★ **Direct Recombination of Electrons and Holes:-** Electrons of conduction band recombine with Holes in the valence band either directly or indirectly. In the direct recombination electrons falling from the conduction band to empty states (holes) in the valence band. The energy lost by an electron in making the transition is given up as a photon. Direct recombination is spontaneous.

The probability of recombining of an electron and a hole is constant in time.

$$\underbrace{\frac{d[n(t)]}{dt}}_{\substack{\text{rate of change of}\\ \text{conduction band}\\ \text{electrons}}} = \underbrace{\alpha_r n_i^2}_{\substack{\text{rate of generation.}\\ \text{(Thermal generation)}}} - \underbrace{\alpha_r n(t)\, p(t)}_{\text{rate of recombination.}} \quad \text{---- (i)}$$

we know that.

$$\text{Rate of recombination} \propto n(t)\, p(t)$$

$$= \alpha_r n(t)\, p(t)$$

Where α_r = Recombination Cofficient.

Let assume Excess EHP is at $t = 0$. Initial electron - Hole concentrations Δn and Δp are equal.

The instantaneous concentrations of excess carries $= \delta n(t), \delta p(t)$

Now we can write equation (i) in the terms of equilibrium values n_0 and p_0 and excess carrier concentrations $\delta n(t) = \delta p(t)$.

$$\frac{d[\delta n(t)]}{dt} = \alpha_r n_i^2 - \alpha_r [n_0 + \delta n(t)][p_0 + \delta p(t)]$$

$$= -\alpha_r [(n_0 + p_0)\delta n(t)] + \delta n^2(t)]$$

$$= -\alpha_r [(n_0 + p_0)\delta n(t) + \delta n^2(t)] \quad \text{---- (ii)}$$

The equation (ii) is nonlinear and it is difficult to solve it (4)
We simplified for the case of Low-level Injection. SO,

If excess carrier concentrations small then we neglect δn^2.

If material is extrinsic then we can neglect the term representing equilibrium minority carriers-

Suppose P type then $P_0 >> n_0$

$$\therefore \frac{d[\delta n(t)]}{dt} = -\alpha_r P_0 \, \delta n(t)$$

The solution of this equation is an exponential decay from the original excess carrier concentration Δn.

$$\boxed{\begin{aligned} \delta n(t) &= \Delta n \, e^{-\alpha_r P_0 t} \\ &= \Delta n \, e^{-t/\tau_n} \end{aligned}}$$

Where, $\tau_n = (\alpha_r P_0)^{-1}$, called decay constant or recombination life time.

$$\boxed{\begin{aligned} \tau_p &= (\alpha_r n_0)^{-1} \\ \tau_n &= (\alpha_r P_0)^{-1} \end{aligned}}$$

• **Problem:-** A sample of GaAs is doped with $10^{15}/cm^3$ (acceptor) The intrinsic carrier concentration of GaAs [illegible] $10^6/cm^3$, the minority electron concentration is n_0 [illegible]. The minority 10^{14} EHP/cm^3 are created at $t = 0$, & τ_n = [illegible] find α_r (Recombination Coeffecient).

Solution:-

$$P_0 \simeq N_A = 10^{15}/cm^3$$

$$n_i = 10^6/cm^3$$

$$n_0 = \frac{n_i^2}{P_0} = \frac{(10^6)^2}{10^{15}} = 10^{-3}$$

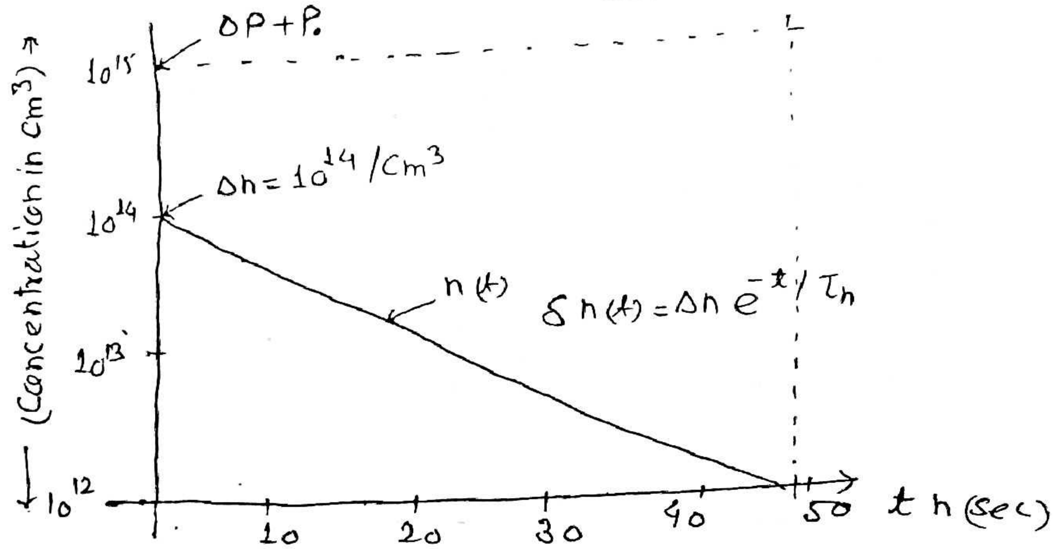
$$P_0 >> n_0$$

$$\therefore \alpha_r = \frac{1}{\tau_n P_0}$$

$$= \frac{1}{10^{-8} Sec \times 10^{15} / Cm^3}$$

$$= 10^{-7} \ Cm^3/Sec$$

$$\underline{\alpha_r = 10^{-7} \ Cm^3/Sec}$$



The exponential decay of $\delta n(t)$ is linear in GaAs.

***Indirect Recombination or Trapping:-** The figure shows- Indirect Recombination

E_r is recombination Level which is bellow E_f at equilibrium and filled with electrons. When excess electrons and holes are created in this material each EHP recombines at E_r in two steps-

- Hole Capture and
- Electron Capture,

Since the recombination Centres are filled at Equilibrium, the first event in the recombination Process is Hole Capture. This process is equivalent an electron of ~~valence band falling~~ at E_r, falling to valence band. and leaving behind an empty state in the recombination level, Thus in Hole Capture, energy is given to Heat to the Lattice.

Falling of electron from E_r to valence band ⟶ Hole Capture,
Conduction band electron falling to E_r ⟶ Electron Capture,

electron Capture must follow the Hole capture means if Hole capture occur the electron capture will occur. Energy is leaving as a heat in both steps.

When both events are occur then recombination Centre is back to it's original state (filled with an electron) but an EHP is missing. Thus one recombination has taken place and the centre is ready to participate in another recombination event by capturing of a hole

Unequal time required for Capturing of each type of Carrier. It mean the electron capture does not follow hole capture immediately after hole capture.

When a carrier is trapped temporarily at a centre and then, is reexcited without recombination taking place, the process is called temporarily trapping.

The effects of recombination and trapping can be measured by an photoconductive decay experiment. The conductivity of the sample during decay is -

$$\boxed{\sigma(t) = q[n(t)\mu_n + p(t)\mu_p]}$$

→ Electron Capture,

→ Recombination level, or, trapping Centre or, defect level.

→ Hole Capture

<u>Steady state Carrier Generation</u> :— *! The steady state electron and Holes concentrations are given in the terms of Fermi levels. The Fermi level E_f is meaningful only when no excess carriers are present. We can write steady state electron and Holes concentrations as expressions in the equilibrium by defining quasi-Fermi levels F_n and F_p for electrons and Holes.

$$n = n_i e^{(F_n - E_i)/kT}$$
$$p = n_i e^{(E_i - F_p)/kT}$$

The thermal generation of EHPs -

$g(T) = g_i$ — for intrinsic Semiconductor,

$g(T) = \alpha_i n_i^2 = \alpha_r n_0 p_0$ ---------(i)

where, α_r = recombination Coefficient.
n_i = Intrinsic Carrier Concentration.
n_0, p_0 = electron, Hole Concentrations at thermal Equilibrium.

If a light is shown on the Sample, an optical generation rate g_{op} will be added to the thermal generation -

$$g(T) + g_{op} = \alpha_r n p$$
$$= \alpha_r (n_0 + \delta n)(p_0 + \delta p) \quad \text{---------(ii)}$$

where, n_0 and, p_0 are equilibrium Concentrations and, δn, δp are departures, for no trapping $\delta n = \delta p$.

Thus (ii) becomes

$$g(T) + g_{op} = \alpha_r [n_0 p_0 + \delta n (n_0 + p_0) + \delta n^2]$$
$$\cancel{g(T)} + g_{op} = \cancel{\alpha_r n_0 p_0} + \alpha_r \delta n (n_0 + p_0) + \alpha_r \delta n^2$$

$$g_{op} = \alpha_r (n_0 + p_0) \delta n$$

$$g_{op} = \frac{\delta n}{\tau_n}$$ δn^2 is neglected for Low level Injection.

Hence excess carrier concentration written as-

$$\boxed{\delta n = \delta p = g_{op} \tau_n}$$

The photoconductivity

$$\boxed{\sigma = q g_{op} (\tau_n \mu_n + \tau_p \mu_p)}$$

Similar to conductivity of Semiconductor.