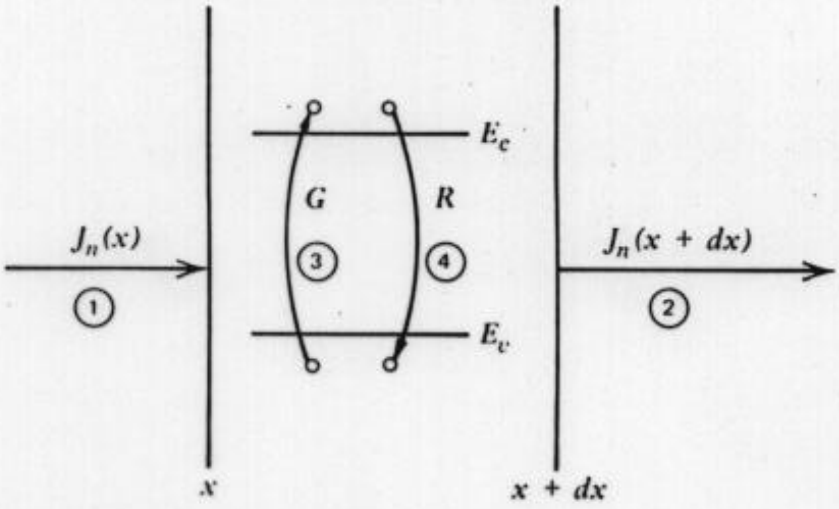
CONTINUITY EQUATION



BALANCE EQUATION

TOTAL INCREASE OF ELECTRONS BETWEEN X AND X+dx PER UNIT TIME : ① - ② + ③ - ④

$$\frac{dn}{dt} A dx = \left[\frac{J_n(x)}{-q} - \frac{J_n(x+dx)}{-q}\right] A + (G_n - R_n) A dx$$

VOLUME BETWEEN X AND X+dx

AREA

TAYLOR EXPANSION

$$J_n(x+dx) = J_n(x) + \frac{\partial J_n}{\partial x} dx + \dots$$

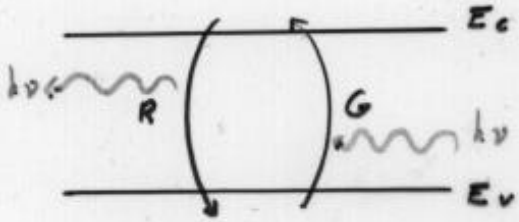
CONTINUITY EQUATION

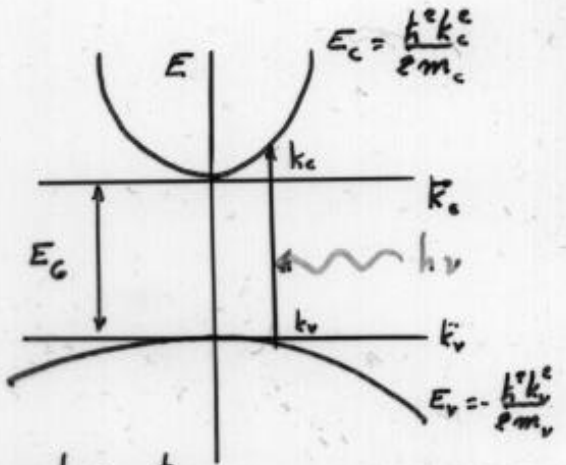
$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G_p - R_p$$

GENERATION-RECOMBINATION

a) DIRECT PROCESSES





ENERGY CONSERVATION : $E_c - E_v = h\nu = \hbar cq$ q : PHOTON WAVE-VECTOR

MOMENTUM CONSERVATION : $\hbar k_c - \hbar k_v = \hbar q = \frac{h\nu}{c} \neq 0$ c : SPEED OF LIGHT

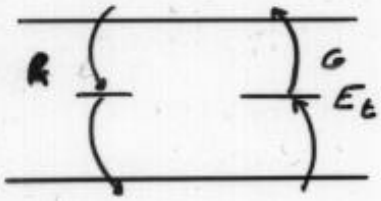
↖ LARGE VALUE

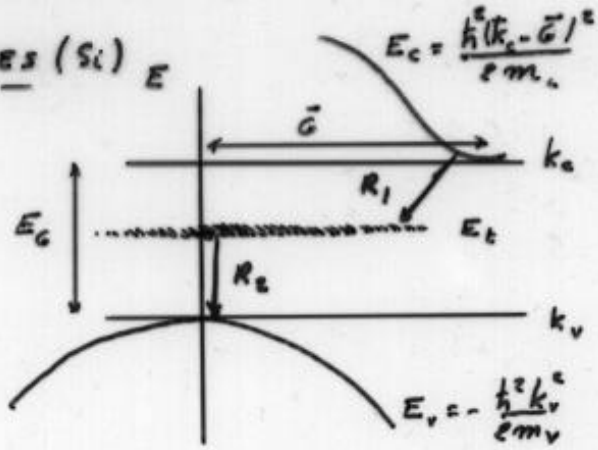
$\Rightarrow \boxed{k_c \simeq k_v}$

RADIATIVE PROCESS ONLY POSSIBLE IN DIRECT GAP SEMICONDUCTORS

E.G. GaAs, InP, InAs, ... NOT Si AND Ge

b) INDIRECT PROCESSES (Si)



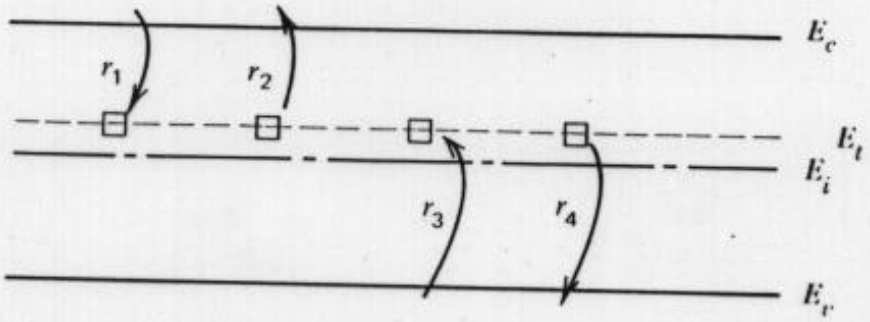


$k_c \neq k_v$: RADIATIVE PROCESSES ARE NOT POSSIBLE

$\Rightarrow$ NON RADIATIVE { RECOMBINATION / GENERATION } DOMINATE

GENERATION AND RECOMBINATION

- ELEMENTARY PROCESSES: CAPTURE - EMISSION

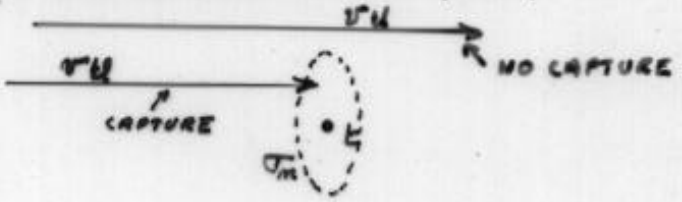


E_t : LOCALIZED STATE DEEP IN THE ENERGY GAP

1. ELECTRON CAPTURE

CAPTURE RATE : $r_1 = n\{N_t[1 - f(E_t)]\} v_{th} \sigma_n$

σ_n : CAPTURE CROSS SECTION (cm^2)



2. ELECTRON EMISSION

EMISSION RATE : $r_2 = N_t f(E_t) e_n$

e_n : EMISSION PROBABILITY (s^{-1})

3. HOLE CAPTURE

CAPTURE RATE : $r_3 = N_t f(E_t) p v_{th} \sigma_p$

4. HOLE EMISSION

EMISSION RATE : $r_4 = N_t [1 - f(E_t)] e_p$

- ELEMENTARY PROCESSES (CONTINUED)

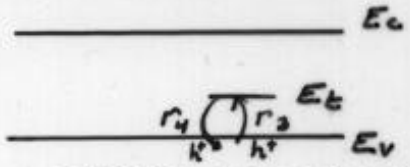
- EQUILIBRIUM : $\begin{cases} r_1 = r_2 \\ r_3 = r_4 \end{cases}$

$$\begin{cases} e_n = v_{th}\,\sigma_n\, n_i \exp\left(\dfrac{E_t - E_i}{kT}\right) \\ e_p = v_{th}\,\sigma_p\, n_i \exp\left(\dfrac{E_i - E_t}{kT}\right) \end{cases}$$

- NON-EQUILIBRIUM : $\begin{cases} r_1 \neq r_2 \\ r_3 \neq r_4 \end{cases}$

EX : EXCESS HOLES $\Rightarrow$ $r_3 > r_4$: E_t CAPTURES A HOLE

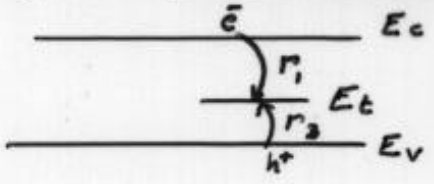
a) E_t AS A TRAP : r_4 INCREASES



E_t EMITS A HOLE TO THE VALENCE BAND

OVERALL, NO HOLE SPENT TIME ON E_t : RECOMB. INCOMPLETED

b) E_t AS A RECOMBINATION CENTER : r_1 INCREASES



E_t CAPTURES AN ELECTRON FROM THE CONDUCTION BAND

OVERALL, AN ELECTRON AND A HOLE HAVE DISAPPEARED: RECOMBINATION COMPLETED

SHOCKLEY-HALL-READ RECOMBINATION (SHR)

- NON-EQUILIBRIUM : $\begin{cases} r_1 \neq r_2 \\ r_3 \neq r_4 \end{cases}$

- NET RECOMBINATION RATE : $\begin{cases} U = R_{sp} - G_{sp} \\ U = r_1 - r_2 = r_3 - r_4 \end{cases}$

$$U = \frac{N_t v_{th} \sigma_n \sigma_p [pn - n_i^2]}{\sigma_p \left[p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right] + \sigma_n \left[n + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right]}$$

$$= \frac{[pn - n_i^2]}{\tau_{no}\left[p + n_i \exp\left(\frac{E_i - E_t}{kT}\right)\right] + \tau_{po}\left[n + n_i \exp\left(\frac{E_t - E_i}{kT}\right)\right]}$$

WITH $\tau_{no} = [N_t v_{th} \sigma_n]^{-1}$ AND $\tau_{po} = [N_t v_{th} \sigma_p]^{-1}$

IF $\sigma_n = \sigma_p = \sigma_0$

$\tau_0 = [N_t v_{th} \sigma_0]^{-1}$

$$U = \frac{(pn - n_i^2)}{\tau_0 \left[p + n + 2 n_i \cosh\left(\frac{E_t - E_i}{kT}\right)\right]} \quad \text{IN } cm^{-3} s^{-1}$$