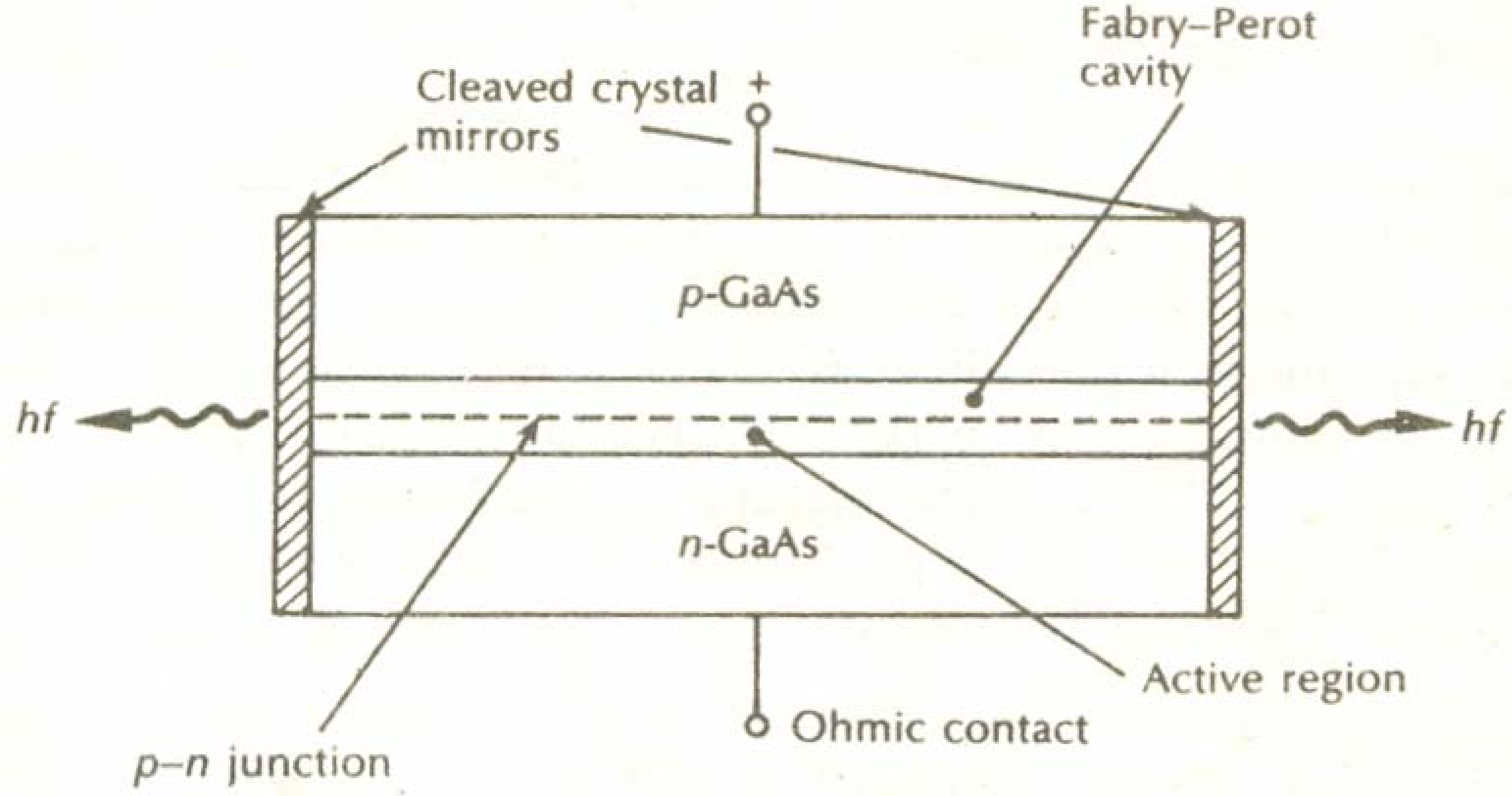
LASERS

SEMI CONDUCTOR INJECTION LASER DIODE

Principle : Stimulated emission by recombination of injected carriers by provision of an optical cavity to provide the feed back of photons

Advantages of ILD :

1. High radiance (due to amplifying effect of stimulated emission).
2. Narrow line width (1 nm) & so less dispersion.
3. Better modulation capabilities.
4. More coherent & hence better focusing capability.
5. Better coupling efficiency of output power into optical fiber



GaAs homojunction injection laser with a Fabry – Perot cavity

EINSTEIN RELATIONS– LASER

- Atomic system is in thermal equilibrium, i.e. the rate of upward transitions must be equal to rate of downward transitions

N_1, N_2 = density of atoms in energy levels E_1 & E_2

g_1, g_2 = corresponding degeneracy's

(no. of sub levels within energy levels E_1 , E_2)

$$\mathbf{N_1 / N_2 = g_1\, e^{-E_1/KT} / g_2\, e^{-E_2/KT}}$$

$$\mathbf{= g_1 / g_2\, e^{(E_2 - E_1)/KT} \quad = \quad g_1 / g_2\, e^{hf/KT} \qquad (1)}$$

Where, $E_2 - E_1$ = hf = energy of single photon

K- Boltzmann's constant, T= abs. temp.

ρf – spectral density, B_{12} – Einst. coefft. of absorption

R_{12} = rate of upward transition = $N_1 \rho f B_{12}$

(R_{12} α $N_1 \rho f$)

R_{21} = downward transition rate = sum of spontaneous and stimulated contributions

$$R_{21} = N_2 A_{21} + N_2 \rho f B_{21}$$

where A_{21}= Einst. Cofft.of spontaneous emission = $1/t_{21}$

t_{21} = spontaneous life time

For thermal equilibrium, $R_{12} = R_{21}$

$$N_1 \rho f B_{12} = N_2 A_{21} + N_2 \rho f B_{21}$$

$$\rho f (N_1 B_{12} – N_2 B_{21}) = N_2 A_{21}$$

$$\rho f = N_2 A_{21}/ N_1 B_{12} – N_2 B_{21} = (A_{21}/ B_{21})/(N_1 B_{12}/N_2 B_{21}) – 1$$

Putting $N_1/N_2 = g_1/g_2\ e^{hf/Kt}$ from = n(1)

$\rho f = (A_{21}/\ B_{21})/(g_1\ B_{12}/g_2 B_{21})\ e^{hf/Kt}\ -1$

$\rho f = (A_{21}/B_{21})/[\ (g_1 B_{12}/g_2\ B_{21}) e^{hf/Kt}\ ] - 1$ = radiation density from a black body (2)

Radiation density for a black body (Planck's Result)

$\rho f = 8\pi\ hf^3/c^3(1/\ e^{hf/\ KT} - 1\ )$ (3)

Comparing the above two results of eq. 2 & 3, we have -

$(A_{21}/B_{21})/(g_1 B_{12}/g_2\ B_{21}) e^{hf/KT} - 1 = 8\pi\ hf^3/c^3\ (1/\ e^{hf/\ KT} - 1)$

$A_{21}/B_{21} = 8\ \pi\ hf^3\ /\ c^3$ **(B)**

$(g_1 B_{12}/g_2\ B_{21}) e^{hf/KT} - 1 = e^{hf\ /Kt} - 1$

$(g_1 B_{12}/g_2\ B_{21}) = 1$ or $B_{12} = (g_2/g_1)\ B_{21}$

If $g_1 = g_2$, $B_{12} = B_{21}$

Einstein Coefft. of absorption = Einstein coefft of stimulated emission

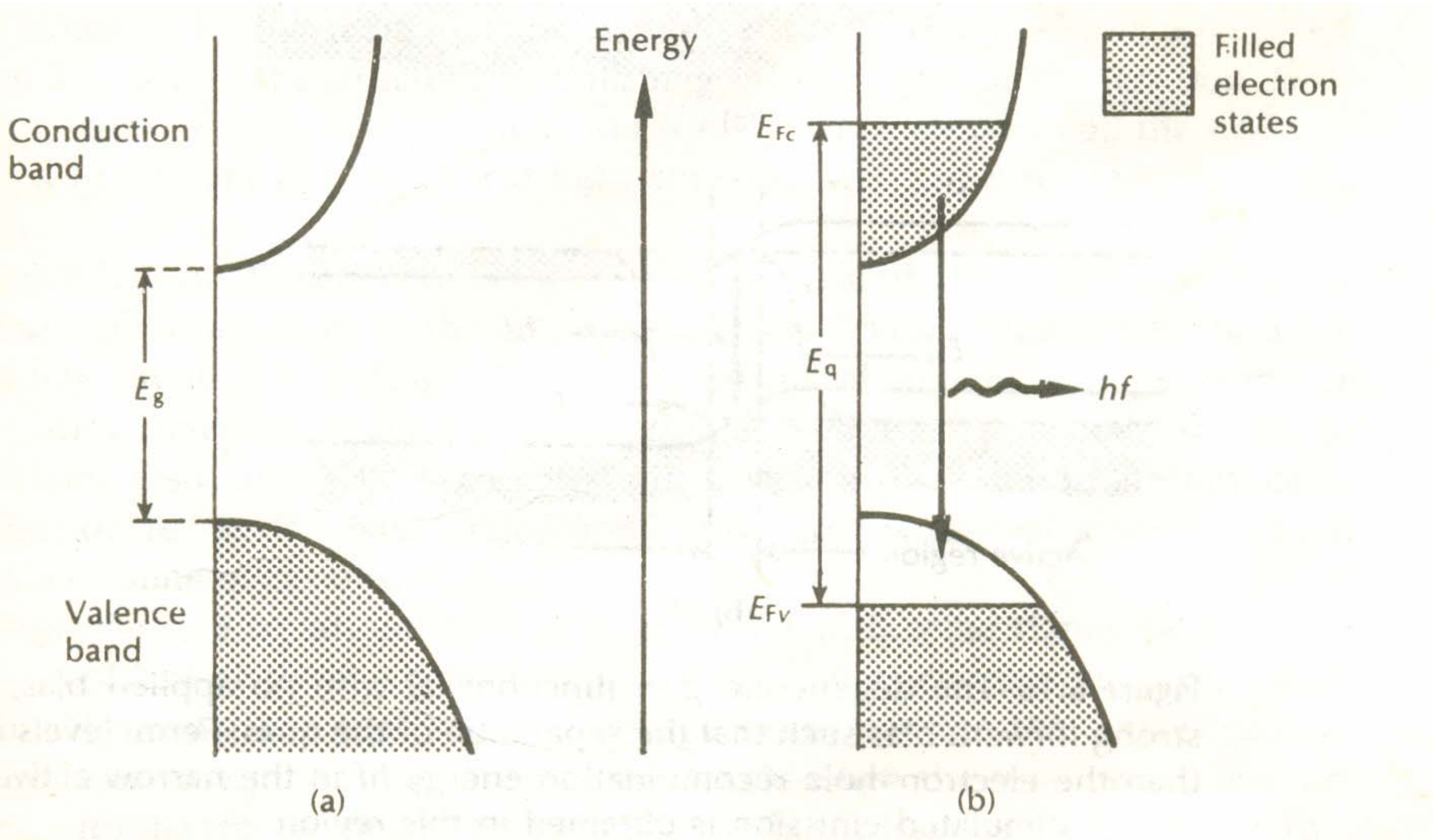
From = n A and= n B

$\rho f = A_{21} / B_{21} (1 / e^{hf/KT} - 1)$

Or $B_{21} \rho f / A_{21} = (1 / e^{hf/KT} - 1)$

= stimulated emission rate / spontaneous emission rate

STIMULATED EMISSION & LASING:-



The filled electron state for an intrinsic direct band gap semiconductor at absolute zero (a) in equilibrium (b) with higher carrier injection

At Abs. zero temperature, conduction band contains no electrons.

Incident photons with energy Eg < (E_{fc} – E_{fv}) can't be absorbed

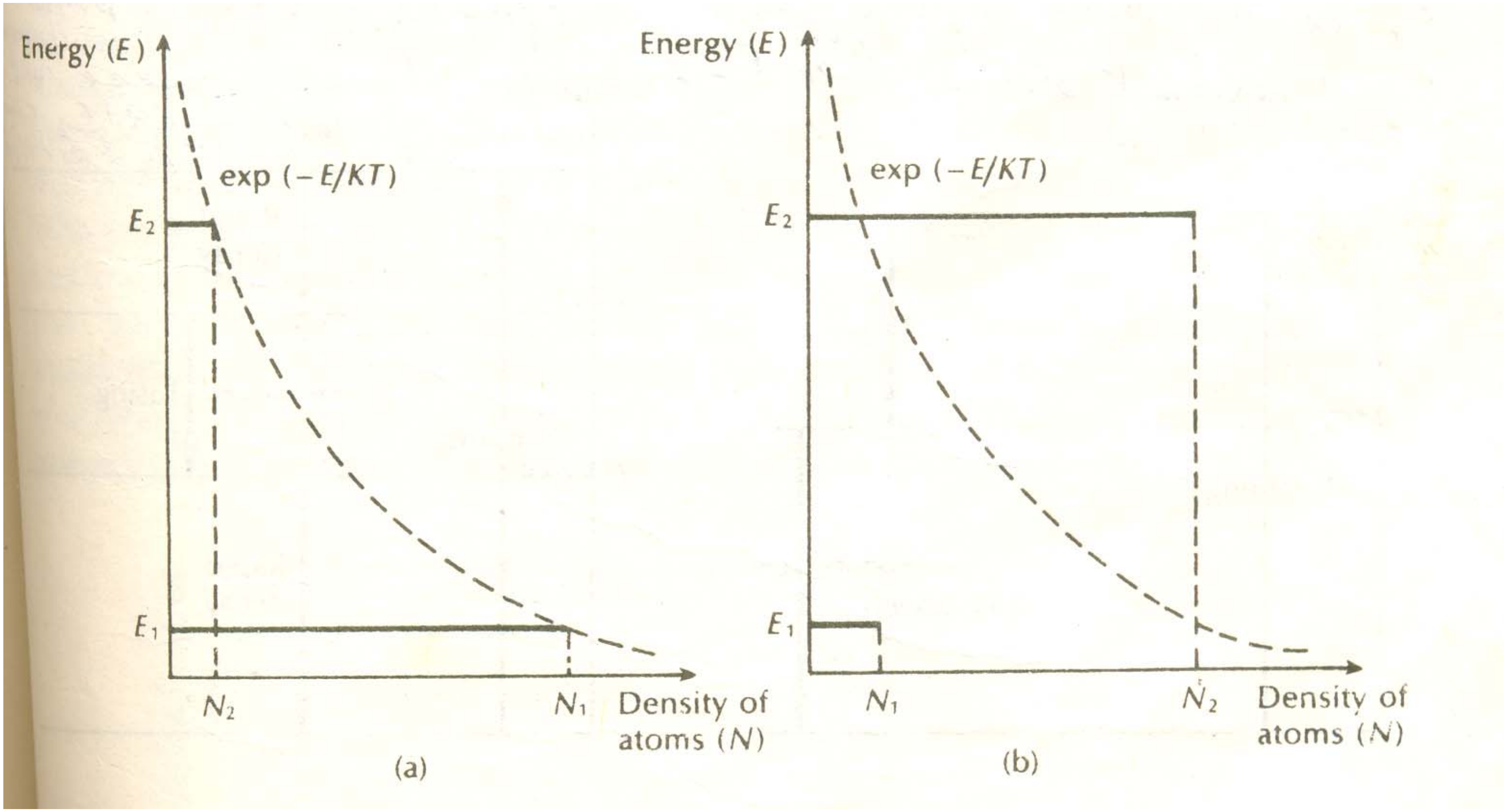
These photons induce downward transition of an electron and thus stimulated emission of another photon.

Basic condition for stimulation : $E_{fc} – E_{fv} > hf > Eg$

Heavy doping satisfies the above condition in a p-n junction thereby providing stimulated emission whereas in a normal p-n junction only spontaneous emission takes place **(LED).**

Another condition (for pn diode) to establish lasing is the provision of optical feedback to give laser oscillation (Fabry – Perot Cavity)

POPULATION INVERSION



(a)Boltzmann distribution for a system in thermal equilibrium;
(b) A non-equilibrium distribution showing population inversion

FOR OPTICAL AMPLICATION : $N_2 > N_1$

(to increase the rate of stimulated emission)

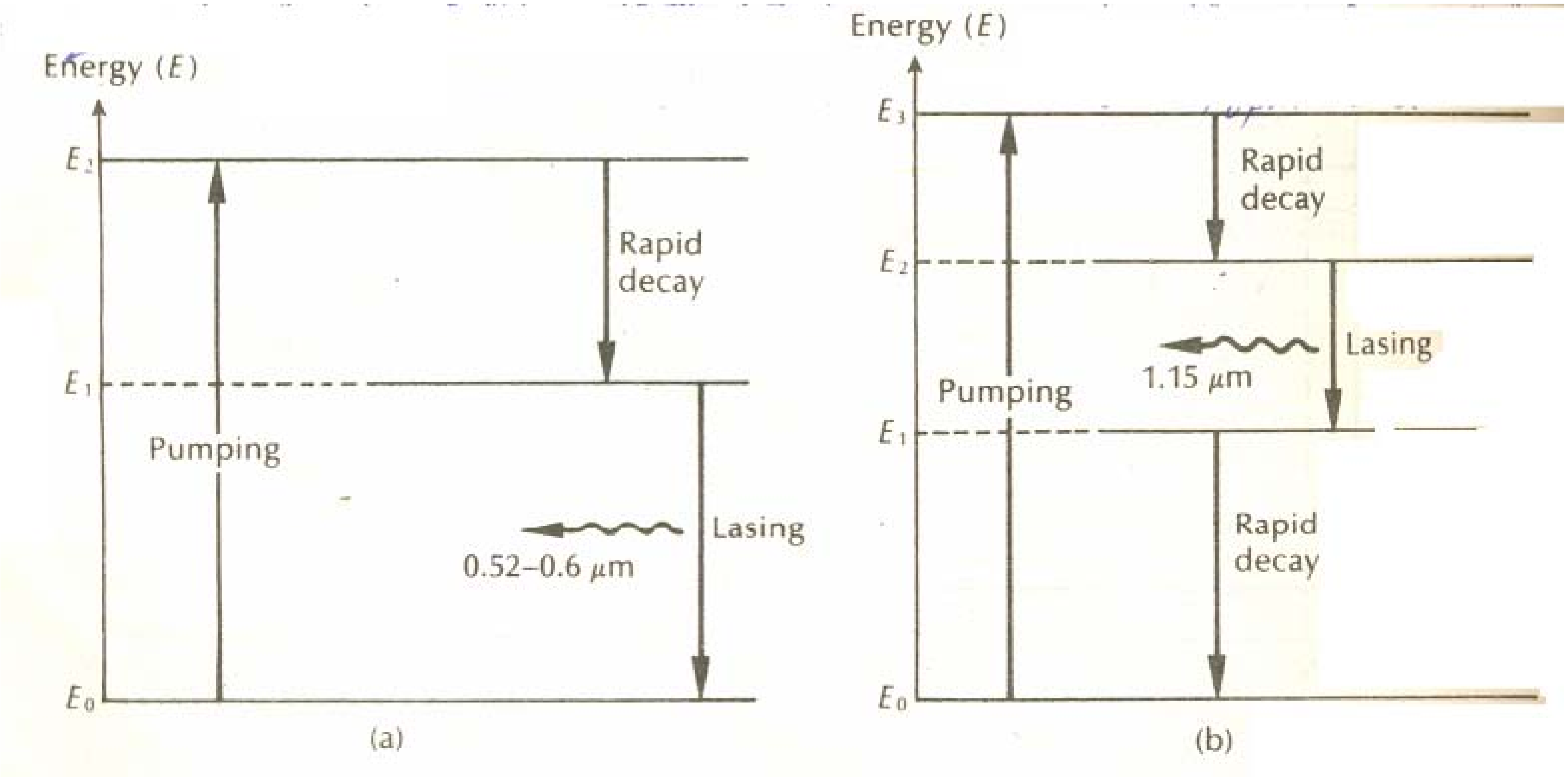
PUMPING :An external energy source is used to excite atoms into the upper energy state, thereby obtaining condition of population inversion.

- Intense radiation from a HF radio field or an optical flash tube is applied.
- The two level system does not lend itself to suitable population inversion.
- From = n $B_{12} = (g_2/g_1) B_{21}$

At best $B_{12} = B_{21}$ (when, $g_1 = g_2$) which means prob. of absorption and stimulated emission are equal ($N_1=N_2$)

- Hence, the necessity to use three or four energy level to obtain population inversion.

THREE AND FOUR LEVEL SYSTEMS - POPULATION INVERSION



Energy level diagrams showing population inversion and lasing for two non-semiconductor lasers: (a) three level system — ruby (crystal) laser; (b) four level system — He—Ne (gas) laser.

Both systems display a central metastable state in which atoms spend an usually long time.

Stimulated emission (lasing) takes place from this metastable state.

With pumping, electrons move from E_0 to E_2 state.

Electrons rapidly decay by non- radiative process to either E_1 or E_0, providing empty states in E_2.

Thus density of atoms in metastable state N_1 increases above the ground state N_0.

$N_1 > N_0$ (population inversion) – LASING

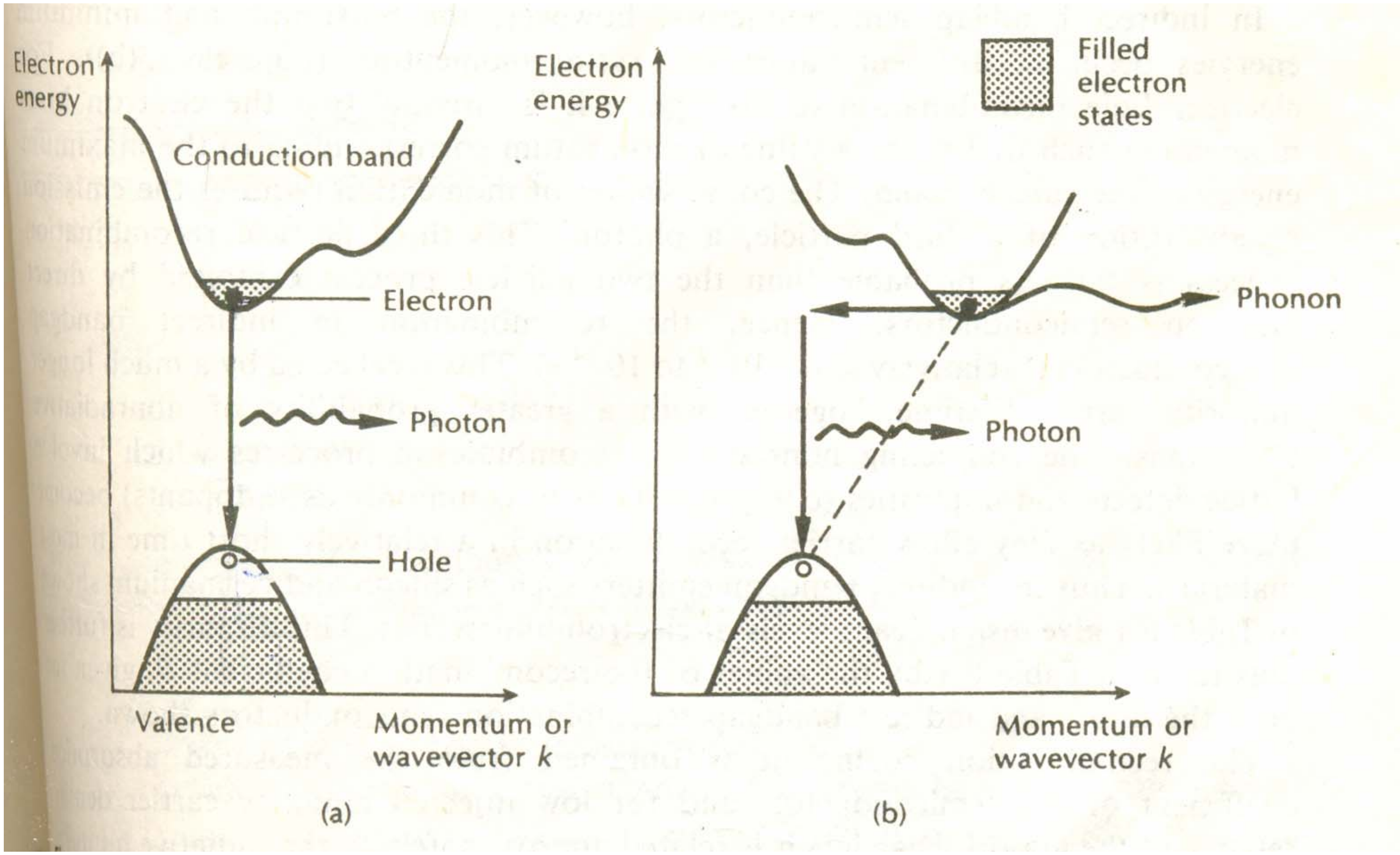
- ***Three level system requires high pump powers***

Four level system

- Pumping excites atoms from E_0 to E_3, and they decay rapidly to meta stable level E_2

Since population of E_3 and E_1 remain essentially unchanged a small increase in no of atoms in E_2 creates population inversion hence lasing takes place between E_2 & E_1

- **FOUR LEVEL SYSTEM HAS MUCH LOWER PUMPING REQUIREMENTS**



Energy — momentum diagrams a) direct bandgap semiconductor; (b) indirect bandgap semiconductor.

Recombination is slow in indirect BG semiconductor

Thus competing non–radiative recombination process becomes more likely (due to impurities/ defects)

DIRECT & INDIRECT BANDGAP SEMICONDUCTORS

Therefore indirect band gap materials give insignificant levels of electroluminescence

p= 2πhk

Avg minority carrier lifetime=10^{-8} to 10^{-10} sec(DBGSC)

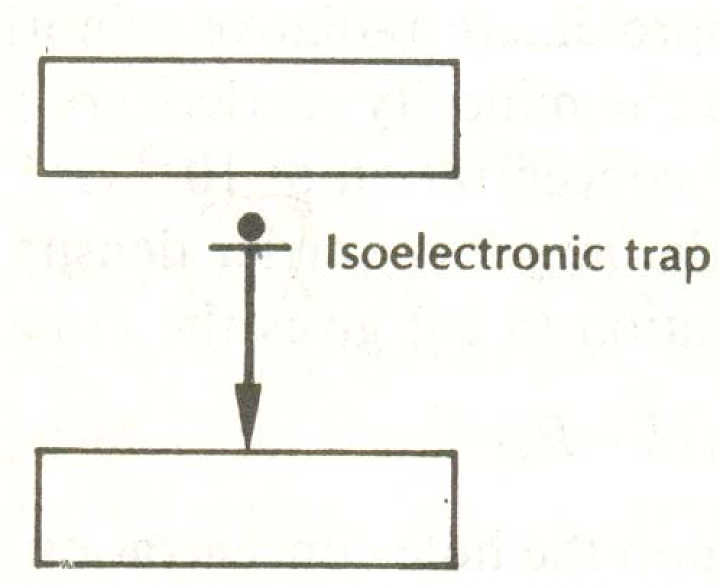
=10^{-2} to 10^{-4} sec(IDBGSC)

Material	Energy Band gap (eV)	Recom.coefft.
GaAs	Direct: 1.43	7.21×10^{-10}
GaSb	Direct : 0.73	2.39×10^{-10}
InAs	Direct : 0.35	8.5×10^{-11}
InSb	Direct : 0.18	4.58×10^{-11}
Si	Indirect : 1.12	1.79×10^{-15}
Ge	Indirect : 0.67	5.25×10^{-14}
GaP	indirect : 2.26	5.37×10^{-14}

Addition of impurity center (N_2) to GaP, indirect BG material converts it into a direct BG material

Nitrogen :- ISOELECTRONIC IMPURITY

(As it has the same no of valance electrons as Phosphorus)



<u>Nitrogen impurity center captures an electron and acts as an ISOELECTRONIC trap which has a large spread of momentum</u>.

Nitrogen :- ISOELECTRONIC IMPURITY

- This trap attracts the oppositely charged carrier (hole) and a direct transition takes place between impurity centre and valence band. **GaP + N_2 becomes an efficient light emitter**. The carrier lifetime is effectively reduced.

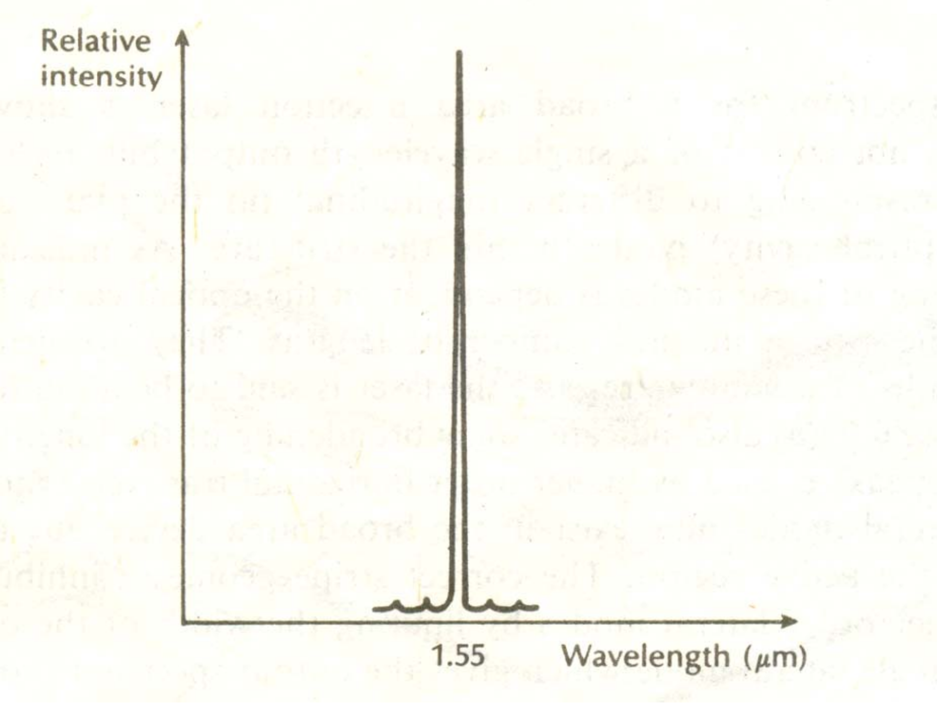
SINGLE MODE OPERATION :

The spectral width of the emission from the single mode device is far smaller than the broadened transition line width, which occurs due to

a) emission over a small frequency band instead on a single frequency.

b) frequency variations due to thermal motion of atoms - Doppler broadening))

c) due to atomic collisions



Typical single longitudinal mode output spectrum from a single-mode injection laser.

OBTAINING A SINGLE MODE OPERATION .

This can be done by reducing the length of the cavity, L until frequency of separation $\delta f = c/2nL$ is larger than the laser transition line width or gain curve. Then only the single mode which falls within the transition line width can oscillate within the laser cavity.

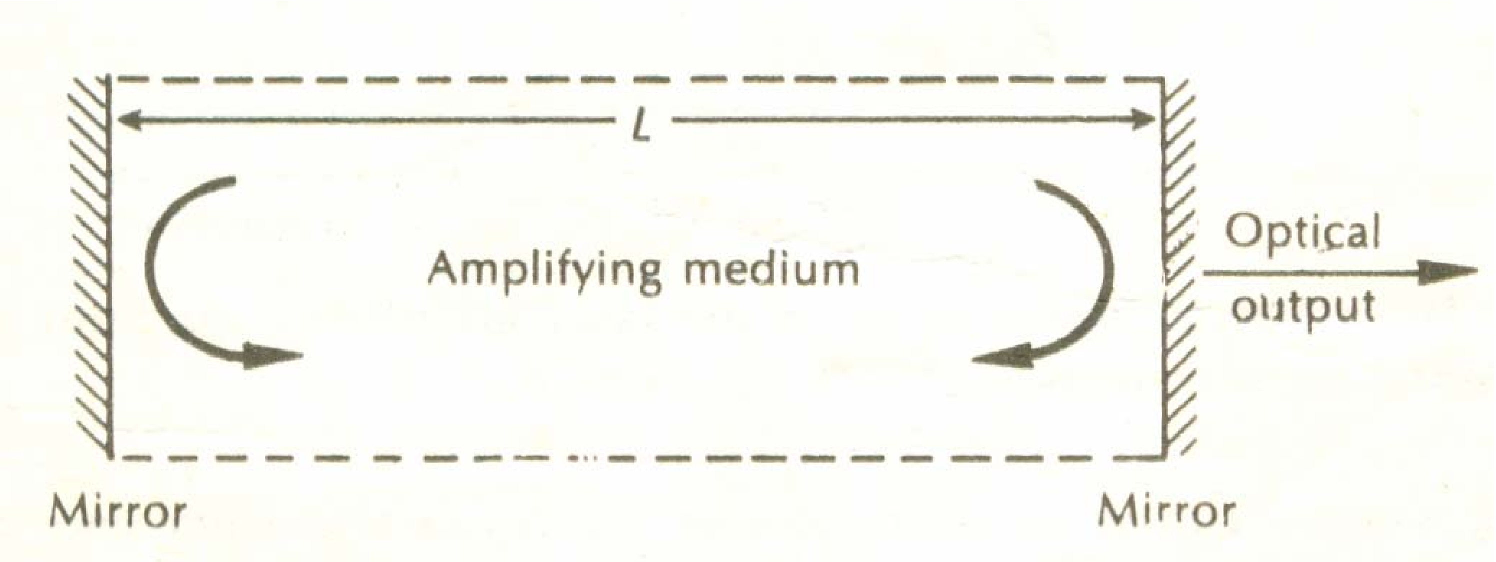
Note : Injection lasers with short cavity lengths (=50 µm) are difficult to handle and have not been very successful.

OPTICAL FEEDBACK AND LASER OSCILLATION

Light amplification in laser occurs due to a photon colliding with an atom (in the excited energy state) to cause stimulated emission of a second photon. Then both these photons release two more.

CONTINUATION OF THIS PROCESS CREATES **AVALANCHE MULTIPLICATION**.

When em waves associated with these photons are in phase, amplified coherent emission is obtained.



The basic laser structure incorporating plane mirrors

The optical cavity formed provides positive feedback of photons by reflection at the mirrors. The structure acts as a FABRY – PEROT resonator.

One mirror is made partially transmitting for useful radiation to escape from cavity.

THRESHOLD CONDITION FOR LASER OSCILLATION

CONDITIONS FOR LASER OSCILLATION

- **Population inversion**
- **Threshold gain within the amplifying medium (to initiate and sustain the laser oscillation).**

Let α = loss coefficient per unit length.

r_1, r_2 = reflectivity of two mirrors.

Fractional loss incurred on each round trip of the beam = $r_1 r_2 e^{-2 \alpha L}$

Fractional gain = e^{2gL} (due to stimulated emission)

where g = gain coefficient per unit length

Hence $e^{2gL} \times r_1 r_2 \, e^{-2\alpha L} = 1$

$r_1 r_2 \, e^{2L(g-\alpha)} = 1$

Or $e^{2L(g-\alpha)} = 1/r_1 r_2$ or $2L(g-\alpha) = \log 1/r_1 r_2$

$(g-\alpha) = 1/2L[\log 1/r_1 r_2]$

$g = l/2L\,[\log 1/r_1 r_2] + \alpha$

(trans. loss thr' mirrors)

Assignment

- What is semiconductor laser diode? Give its advantages and disadvantages.
- Derive EINSTEIN relation for lasers.
- What is Threshold condition for laser oscillation?
- Explain three and four level system - population inversion.