uses a CCD to make a fixed telescope behave like a tracking telescope and follow the motion of the sky.

The charges in the CCD are transferred and read in a direction parallel to the motion of the sky, and at the same speed. In this way, the telescope can image a larger region of the sky than its normal field of view.

Digital color cameras generally use a Bayer mask over the CCD. Each square of four pixels has one filtered red, one blue, and two green (the human eye is more sensitive to green than either red or blue). The result of this is that luminance information is collected at every pixel, but the color resolution is lower than the luminance resolution. Better color separation can be reached by three-CCD devices (3CCD) and a dichroic beam splitter prism, that splits the image into red, green and blue components. Each of the three CCDs is arranged to respond to a particular color. Many professional video camcorders, and some semi-professional camcorders, use this technique, although developments in competing CMOS technology have made CMOS sensors, both with beam-splitters and bayer filters, increasingly popular in high-end video and digital cinema cameras. Another advantage of 3CCD over a Bayer mask device is higher quantum efficiency (and therefore higher light sensitivity for a given aperture size). This is because in a 3CCD device most of the light entering the aperture is captured by a sensor, while a Bayer mask absorbs a high proportion (about 2/3) of the light falling on each CCD pixel.

4.19 Solar cell:

A solar cell, or photovoltaic is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect, which is a physical and chemical phenomenon. It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage, or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known as solar panels. Solar cells are described as being photovoltaic irrespective of whether the source is sunlight or an artificial light. They are used as a photodetector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity.

Solar cells can be classified into first, second and third generation cells. The first generation cells—also called conventional, traditional or wafer-based cells—are made of crystalline silicon, the commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon. Second generation cells are thin film solar cells, that include amorphous silicon, CdTe and CIGS cells and are commercially significant in utility-scale photovoltaic power stations, building integrated photovoltaics or in small stand-alone power system. The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics—most of them have not yet been commercially applied and are still in the research or development phase. Many use organic materials, often organometallic compounds as well as inorganic substances. Despite the fact that their efficiencies had been low and the stability of the absorber material was often too short for commercial applications, there is a lot of research invested into these technologies as they promise to achieve the goal of producing low-cost, high-efficiency solar cells.

Theory:

The operation of a solar cell or photovoltaic (PV) cell requires 3 basic attributes:

The absorption of light, generating either electron-hole pairs or excitons.

The separation of charge carriers of opposite types.

The separate extraction of those carriers to an external circuit.

Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon. Electrons are excited from their current molecular/atomic orbital. Once excited an electron can either dissipate the energy as heat and return to its orbital or travel through the cell until it reaches an electrode. Current flows through the material to cancel the potential and this electricity is captured (Fig.4.26(c-d)). The chemical bonds of the material are vital for this process to work, and usually silicon is used in two layers, one layer being bonded with boron, the other phosphorus. These layers have different chemical electric charges and subsequently both drive and direct the current of electrons. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity. An inverter can convert the power to alternating current (AC).The most commonly known solar cell is configured as a large-area p–n junction made from silicon.
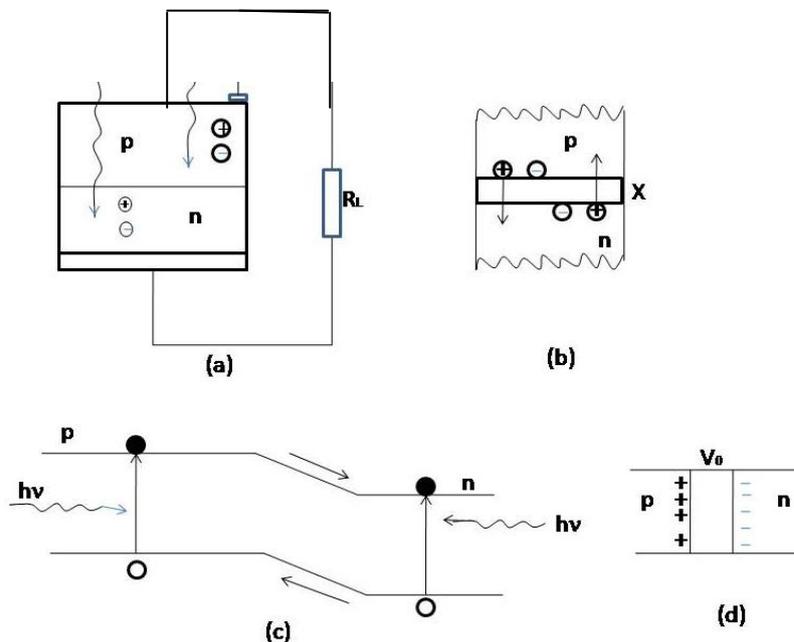

Fig.4.26 (a) p-n junction solar cell with load resistance, R_L (b) Diffusion of electrons and holes (c) Energy band diagram corresponding to (b) and (d) Formation of the open circuit voltage V_0
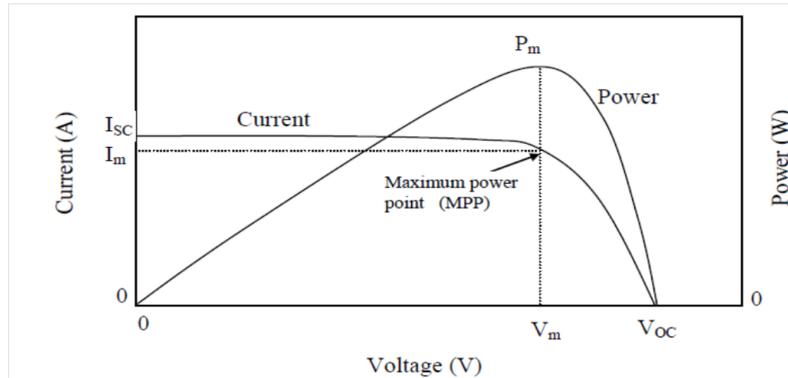
Fig.4.27 I-V Characteristics of solar panel

The calculation of the maximum power of a solar cell is illustrated by Figure 4.26(a) and Figure 4.26(b). The sign convention of the current and voltage is shown as well. It considers a current coming out of the cell to be positive as it leads to electrical power generation. The power generated depends on the solar cell itself and the load connected to it. As an example, a resistive load is shown in the diagram (Fig.4.26(a)). We identify the open-circuit voltage, V_{oc}, as the voltage across the illuminated cell at zero current. The *short-circuit* current, I_{sc}, is the current through the illuminated cell if the voltage across the cell is zero. The *short-circuit* current is close to the photocurrent while the *open-circuit* voltage is close to the turn-on voltage of the diode as measured on a current scale similar to that of the photocurrent (Fig.4.26(d)). The power equals the product of the diode voltage and current and at first increases linearly with the diode voltage but then rapidly goes to zero as the voltage approaches the turn-on voltage of the diode. The maximum power is obtained at a voltage labeled as V_m with I_m being the current at that voltage. The fill factor of the solar cell is defined as the ratio of the maximum power of the cell to the product of the *open-circuit* voltage, V_{oc}, and the *short-circuit* current, I_{sc}. Fig.4.27 illustrates the I-V curveand power output of solar panel.

Efficiency:

The Shockley-Queisser limit for the theoretical maximum efficiency of a solar cell. Semiconductors with band gap between 1 and 1.5eV, or near-infrared light, have the greatest potential to form an efficient single-junction cell. Solar cell efficiency may be broken down into reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency and conductive efficiency. The overall efficiency is the product of these individual metrics. A solar cell has a voltage dependent efficiency curve, temperature coefficients, and allowable shadow angles. Due to the difficulty in measuring these parameters directly, other parameters are substituted: thermodynamic efficiency, quantum efficiency, integrated quantum efficiency, VOC ratio, and fill factor. Reflectance losses are a portion of quantum efficiency under "external quantum efficiency". Recombination losses make up another portion of quantum efficiency, VOC ratio, and fill factor. Resistive losses are predominantly categorized under fill factor, but also make up minor portions of quantum efficiency, VOC ratio.

The fill factor is the ratio of the actual maximum obtainable power to the product of the open circuit voltage and short circuit current. This is a key parameter in evaluating performance. In 2009, typical commercial solar cells had a fill factor > 0.70. Grade B cells were usually between 0.4 and 0.7. Cells with a high fill factor have a low equivalent series resistance and a high equivalent shunt resistance, so less of the current produced by the cell is dissipated in internal losses. Single p–n junction crystalline silicon devices are now approaching the theoretical limiting power efficiency of 33.7%, noted as the Shockley–Queisser limit in 1961. In the extreme, with an infinite number of layers, the corresponding limit is 86% using concentrated sunlight.

In December 2014, a solar cell achieved a new laboratory record with 46 percent efficiency in a French-German collaboration. In 2014, three companies broke the record of 25.6% for a silicon solar cell. Panasonic's was the most efficient.

4.20 Noise in Optical Detector

Following types of noise are prominent in photodetector system :
1. Dark current noise , 2.Thermal noise, 3. Quantum noise, 4. Surface leakage current
5. Amplifier noise and 6.Statistical gain fluctuation (in avalanche diode)

The phenomenon of incident photons falling on the detector is a statistical process, that is, the photons are arriving at detector in random manner as per time varying Poisson statistical process. Besides random arrival of photon at the detector, it is difficult to predict how many electron-hole pairs are produced by a known incident photon energy (hv) in the detector and hence, shot noise or quantum noise vary from photon to photon. Similarly in an avalanche photodiode, it is shot noise due to statistical nature of multiplication of photons causing statistical gain. The thermal noise in a photodiode is produced due to the fact that the photon energy incident on the photodetector is comparable with the thermal energy (KT) in the optical region and hence even at room temperature ($T= 300 K$), the internal vibrations of atoms can produce thermal heating which may generate electron hole pairs in the absence of incident photons. The thermal noise is thus produced at room temperature and also at higher temperature.

The dark current always flows in the photodiode due to stray radiations of light from other sources as optical radiations in the near *IR* regions are produced by various sources which produce a small dark current in the photodetector in the absence of incident photons from laser /LED photon sources.

Quantum Noise

The quantum noise is due to statistical generation of electron-hole pairs which are generated by the incident photons. The absorption of photons in the detector device is responsible for genearion of electron-hole carriers. The absorption of photons and generations of charge carriers is a statistical process which follows the Poisson distribution. These processes are explained in the following paragraphs by theoretical values. If energy $E = hv$ falls on photodiode and since $hv > KT$ in the optical region, quantum noise plays dominate role over the thermal fluctuation noise.

The creation of electron-hole carriers in a material by incident photons is a discrete process in which the incident photons are absorbed by material and the absorbed photons create the charge carriers. This is a statistical process and is governed by Poisson distribution as mentioned above. The probability $P(z)$ of detecting Z photons in time period T, when it is expected on average to detect Z_m photons, obeys Poisson distribution as :

$$P(z) = \frac{Z_m^2 \exp(-Z_m)}{Z!} \qquad (4.16)$$

where Z_m is the variance of probability distribution. The electron rate regenerated by incident photons is given by

$r_e = \eta p_o / h\nu$

If no. of electrons generated – no. of absorbed photons then in a time T,

$$Z_m = \eta p_o T / h\nu \qquad (4.17)$$

The value of Z_m varies from 10 to 1000 for multiple and single frequency output.

Thermal noise

It is the spontaneous fluctuation due to thermal interaction between the free electrons and the vibrating ions. The thermal noise current i_T in a resistor is given by

$$\overline{i_T^2} = 4\frac{kTB}{R} \qquad (4.18)$$

where, k is Boltzmann constant, T is absolute temperature, B is electrical bandwidth and R is resistance.

Dark current noise

When there is no optical power incident on photodiode, a small reverse leakage current still flows from device terminals. It gives random fluctuations about the average particle flow of the photocurrent. It is called dark noise. It is given by

$$\overline{i_d^2} = 2eBI_d \qquad (4.19)$$

where, e is electron charge, I_d is dark current and B is electrical bandwidth.

It may be reduced by careful design and fabrication of detector.

Detector parameters

The quantum efficiency η is the number of electron – hole carrier pairs generated per incident photon of energy $h\nu$ and is defined as :

$$\eta = \frac{\text{No. of electrons} - \text{hole pairs generated}}{\text{No. of incident photons}}$$

$$\frac{I_p h\nu}{P_o q} \qquad (4.20)$$

where I_p is the average photocurrent generated by a steady state average optical power P_0 incident on the photodiode.

The performance of a photodetector is generally measured in terms of responsivity R which is related to quantum efficiency η as per equation given below:

$$R = \frac{I_P}{P_0} = \frac{\eta q}{h\nu} \qquad (4.21)$$

If we assume that the noise power generate in a detector is proportional to its sensitive area A then the noise current (or voltage) will vary as $A^{1/2}$. Thus, we may define a unit NEP* which takes into account the effects of variable bandwidth and detector area as :

$$NEP* = \frac{NEP}{(A\Delta f)^{1/2}}$$

(4.22)

It is the reciprocal of this quantity, known as the specific detectivity D* that is commonly used, thus:

$$D* = \frac{(A\Delta f)^{1/2}}{NEP} \qquad (4.23)$$

The value of D* for a particulars detector will depend on the wavelength of the signal radiation and the frequency at which it is modulated and is often quoted in the format $D*(R,f)$. The highest D* value is generally the best choice at a particulars wavelength provided that other criteria such as frequency response are met and that the noise is not background –radiation limited.

UNIT-V

Display devices

5.1 Introduction: A display device is an output device for presentation of information in visual or tactile form . When the input information is supplied as an electrical signal, the display is called an electronic display . Common applications for electronic visual displays are televisions or computer monitors.

5.2 Photoluminescence: Photoluminescence (abbreviated as PL) is light emission from any form of matter after the absorption of photons (electromagnetic radiation). It is one of many forms of luminescence (light emission) and is initiated by photoexcitation (excitation by photons), hence the prefix *photo-*. Observation of photoluminescence at a certain energy can be viewed as indication that excitation populated an excited state associated with this transition energy. Photoluminescence is an important technique for measuring the purity and crystalline quality of semiconductors such as GaAs and InP and for quantification of the amount of disorder present in a system. Several variations of photoluminescence exist, including photoluminescence excitation (PLE) spectroscopy. Time-resolved photoluminescence (TRPL) is a method where the sample is excited with a light pulse and then the decay in photoluminescence with respect to time is measured. This technique is useful for measuring the minority carrier lifetime of III-V semiconductors like gallium arsenide (GaAs).

(i) Forms of photoluminescence: Photoluminescence processes can be classified by various parameters such as the energy of the exciting photon with respect to the emission. Resonant excitation describes a situation in which photons of a particular wavelength are absorbed and equivalent photons are very rapidly re-emitted. This is often referred to as resonance

fluorescence. For materials in solution or in the gas phase, this process involves electrons but no significant internal energy transitions involving molecular features of the chemical substance between absorption and emission. In crystalline inorganic semiconductors where an electronic band structure is formed, secondary emission can be more complicated as events may contain both coherent such as resonant Rayleigh scattering where a fixed phase relation with the driving light field is maintained (i.e. energetically elastic processes where no losses are involved) and incoherent contributions (or inelastic modes where some energy channels into an auxiliary loss mode),

The latter originate, e.g., from the radiative recombination of excitons, Coulomb-bound electron-hole pair states in solids. Resonance fluorescence may also show significant quantum optical correlations.

5.3 What is Electroluminescence? There are two main ways of producing light: incandescence and luminescence. In incandescence, electric current is passed through a conductor (filament) whose resistance to the passage of current produces heat. The greater the heat of the filament, the more light it produces. Luminescence, in contrast, is the name given to "all forms of visible radiant energy due to causes other than temperature.

(i) Electroluminescent display:

   Electroluminescent Displays (ELDs) are a type of Flat panel display created by sandwiching a layer of electroluminescent material such as GaAs between two layers of conductors. When current flows, the layer of material emits radiation in the form of visible light. Electroluminescence (EL) is an optical and electrical phenomenon where a material emits light in response to an electric current passed through it, or to a strong electric field.

Mechanism: EL works by exciting atoms by passing an electric current through them, causing them to emit photons. By varying the material being excited, the colour of the light emitted can be changed. The actual ELD is constructed using flat, opaque electrode strips running parallel to each other, covered by a layer of electroluminescent material, followed by another layer of electrodes, running perpendicular to the bottom layer. This top layer must be transparent in order to let light escape. At each intersection, the material lights, creating a pixel.

An electroluminescent (EL) device is similar to a laser in that photons are produced by the return of an excited substance to its ground state, but unlike lasers EL devices require much less energy to operate and do not produce coherent light. EL devices include *light emitting diodes*, which are discrete devices that produce light when a current is applied to a doped p-n junction of a semiconductor, as well as EL displays (ELDs) which are matrix-addressed devices that can be used to display text, graphics, and other computer images. EL is also used in lamps and backlights.

There are four steps necessary to produce electroluminescence in ELDs:

1.   Electrons tunnel from electronic states at the insulator/phosphor interface;

2.   Electrons are accelerated to ballistic energies by high fields in the phosphor;

3. The energetic electrons impact-ionize the luminescent center or create electron-hole pairs that lead to the activation of the luminescent center; and

4. The luminescent center relaxes toward the ground state and emits a photon.

All ELDs have the same basic structure. There are at least six layers to the device. The first layer is a base plate (usually a rigid insulator like glass), the second is a conductor, the third is an insulator, the fourth is a layer of phosphors, and the fifth is an insulator, and the sixth is another conductor. ELDs are quite similar to capacitors except for the phosphor layer (Fig.5.1)
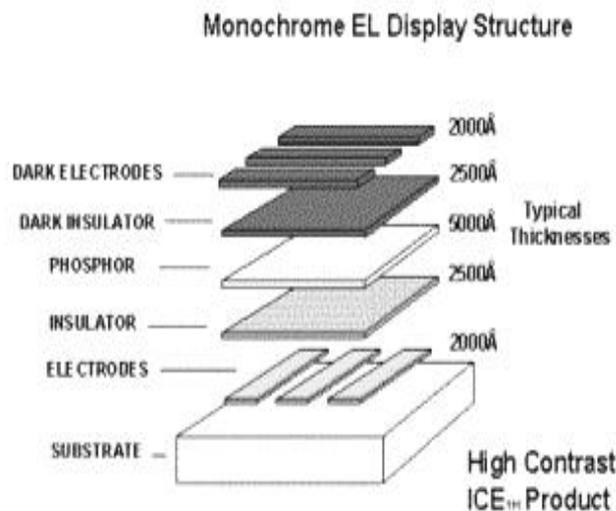

Figure 5.1. Structure of an Electroluminescent Display

5.4 LED Display:

(i) What is an LED Display?

An LED display, or light emitting diode display, is a flat panel display that uses light emitting diodes as the video display. An LED display panel can be either a small display or part of a larger display. LED diodes are used in order to make up an LED display. LED displays are also used in billboards and store signs. An LED panel consists of several LEDs, whereas an LED display consists of several LED panels. LEDs used in order to make up LED displays offer several advantages in comparison to other light emitting sources. A light emitting diode is made up of a semiconductor chip which is surrounded by a transparent plastic case. The plastic case allows the light to pass through it. The emission of different colors including ultraviolet and infrared light depends on the semiconductor material which is used in the diode.

(ii) Types of LED Displays

There are many different kinds of LED Displays.. The most common types for display type are light bar, seven segment and dot matrix. We also carry many other different types of

display. Digit/Alpha/Matrix Size can range from 0.03 in to 0.40 in, with the most common sizes being 0.2 in, 0.3 in and 0.4 in.

(iii) Applications for LED Displays:

LED displays are often found outdoors in billboards and store signs. They can also be found in destination signs on public transportation vehicles or as part of transparent glass area. LED panels can either be used for lighting or for general illumination, task lighting or stage lighting. LED displays can be found in sports stadiums, public squares, train stations, airports, highways, commercial plazas, subways, parks, shopping centers, on tall buildings and for corporate image promotion and advertising. Due to the far viewing distances in sports venues, the high brightness of LED displays can meet this special requirement and ensure that viewers get clear images.

5.5 Drive circuitry

  In electronics, a driver is an electrical circuit or other electronic component used to control another circuit or component, such as a high-power transistor, liquid crystal display (LCD), and numerous others. They are usually used to regulate current flowing through a circuit or to control other factors such as other components, some devices in the circuit. The term is often used, for example, for a specialized integrated circuit that controls high-power switches in switched-mode power converters. An amplifier can also be considered a driver for loudspeakers, or a constant voltage circuit that keeps an attached component operating within a broad range of input voltages.

Typically the driver stage(s) of a circuit requires different characteristics to other circuit stages. For example in a transistor power amplifier, typically the driver circuit requires current gain, often the ability to discharge the following transistor bases rapidly, and low output impedance to avoid or minimize distortion.

(i)   ***Driver Circuits***: Driver circuits are most commonly used to amplify signals from controllers or microcontrollers in order to control power switches in semiconductor devices. Driver circuits often take on additional functions which include isolating the control circuit and the power circuit, detecting malfunctions, storing and reporting failures to the control system, serving as a precaution against failure, analyzing sensor signals, and creating auxiliary voltages.

(ii)   ***Thyristor Driver Circuits:*** In thyristor driver circuits, appropriate control signals are used to generate gate current pulses in order to trigger the thyristor. A transformer often isolates the control circuit from the high voltages of the power circuit (Fig.5.2)

(iii)   ***Drive circuits for LED and Laser***

        LEDs are mostly driven by a digital signal through it can also be modulated with an analog signal. There are various types of driver circuits for LED modulator of which two most popular are shown in Fig.5.3 . LEDs are easy to turn ON quickly, but are difficult to turn OFF because of the relatively long carrier life time. In 5.3(a), resistor R_2 provides the necessary current to turn ON the LED.

Typically R_2 would be in the 40 KΩ range. This makes the turn on current ~ 100 mA peak for a +5V supply. Transistor Q_1 will an impedance of a few ohms, which provides a much larger discharge current allowing the LED to turn OFF quickly. A disadvantage of this circuit is that it draws more current and power when the LED is OFF than the LED is ON.
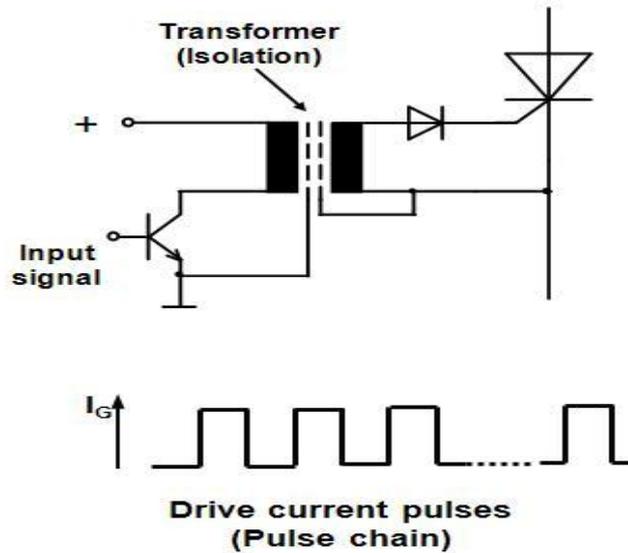

Figure 5.2. *Principle of a thyristor driver circuit*

A better version of the circuit is shown in Fig.5.3(b). Two additional resistors and two capacitors have been added to the basic circuit to improve the operating speed. Capacitor C_1 serves to improve the turn ON and turn OFF characteristics of the transistor itself. Resistors R_3, R_4, and capacitor C_2 provide overdrive when the LED is turned ON and underdrive when the transistor is turned OFF. The overdrive and underdrive accelerates the LED transitions. The R_3C_2 time constant is made approximately equal to the rise and fall time of the LED itself when driven with a digital signal. All these tricks together can increase the operating speed of LED and the driver circuit to about 270 Mb/s and can be pushed up to 1Gb/s. Lasers, of course, can operate mush faster but their drive circuits are much more complex due to compensate for variations in temperature, drive current and power supply voltage.
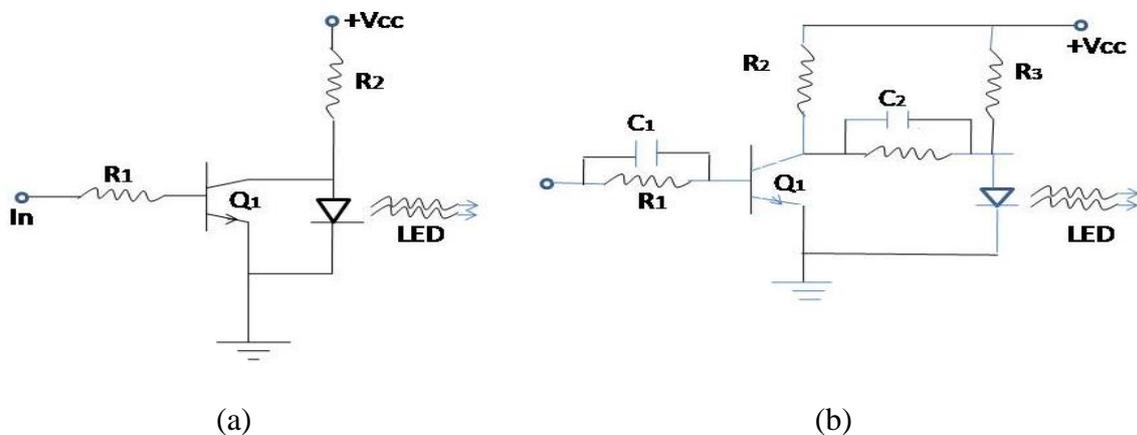

Fig.5.3 LED drive circuits (a) Simple circuit (b) Improved version of (a)

5.6 What is plasma?

The central element in a fluorescent light is a plasma, a gas made up of free-flowing ions (electrically charged atoms) and electrons (negatively charged particles). Under normal conditions, a gas is mainly made up of uncharged particles. That is, the individual gas atoms include equal numbers of protons (positively charged particles in the atom's nucleus) and electrons. The negatively charged electrons perfectly balance the positively charged protons, so the atom has a net charge of zero.

(i) Plasma display:

A plasma display is a computer video display in which each pixel on the screen is illuminated by a tiny bit of plasma or charged gas, somewhat like a tiny neon light. Plasma displays are thinner than cathode ray tube (CRT) displays and brighter than liquid crystal displays (LCD). In addition to the advantage of slimness, a plasma display is flat rather than slightly curved as a CRT display is and therefore free of distortion on the edges of the screen. Unlike many LCD displays, a plasma display offers a very wide viewing angle. Plasma displays come in conventional PC displays sizes and also in sizes up to 60 inches for home theater and high definition television .

The basic idea of a plasma display is to illuminate tiny, colored fluorescent lights to form an image. Each pixel is made up of three fluorescent lights -- a red light, a green light and a blue light. Just like a CRT television, the plasma display varies the intensities of the different lights to produce a full range of colors.

IBM built a monochrome plasma display in the 1980s that displayed orange letters against a black screen. Today's displays contain a grid of cells in which gas reacts with phosphors in varying degrees in red, green, or blue subpixels, making it possible to produce over 16 million different colors.

(ii) Architecture and working of Plasma Panel Display

In a plasma panel display, two glass plates having horizontal and vertical gold electrodes are kept. These gold electrodes are covered with dielectric material (Fig.5.4).
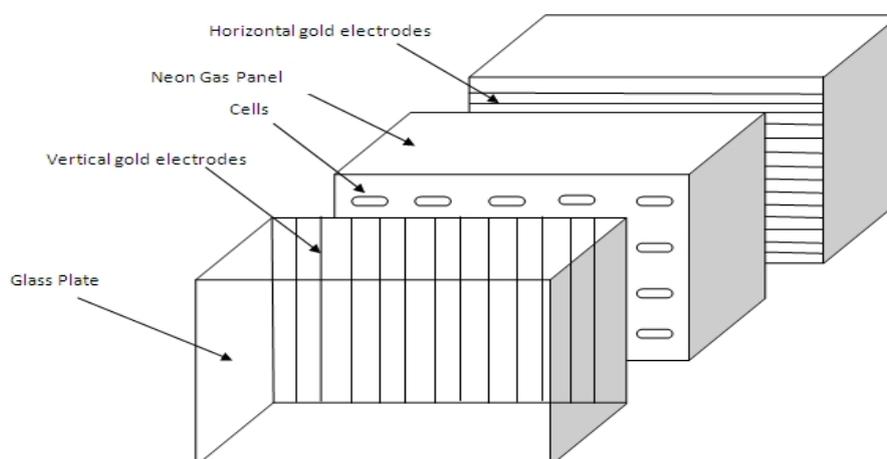

Fig.5.4 Architecture of Plasma Panel Display

In between these two glass plates there is another glass plate filled with neon gas. When voltage is applied through the gold electrodes the neon gas is split in to independent cells and they start to glow. By applying voltages through the gold electrodes this glow can be controlled, thus, creating a display. No refresh is required in a Plasma panel display.

(iii) General characteristics: Plasma displays are bright (1,000 lux or higher for the module), have a wide color gamut, and can be produced in fairly large sizes—up to 3.8 metres (150 in) diagonally. They had a very low-luminance "dark-room" black level compared with the lighter grey of the unilluminated parts of an LCD screen at least in the early history of the competing technologies. Power consumption varies greatly with picture content, with bright scenes drawing significantly more power than darker ones . The plasma that illuminates the screen can reach a temperature of at least 1200 °C (2200 °F). Typical power consumption is 400 watts for a 127 cm (50 in) screen. 200 to 310 watts for a 127 cm (50 in) display when set to cinema mode. Plasma screens are made out of glass. This may causes glare from reflected objects in the viewing area.

(iv) Native plasma television resolutions: Fixed-pixel displays such as plasma TVs scale the video image of each incoming signal to the native resolution of the display panel. The most common native resolutions for plasma display panels are 853×480 (EDTV), 1,366×768 or 1,920×1,080 (HDTV). As a result, picture quality varies depending on the performance of the video scaling processor and the upscaling and downscaling algorithms used by each display manufacturer.

(v) Enhanced-definition plasma television: Early plasma televisions were enhanced-definition (ED) with a native resolution of 840×480 (discontinued) or 853×480, and down-scaled their incoming High-definition video signals to match their native display resolution.

(vi) High-definition plasma television: Early high-definition (HD) plasma displays had a resolution of 1024x1024 and were alternate lighting of surfaces (ALiS) panels made by Fujitsu/Hitachi. These were interlaced displays, with non-square pixels.

Modern HDTV plasma televisions usually have a resolution of 1,024×768 found on many 42 inch plasma screens, 1,280×768, 1,366×768 found on 50 in, 60 in, and 65 in plasma screens, or 1,920×1,080 found in plasma screen sizes from 42 inch to 103 inch. These displays are usually progressive displays, with square pixels, and will up-scale their incoming standard-definition signals to match their native display resolution. 1024x768 resolution requires that 720p content be downscaled.

(vii) Contrast ratio: Contrast ratio is the difference between the brightest and darkest parts of an image, measured in discrete steps, at any given moment. Generally, the higher the contrast ratio, the more realistic the image is . Contrast ratios for plasma displays are often advertised as high as 5,000,000:1. On the surface, this is a significant advantage of plasma over most other current display technologies, a notable exception being organic light-emitting diode.

(viii) Screen burn-in: Image burn-in occurs on CRTs and plasma panels when the same picture is displayed for long periods. This causes the phosphors to overheat, losing some of their luminosity and producing a "shadow" image that is visible with the power off. Burn-in is especially a problem on plasma panels because they run hotter than CRTs. Early plasma televisions were plagued by burn-in, making it impossible to use video games or anything else that displayed static images.

Plasma displays also exhibit another image retention issue which is sometimes confused with screen burn-in damage. In this mode, when a group of pixels are run at high brightness (when displaying white, for example) for an extended period, a charge build-up in the pixel structure occurs and a ghost image can be seen. However, unlike burn-in, this charge build-up is transient and self-corrects after the image condition that caused the effect has been removed and a long enough period has passed (with the display either off or on).

(ix) Plasma display advantages and disadvantages:

Advantages:

(i) Capable of producing deeper blacks allowing for superior contrast ratio.

(ii) Wider viewing angles than those of LCD; images do not suffer from degradation at less than straight ahead angles like LCDs. LCDs using IPS technology have the widest angles, but they do not equal the range of plasma primarily due to "IPS glow", a generally whitish haze that appears due to the nature of the IPS pixel design.

(iii) Less visible motion blur, thanks in large part to very high refresh rates and a faster response time, contributing to superior performance when displaying content with significant amounts of rapid motion. Superior uniformity. LCD panel backlights nearly always produce uneven brightness levels, although this is not always noticeable. High-end computer monitors have technologies to try to compensate for the uniformity problem.

(iv) Unaffected by clouding from the polishing process. Some LCD panel types, like IPS, require a polishing process that can introduce a haze usually referred to as "clouding".

(v) Less expensive for the buyer per square inch than LCD, particularly when equivalent performance is considered.

Disadvantages:

(i) Earlier generation displays were more susceptible to screen burn-in and image retention. Recent models have a pixel orbiter that moves the entire picture slower than is noticeable to the human eye, which reduces the effect of burn-in but does not prevent it.

(ii) Due to the bistable nature of the colour and intensity generating method, some people will notice that plasma displays have a shimmering or flickering effect with a number of hues, intensities and dither patterns. Earlier generation displays (circa 2006 and prior) had phosphors that lost luminosity over time, resulting in gradual decline of absolute image brightness. Newer models have advertised lifespans exceeding 100 000 hours, far longer than older CRTs.

(iii) Uses more electrical power, on average, than an LCD TV using an LED backlight. Older CCFL backlights for LCD panels used quite a bit more power, and older plasma TVs used quite a bit more power than recent models.

(iv) Does not work as well at high altitudes above 6,500 feet (2,000 metres] due to pressure differential between the gases inside the screen and the air pressure at altitude. It may cause a buzzing noise. Manufacturers rate their screens to indicate the altitude parameters.

(v) For those who wish to listen to AM radio, or are amateur radio operators (hams) or shortwave listeners (SWL), the radio frequency interference (RFI) from these devices can be irritating or disabling. Plasma displays are generally heavier than LCD, and may require more careful handling such as being kept upright.

5.7 What are liquid crystals ?:   Materials in nature can be divided into different phases, also called states of matter, depending on the mobility of the individual atoms or molecules. The obvious states of matter are the solid, the fluid and the gaseous state. In the solid state, intermolecular forces keep the molecules close together at a fixed position and orientation, so the material remains in a definite shape. In the fluid state, the molecules are still packed closely together, but they are able to move around. Hence a fluid does not have a rigid shape, but adapts to the contours of the container that holds it. Like a liquid a gas has no fixed shape, but it has little resistance to compression because there is enough empty space for the molecules to move closer. Whereas a liquid placed in a container will form a puddle at the bottom of the container, a gas will expand to fill the container.

Apart from the three familiar states, there exist a large number of other intermediate phases. A simple example is a gel. A gel is not quite solid, neither is it a liquid. *Liquid crystals are another important intermediate phase which exhibits features from both the solid and the fluid state. Liquid crystals have the ordering properties of solids but they flow like liquids.* Liquid crystalline materials have been observed for over a century but were not recognized as such until 1880s. In 1888, Friedrich Reinitzer is credited for the first systematic description of the liquid crystal phase and reported his observations when he prepared cholesteryl benzoate, the first liquid crystal.

The following parameters describe the liquid crystalline structure:

> (i) Positional Order
>
> (ii) Orientational Order
>
> (iii) Bond Orientational Order

Each of these parameters describes the extent to which the liquid crystal sample is ordered. Positional order refers to the extent to which an average molecule or group of molecules shows translational symmetry . Orientational order, as discussed above, represents a measure of the tendency of the molecules to align along the director on a long-range basis. Bond Orientational Order describes a line joining the centers of nearest-neighbor molecules without requiring a regular spacing along that line. Thus, a relatively long-range order with respect to the line of centers but only short range positional order along that line.

Liquid crystals are composed of moderate size organic molecules which tend to be elongated, like a cigar. At high temperatures, the molecules will be oriented arbitrarily, as

shown in the figure below (Fig.5.5), forming an isotropic liquid. Because of their elongated shape, under appropriate conditions, the molecules exhibit orientational order such that all the axes line up and form a so-called nematic liquid crystal. The molecules are still able to move around in the fluid, but their orientation remains the same. Not only orientational order can appear, but also a positional order is possible. Liquid crystals exhibiting some positional order are called smectic liquid crystals. In smectics, the molecular centers of mass are arranged in layers and the movement is mainly limited inside the layers.
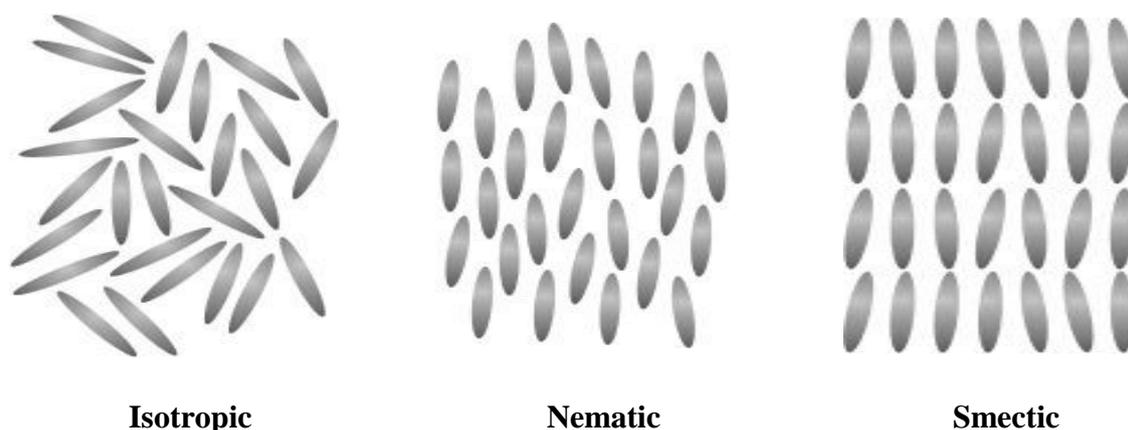

| Isotropic | Nematic | Smectic |

Fig.5.5. Different phases of liquid crystal

The nematic liquid crystal phase is by far the most important phase for applications. In the nematic phase all molecules are aligned approximately parallel to each other. In each point a unit vector can be defined, parallel to the average direction of the long axis of the molecules in the immediate neighborhood. This vector, known as the director, is not constant throughout the whole medium, but is a function of space. The figure (5.6) below shows the molecular structure of a typical rod-like liquid crystal molecule. It consists of two or more ring systems connected by a central linkage group.
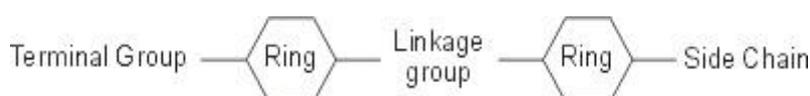

Fig. 5.6 Typical shape of a liquid crystal molecule

The presence of the rings provides the short range molecular forces needed to form the nematic phase, but also affects the electrical and elastic properties. The chemical stability of liquid crystals, their resistance to e.g. moisture or ultraviolet radiation, depends strongly on the central linkage group. Compounds with a single bond in the center are among the most stable ones. At one side of the rings there is a long side chain which strongly influences the elastic constants and the transition temperature of the liquid crystal phases. At the other end, a terminal group is connected, which determines the dielectric constant and its anisotropy. A few examples of molecules that exhibit a liquid crystal phase are shown below. Beside these simple examples, more complicated ways of stacking are possible, giving rise to many other types of liquid crystals. Chiral molecules, molecules without mirror symmetry, can give rise to helices comprising cholesteric liquid crystal phases. In ferroelectric or antiferroelectric liquid crystals the smectic layers possess a permanent polarization which is constant or alternating between successive layers respectively. Apart from the rod-like molecules, more

advanced-shaped liquid crystals are possible such as disk-like or banana-shaped liquid crystals which can give rise to other types of ordering. Discotic liquid crystals can be stacked a columnar phase, the bottom picture illustrates a possibility for stacking banana shaped liquid crystal
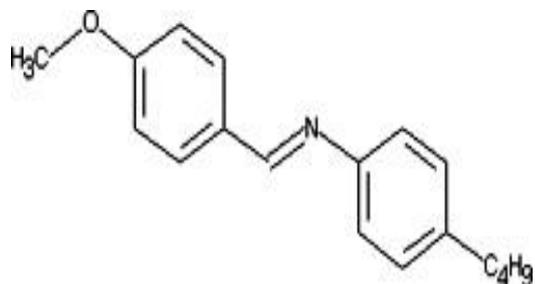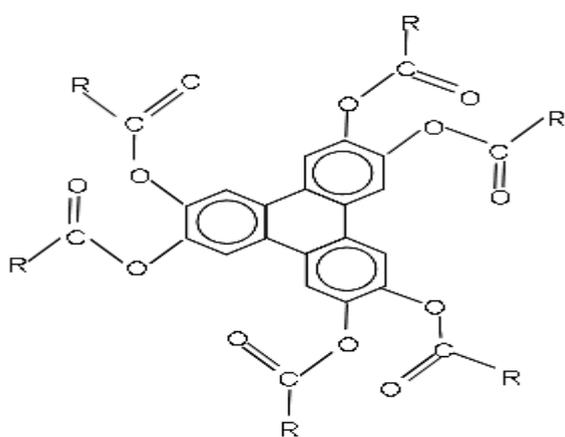

MBBA
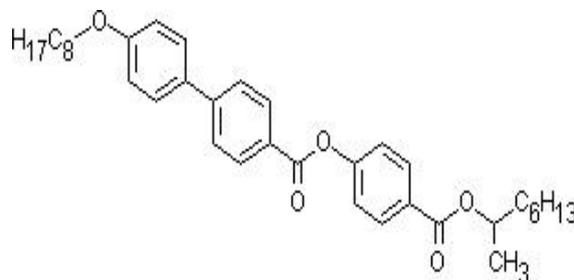
MHPOBC

Discotic shaped liquid crystals
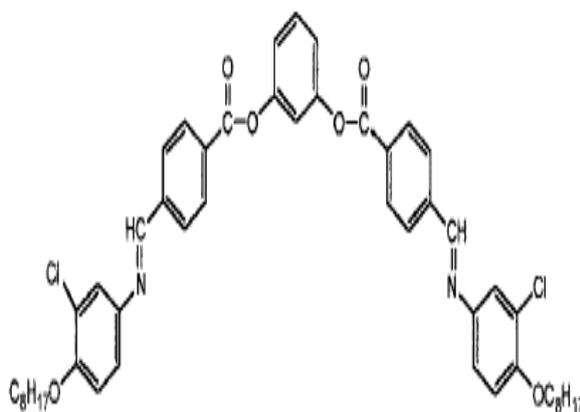

Banana shaped liquid crystals

Examples of molecules which give rise to discotic and banana shaped liquid crystal phases are shown below.

Discotic shaped liquid crystal molecule

**Banana shaped liquid crystal molecule**

One type of liquid crystal molecule can exhibit many different liquid crystal phases. The phase in which a pure liquid crystal (with only one type of molecule) exists depends on the temperature. Pure liquid crystals, or mixtures of them, in which the phase is controlled by temperature are called thermotropic liquid crystals. The Brownian motion of the molecules increases with the temperature, reducing the order in the material. At high temperature, orientational order is lost and the material changes to the isotropic phase. When decreasing the temperature, the material changes to the nematic phase. The temperature at which the phase transition occurs, is specific for each material and is called the nematic-isotropic transition temperature or clearing point. By further lowering the temperature, the phase can change to the smectic A phase, the smectic C and finally to the solid state. Each of the phase transitions occurs at a specific temperature, but depending on the material additional phases can appear or some can be missing.

Beside the thermotropic liquid crystals, a different class of liquid crystals is called lyotropic. These are mixtures of rod-like molecules in an isotropic solvent and the concentration of the solution is primarily responsible for the occurring phase. Lyotropic liquid crystals are mainly of interest in biological applications and exhibit a considerable number of different phases. In our research, only thermotropic liquid crystal are examined. The ordering of the liquid crystal molecules may seem strange, but in our daily environment similar arrangements are common.

(i) Chemical Properties of Liquid Crystals

Liquid crystals can be classified into two main categories: thermotropic liquid crystals, and lyotropic liquid crystals. These two types of liquid crystals are distinguished by the mechanisms that drive their self-organization, but they are also similar in many ways. Thermotropic transactions occur in most liquid crystals, and they are defined by the fact that the transitions to the liquid crystalline state are induced thermally. That is, one can arrive at the liquid crystalline state by raising the temperature of a solid and/or lowering the temperature of a liquid. Thermotropic liquid crystals can be classified into two types: enantiotropic liquid crystals, which can be changed into the liquid crystal state from either lowering the temperature of a liquid or raising of the temperature of a solid, and monotropic liquid crystals, which can only be changed into the liquid crystal state from either an increase in the temperature of a solid or a decrease in the temperature of a liquid, but not both. In general, thermotropic mesophases occur because of anisotropic dispersion forces between the molecules and because of packing interactions. In contrast to thermotropic mesophases, lyotropic liquid crystal transitions occur with the influence of solvents, not by a change in temperature. Lyotropic mesophases occur as a result of solvent-induced aggregation of the constituent mesogens into micellar structures. Lyotropic mesogens are typically amphiphilic , meaning that they are composed of both lyophilic (solvent- attracting) and lyophobic (solvent-repelling) parts. This causes them to form into micellar structures in the

presence of a solvent, since the lyophobic ends will stay together as the lyophilic ends extend outward toward the solution. As the concentration of the solution is increased and the solution is cooled, the micelles increase in size and eventually coalesce. This separates the newly formed liquid crystalline state from the solvent. A very large number of chemical compounds are known to exhibit one or several liquid crystalline phases. Despite significant differences in chemical composition, these molecules have some common features in chemical and physical properties. There are two types of thermotropic liquid crystals: discotics and rod-shaped molecules. Discotics are flat disc-like molecules consisting of a core of adjacent aromatic rings. This allows for two dimensional columnar ordering. Rod-shaped molecules have an elongated, anisotropic geometry which allows for preferential alignment along one spatial direction. The rod-like low molar mass (LMM) liquid crystals, such as 5CB shown in the following diagram:

5CB   *p-n* pentyl-*p'*-cyanobiphenyl (PCB)
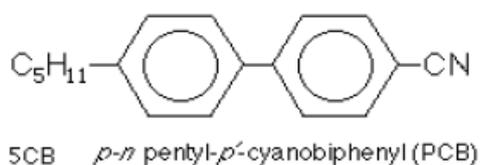
require an extended conformation of the molecule which must be maintained through the rigidity and linearity of its constituents. That is, in order for a molecule to display the characteristics of a liquid crystal, it must be rigid and rod-shaped. This is accomplished by the interconnection of two rigid cyclic units. The interconnecting group should cause the resulting compound to have a linear planar conformation. Linking units containing multiple bonds such as -(CH=N)-, - N=N-, - (CH=CH)n-, - CH=N-N=CH-, etc. are used since they restrict the freedom of rotation. These groups can conjugate with phenylene rings, enhancing the anisotropic polarizability. This increases the molecular length and maintains the rigidity.

(ii) Applications of Liquid Crystals: Liquid crystal technology has had a major effect many areas of science and engineering, as well as device technology. Applications for this special kind of material are still being discovered and continue to provide effective solutions to many different problems.

5.8 LCD Display:

By far the most important application of liquid crystals is display devices. Liquid crystal displays (LCDs) are used in watches, calculators, and laptop computer screens, and for instrumentation in cars, ships, and airplanes. Several types of LCDs exist. In general their value is due to the fact that the orientation of the molecules in a nematic phase substance can be altered by the application of an external electric field, and that liquid crystals are anisotropic fluids, that is, fluids whose physical properties depend on

the direction of measurement. It is not pure liquid crystalline compounds that are used in LCDs, but liquid crystal mixtures having optimized properties.

The simplest LCDs that display letters and numbers have no internal light source. They make use of surrounding light, which is selectively reflected or absorbed. An LCD is analogous to a mirror that is made nonreflective at distinct places on its surface for a certain period. The main advantage of an LCD is low energy consumption. More advanced LCDs need back light, color filters, and advanced electronics to display complex figures. The best-known LCD is the so-called twisted nematic display.

(i) **Liquid Crystal Thermometers:** As demonstrated earlier, chiral nematic (cholesteric) liquid crystals reflect light with a wavelength equal to the pitch. Because the pitch is dependent upon temperature, the color reflected also is dependent upon temperature. Liquid crystals make it possible to accurately gauge temperature just by looking at the color of the thermometer. By mixing different compounds, a device for practically any temperature range can be built. The "mood ring", a popular novelty a few years ago, took advantage of the unique ability of the chiral nematic liquid crystal. More important and practical applications have been developed in such diverse areas as medicine and electronics. Special liquid crystal devices can be attached to the skin to show a "map" of temperatures. This is useful because often physical problems, such as tumors, have a different temperature than the surrounding tissue. Liquid crystal temperature sensors can also be used to find bad connections on a circuit board by detecting the characteristic higher temperature.

((ii) **Optical Imaging recording:** In this technology, a liquid crystal cell is placed between two layers of photoconductor. Light is applied to the photoconductor, which increases the material's conductivity. This causes an electric field to develop in the liquid crystal corresponding to the intensity of the light. The electric pattern can be transmitted by an electrode, which enables the image to be recorded. This technology is still being developed and is one of the most promising areas of liquid crystal research.

(iii) **Other Liquid Crystal Applications:** Liquid crystals have a multitude of other uses. They are used for nondestructive mechanical testing of materials under stress. This technique is also used for the visualization of RF (radio frequency) waves in waveguides. They are used in medical applications where, for example, transient pressure

transmitted by a walking foot on the ground is measured. Low molar mass (LMM) liquid crystals have applications including erasable optical disks, full color "electronic slides" for computer-aided drawing (CAD), and light modulators for color electronic imaging. As new properties and types of liquid crystals are investigated and researched, these materials are sure to gain increasing importance in industrial and scientific applications.

5.9   LED Numeric Displays:

Numeric LED displays, sometimes referred to as 7 segment displays due to the layout of the display allowing to show only numbers, are an eye catching way to display numeric information. This type of display is used for applications such as LED Fuel Price Signs, LED Time & Temperature displays and LED Countdown Clocks where displaying highly visible prices and other numeric information is vital.

(i) Concept and visual structure: The individual segments of a seven-segment display 16x8-grid showing the 128 states of a seven-segment display. The common segment displays shown side by side: 7-segment, 9-segment, 14-segment and 16-segment displays. The seven elements of the display can be lit in different combinations to represent the arabic numerals. Often the seven segments are arranged in an oblique (slanted) arrangement, which aids readability. In most applications, the seven segments are of nearly uniform shape and size (usually elongated hexagons, though trapezoids and rectangles can also be used), though in the case of adding machines, the vertical segments are longer and more oddly shaped at the ends in an effort to further enhance readability. The numerals 6 and 9 may be represented by two different glyphs on seven-segment displays, with or without a 'tail'. The seven segments are arranged as a rectangle of two vertical segments on each side with one horizontal segment on the top, middle, and bottom. Additionally, the seventh segment bisects the rectangle horizontally. There are also fourteen-segment displays and sixteen-segment displays (for full alphanumerics); however, these have mostly been replaced by dot matrix displays. The segments of a 7-segment display are referred to by the letters A to G, where the optional decimal point (an "eighth segment", referred to as DP) is used for the display of non-integer numbers.

(ii) Implementations: Seven-segment displays may use a liquid crystal display (LCD), a light-emitting diode (LED) for each segment, or other light-generating or controlling techniques such as cold cathode gas discharge, vacuum fluorescent, incandescent

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filaments, and others. For gasoline price totems and other large signs, vane displays made up of electromagnetically flipped light-reflecting segments (or "vanes") are still commonly used. An alternative to the 7-segment display in the 1950s through the 1970s was the cold-cathode, neon-lamp-like nixie tube. Starting in 1970, RCA sold a display device known as the Numitron that used incandescent filaments arranged into a seven-segment display. In a simple LED package, typically all of the cathodes (negative terminals) or all of the anodes (positive terminals) of the segment LEDs are connected and brought out to a common pin; this is referred to as a "common cathode" or "common anode" device. Hence a 7 segment plus decimal point package will only require nine pins, though commercial products typically contain more pins, and/or spaces where pins would go, in order to match standard IC sockets. Integrated displays also exist, with single or multiple digits. Some of these integrated displays incorporate their own internal decoder, though most do not: each individual LED is brought out to a connecting pin as described. A multiplexed 4-digit, seven-segment display with only 12 pins Multiple-digit LED displays as used in pocket calculators and similar devices used multiplexed displays to reduce the number of I/O pins required to control the display. For example, all the anodes of the A segments of each digit position would be connected together and to a driver circuit pin, while the cathodes of all segments for each digit would be connected. To operate any particular segment of any digit, the controlling integrated circuit would turn on the cathode driver for the selected digit, and the anode drivers for the desired segments; then after a short blanking interval the next digit would be selected and new segments lit, in a sequential fashion. In this manner an eight digit display with seven segments and a decimal point would require only 8 cathode drivers and 8 anode drivers, instead of sixty-four drivers and IC pins. Often in pocket calculators the digit drive lines would be used to scan the keyboard as well, providing further savings; however, pressing multiple keys at once would produce odd results on the multiplexed display. A single byte can encode the full state of a 7-segment-display. The most popular bit encodings are gfedcba and abcdefg, where each letter represents a particular segment in the display. In the gfedcba representation, a byte value of 0x06 would (in a common-anode circuit) turn on segments 'c' and 'b', which would display a '1'.

(iv)   **Displaying letters::** Hexadecimal digits can be displayed on seven-segment displays. A combination of uppercase and lowercase letters is used for A–F; this is done to obtain a unique, unambiguous shape for each hexadecimal digit

(otherwise, a capital D would look identical to an 0/O and a capital B would look identical to an 8). Also the digit 6 must be displayed with the top bar lit to avoid ambiguity with the letter b.

(iv) Hexadecimal encodings for displaying the digits 0 to F

Digit	gfedcba	abcdefg	a	b	c	d	e	f	g
0	0×3F	0×7E	on	on	on	on	on	on	off
1	0×06	0×30	off	on	on	off	off	off	off
2	0×5B	0×6D	on	on	off	on	on	off	on
3	0×4F	0×79	on	on	on	on	off	off	on
4	0×66	0×33	off	on	on	off	off	on	on
5	0×6D	0×5B	on	off	on	on	off	on	on
6	0×7D	0×5F	on	off	on	on	on	on	on
7	0×07	0×70	on	on	on	off	off	off	off
8	0×7F	0×7F	on	on	on	on	on	on	on
9	0×6F	0×7B	on	on	on	on	off	on	on
A	0×77	0×77	on	on	on	off	on	on	on
b	0×7C	0×1F	off	off	on	on	on	on	on
C	0×39	0×4E	on	off	off	on	on	on	off
d	0×5E	0×3D	off	on	on	on	on	off	on
E	0×79	0×4F	on	off	off	on	on	on	on
F	0×71	0×47	on	off	off	off	on	on	on