Recombination and Generation:

T.E $\Rightarrow$ $p \cdot n = n_i^2$

out of equilibrium $\Rightarrow$
$pn > n_i^2$ $\Rightarrow$ recombination
$p \cdot n < n_i^2$ $\Rightarrow$ generation

Recombination rate: $R = r_{rad} \cdot p \cdot n$

$r_{rad} \approx 10^{-10}\ cm^3/s$ direct band gap

$\approx 10^{-15}\ cm^3/s$ indirect band gap (unlikely)

Net transition rate:

$$U = R - G = r_{rad}\,(p \cdot n - n_i^2)$$

Under low injection: $(\Delta p' \ll N_D)$

n-type semiconductor: $U = r_{rad}\,(np - n_0 p_0) \simeq r_{rad}\,(n_0 + p_0) \cdot n'$, $n' = p'$

$n = N_D$ $\Rightarrow$ $U = r_{rad}\,(\underbrace{\cancel{n \cdot p}}_{n_i^2} + n \cdot p' - \cancel{n_i^2})$

$p = p_0 + \Delta p'$

$$U \simeq r_{rad} \cdot N_D \cdot p' \underset{\text{Def.}}{\equiv} \frac{p'}{\tau_p}$$ extra # carriers per time.

Definition of lifetime:

Average time for a minority carrier to recombine:

$$\begin{cases} \tau_p = \dfrac{1}{r_{rad} \cdot N_D} & : \text{n-type} \\[2ex] \tau_n = \dfrac{1}{r_{rad} \cdot N_A} & : \text{p-type} \end{cases}$$

Exercise:

- Consider n-type Si, under low level approximation, and $N_D = 10^{17}\ cm^{-3}$
- Assume a trap at E_i with $N_t = 10^{16}\ cm^{-3}$ and $C_e = C_h = 10^{-11}\ cm^3/s$

$\Rightarrow n_0 \sim N_D = 10^{17}\ cm^{-3}$

we know that:

$$\tau_{rad} = \frac{1}{r_{rad} \cdot n_0} = \frac{1}{2\times 10^{-15}\ cm^3/s \times 10^{17}\ cm^{-3}} = 5ms$$

$$\tau_{Auger} = \frac{1}{r_{ech} \cdot n_0^2} = \frac{1}{1.8\times 10^{-31}\ cm^6/s \times (10^{17}\ cm^{-3})^2} = 0.56\ ms$$

$$\tau_{tr} = \tau_{h0} = \frac{1}{10^{16}\ cm^{-3} \times 10^{-11}\ cm^3/s} = 10\mu s$$

thus

$$\tau = \frac{1}{\frac{1}{\tau_{rad}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{tr}}} =$$

$$= \frac{1}{\frac{1}{5\times 10^{-3}} + \frac{1}{5.6\times 10^{-4}} + \frac{1}{10^{-5}}} = \underline{\underline{9.8\mu s}}$$

$\Rightarrow$ Recombination lifetime is Dominated by trap-assisted recombinations.

Course 7

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R$$

if $G > R \Rightarrow \frac{dn}{dt} > 0$, $\frac{dp}{dt} > 0 \Rightarrow$ we generate carriers n and p

with external generation (for example shining light):

$$G = G_{ext} + G_{int}$$

then:

$$\frac{dn}{dt} = \frac{dp}{dt} = G_{ext} \underbrace{- G_{int} - R}_{U} = G_{ext} - U$$

Under low-level injection:

$U_i \simeq \frac{n'}{\tau_i}$, $\frac{dn}{dt} = \frac{dn'}{dt}$, since $n = n_0 + n'$ and assuming that n_0 is time independent.

$$\boxed{\frac{dn'}{dt} = G_{ext} - \frac{n'}{\tau}}$$

Case 1: static case where $\frac{dn}{dt} = 0$ (nothing changes as a function of time)

$$\Rightarrow n' = G_{ext} \cdot \tau$$

excess carriers is the generation rate times the carrier lifetime.

Case 2: if $G_{ext} = 0$

the homogeneous solution is $n' \propto e^{-t/\tau}$: excess carriers decay with a time τ

1) Turn-on transient :

- Lights are turned ON at $t = 0$:

$$\begin{cases} t = 0 , & n' = 0 \\ t = \infty , & n' = g_e \cdot \tau \end{cases}$$

- τ is a characteristic time of the problem

$$\Rightarrow \boxed{n'(t) = g_e \tau \left(1 - e^{-t/\tau}\right)}$$

- $t \gg \tau$: rate of generation of carriers decrease towards 0

1. Initially : n' increases since $G > R$

2. As n' builds up, R increases but G does not change.

3. n' is constant when $G = R$ $\Rightarrow$ steady - state is reached!

2) turn - off transient

- Lights are ON for $t < 0$

- $t > 0$, $G_{ext} = 0$

boundary conditions :

$$\begin{cases} t = 0 , & n' = g_e \tau \\ t = \infty , & n' = 0 \quad \text{(lights are OFF)} \end{cases}$$

$$\Rightarrow \boxed{n'(t) = g_e \tau e^{-t/\tau}}$$

1. After equilibrium is disrupted, it takes $t > \tau$ to re-establish it.

2. After equilibrium is disrupted : $\underline{R}$ not balanced by $(G_{ext} + G_{int})$

$\Rightarrow R > G$, thus n' is reducing and so R

until $R = G$

Internal Quantum Efficiency

$$\text{Internal Quantum Efficiency (IQE)} = \frac{\text{radiative recombination rate}}{\text{total recombination rate}}$$

$$U_i = \frac{n'}{\tau_i}$$

in LLI :

$$\tau_{rad} = \frac{1}{\underbrace{r_{rad}}_{\text{recombination constant}}(n_0 + p_0)} \Rightarrow U_{rad} = n' \cdot r_{rad} \cdot (n_0 + p_0)$$

$$\tau_{Aug} = \frac{1}{(r_{eeh} n_0 + r_{ehh} p_0)(n_0 + p_0)} \Rightarrow U_{Aug}$$

$$\tau_{tr} = \frac{\tau_{h_0} n_0 + \tau_{e_0} p_0}{n_0 + p_0} \Rightarrow U_{tr}$$

Let's assume n-type material :

$$U_{rad} = n' \cdot r_{rad} \cdot n_0$$

$$U_{Aug} = n' \cdot r_{eeh} \cdot n_0^2 \Rightarrow U = n'/\tau_{h_0} + n' r_{rad} \cdot n_0 + n' \cdot r_{eeh} n_0^2$$

$$U_{tr} = n'/\tau_{h_0}$$

$$IQE = \frac{\cancel{n'} \cdot r_{rad}\, n_0}{\cancel{n'}/\tau_{h_0} + \cancel{n'} \cdot r_{eeh} \cdot n_0^2 + \cancel{n'}\, r_{rad} \cdot n_0}$$

or

$$IQE = \frac{1/\tau_{rad}}{1/\tau_{tr} + 1/\tau_{Aug} + 1/\tau_{rad}}$$