Chem 140a

Lecture Notes #9: Class #11

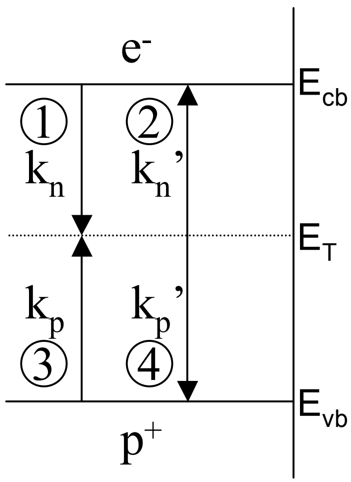
Recombination under different light intensity
- Low level injection vs High level injection

<Review>

We looked at recombination/generation

: We usually work away from the equilibrium. so we want to understand R-G process

Typically we add more carriers so that np>n_i^2 → <u>Recombination</u> is dominant



$$r_n = \left.\frac{dn}{dt}\right|_R = \left.\frac{dn}{dt}\right|_1 + \left.\frac{dn}{dt}\right|_2 = -k_n \cdot n_b \cdot (1 - f_T) \cdot N_T + k_n' \cdot f_T \cdot N_T$$

$$r_p = \left.\frac{dp}{dt}\right|_R = \left.\frac{dp}{dt}\right|_3 + \left.\frac{dp}{dt}\right|_4 = -k_p \cdot p_b \cdot f_T \cdot N_T + k_p' \cdot (1 - f_T) \cdot N_T$$

By applying equilibrium conditions: Principle of detailed balance

$$\boxed{r_n = r_p = 0}$$

$$k_n n_{b,0} (1 - f_T) N_T = k_n' f_T N_T$$

$$k_n' = \frac{1 - f_T}{f_T} k_n n_{b,0}$$

<Review>

Then we calcaulated

$$\frac{1-f_T}{f_T} = \exp[-(E_F - E_T)/kT]$$

$$\therefore k_n' = k_n(\frac{1-f_T}{f_T})n_{b,0} = k_n n_{b,0}\exp[-(E_F - E_T)/kT] = k_n N_C \exp[-(E_C - E_T)/kT]$$

$$(\because\ n_{b,0} = \mathrm{N_C}\exp[-(E_C - E_F)/kT])$$

k_n' doesn't depend on the Fermi level and only depends on the trap energy level

Let $\mathrm{n_1} = \mathrm{N_C}\exp[-(E_C - E_T)/kT]$

$\mathrm{p_1} = \mathrm{N_V}\exp[-(E_T - E_V)/kT]$ **Then,**

$\underline{k_n' = k_n n_1}$

$\underline{k_p' = k_p p_1}$

By plugging in k_n' and k_p' ,

$$\mathrm{r_n} = \left.\frac{dn}{dt}\right|_R = -k_n \cdot n_b \cdot (1-f_T)\cdot N_T + k_n \cdot n_1 \cdot f_T \cdot N_T$$

$$\mathrm{r_p} = \left.\frac{dp}{dt}\right|_R = -k_p \cdot p_b \cdot f_T \cdot N_T + k_p \cdot p_1 \cdot (1-f_T)\cdot N_T$$

<Review>

For steady state assumed case,

$$U_{bulk} = -\left.\frac{dn}{dt}\right|_R = -\left.\frac{dp}{dt}\right|_R = \text{ recombination rate}$$

Plug in our values for r_n & r_p

$$k_n \cdot n_b \cdot (1 - f_T) \cdot N_T - k_n \cdot n_1 \cdot f_T \cdot N_T = k_p \cdot p_b \cdot f_T \cdot N_T - k_p \cdot p_1 \cdot (1 - f_T) \cdot N_T$$

N_Ts cancel and solve for f_T

$$f_T = \frac{k_n \cdot n_b + k_p \cdot p_1}{k_n \cdot n_b + k_n \cdot n_1 + k_p \cdot p_b + k_p \cdot p_1}$$

$$1 - f_T = \frac{k_p \cdot p_b + k_n \cdot n_1}{k_n \cdot n_b + k_n \cdot n_1 + k_p \cdot p_b + k_p \cdot p_1}$$

Now that we have f_T and 1-f_T we can use them to calculate U.

<Review>

$$U_{bulk} = -\left.\frac{dn}{dt}\right|_R = -\left.\frac{dp}{dt}\right|_R$$

$$= -k_n \cdot n_b \cdot (1 - f_T) \cdot N_T + k_n \cdot n_1 \cdot f_T \cdot N_T$$

$$U_{bulk} = N_T \frac{k_n \cdot n_b \cdot (k_p \cdot p_b + k_n \cdot n_1) - k_n \cdot n_1 \cdot (k_n \cdot n_b + k_p \cdot p_1)}{k_n \cdot (n_b + n_1) + k_p \cdot (p_b + p_1)}$$

$$U_{bulk} = N_T \frac{k_n \cdot k_p \cdot (n_b \cdot p_b - n_1 \cdot p_1)}{k_n \cdot (n_b + n_1) + k_p \cdot (p_b + p_1)}$$

$$n_1 \cdot p_1 = \mathrm{N_C} \exp[-(E_C - E_T)/kT] \cdot \mathrm{N_V} \exp[-(E_T - E_V)/kT]$$

$$= \mathrm{N_C} \cdot \mathrm{N_V} \cdot \exp[-(E_C - E_V)/kT] = n_i^2$$

So the recombination rate in bulk,

$$U_{bulk} = N_T \frac{k_n \cdot k_p \cdot (n_b \cdot p_b - n_i^2)}{k_n \cdot (n_b + n_1) + k_p \cdot (p_b + p_1)}$$

Surface Recombination

It turns out we can write the same equation for the surface, but by modifying all terms to be surface related ones

$$U_{surface} = N_{T,S} \frac{k_{n,s} \cdot k_{p,s} \cdot (n_s \cdot p_s - n_i^2)}{k_{n,s} \cdot (n_s + n_{1,s}) + k_{p,s} \cdot (p_s + p_{1,s})}$$

$N_{T,S}$: different from the bulk. Unit is [cm^{-2}], not [cm^{-3}]

$\rightarrow k_{n,s}$ and $k_{p,s}$ are different from the bulk

$E_{T,S}$ is different from E_T (bulk) $\rightarrow$ $n_{1,s}$ is different from n_1 (bulk)

n_i^2 is the only term that is the same

Surface vs Bulk Recombination

Units

$$U_{bulk} = N_T \frac{k_n \cdot k_p \cdot (n_b \cdot p_b - n_i^2)}{k_n \cdot (n_b + n_1) + k_p \cdot (p_b + p_1)}$$

$$\rightarrow \quad U_{bulk} \; : \; \frac{\text{particles}}{cm^3 \cdot s} = [cm^{-3}] \frac{[\frac{cm^3}{s}][\frac{cm^3}{s}][cm^{-6}]}{[\frac{cm^3}{s}][cm^{-3}]}$$

$$U_{surface} = N_{T,S} \frac{k_{n,s} \cdot k_{p,s} \cdot (n_s \cdot p_s - n_i^2)}{k_{n,s} \cdot (n_s + n_{1,s}) + k_{p,s} \cdot (p_s + p_{1,s})}$$

$$\rightarrow \quad U_{surface} \; : \; \frac{\text{particles}}{cm^2 \cdot s} = \text{flux} = [cm^{-2}] \frac{[\frac{cm^3}{s}][\frac{cm^3}{s}][cm^{-6}]}{[\frac{cm^3}{s}][cm^{-3}]}$$

Surface vs Bulk Recombination

For the bulk recombination,

$$U_{bulk} = N_T \frac{k_n \cdot k_p \cdot (n_b \cdot p_b - n_i^2)}{k_n \cdot (n_b + n_1) + k_p \cdot (p_b + p_1)}$$

Divide by $k_n \cdot k_p \cdot N_T$

$$\rightarrow \quad U_{bulk} = \frac{n_b \cdot p_b - n_i^2}{\frac{1}{N_T \cdot k_p} \cdot (n_b + n_1) + \frac{1}{N_T \cdot k_n} \cdot (p_b + p_1)}$$

$$N_T \cdot k_p : [cm^{-3}] \cdot [cm^3 / s] = 1/s \;\rightarrow \frac{1}{N_T \cdot k_p} = \tau_p$$

Similarly, $$\frac{1}{N_T \cdot k_n} = \tau_n$$

where τ **is the lifetime of carrier**

$$U_{bulk} = \frac{n_b \cdot p_b - n_i^2}{\tau_p \cdot (n_b + n_1) + \tau_n \cdot (p_b + p_1)}$$

Surface vs Bulk Recombination

For the bulk recombination,

$$\tau_n = \frac{1}{N_T \cdot k_n} \quad / \quad \tau_p = \frac{1}{N_T \cdot k_p}$$

What is a good values for τ_n or τ_p?

Recall $k_n = cm^3 / s = cm^2 \cdot cm / s = \sigma V_{th}$

Assume atom radius of 3 Å, $\pi r^2 = 10^{-15} cm^2$

$$V_{th} \approx 10^7 \, cm / s \qquad \rightarrow k_n = 10^{-15} \cdot 10^7 \, cm^3 / s = 10^{-8} \, cm^3 / s$$

Good approximation to say "$k_n = k_p$"

For low trap density in the bulk, let's say $10^{11} cm^{-3}$

$$\rightarrow \tau_{n,b} = \frac{1}{10^{11} \cdot 10^{-8}} = \frac{1}{10^3} = ms \text{ (About right for bulk Si)}$$

But for the surface recombination, this doesn't work the same way

Bulk Recombination: under Low Level Injection

For n-type bulk,

Low-level injection

$$\mathrm{N_D} = n_{b,0} \gg \Delta n = \Delta p \gg p_{b,0}$$

$$U_{bulk}(LLI) = N_T \frac{k_n \cdot k_p \cdot [(N_D + \Delta n)\cdot(\Delta p + p_{b,0}) - n_i^2)]}{k_n \cdot (N_D + n_1) + k_p \cdot (p + p_1)}$$

$$\nwarrow N_D \gg n_i \approx n_1 \quad \nwarrow p = \Delta p + p_{b,0}$$

$$U_{bulk}(LLI) = N_T \frac{k_n \cdot k_p \cdot [N_D\Delta p + \Delta n\Delta p + N_D p_{b,0} + \Delta n p_{b,0} - n_i^2]}{k_n \cdot (N_D) + k_p \cdot (p + p_1)}$$

$(n_i^2 = n_{b,0} p_{b,0} = N_D p_{\mathrm{b},0} \rightarrow$ **So** $N_D p_{b,0}$ **and** n_i^2 **are canceled each othe**

$$U_{bulk}(LLI) = N_T \frac{k_n \cdot k_p \cdot N_D\Delta p}{k_n \cdot (N_D) + k_p \cdot (\Delta \mathrm{p} + \mathrm{p_{b,0}} + p_1)}$$

If $k_n \approx k_p$**, then whole** k_p **terms go away.**

$$\boxed{U_{bulk}(LLI) = N_T k_p \Delta p}$$

Bulk Recombination: under Low Level Injection

$$U_{bulk}(LLI) = N_T k_p \Delta p$$

Remember, rate=(rate constant)×(concentration)

We can generalize and define

$U \equiv S\Delta p$ **for n-type**

where S, the recombination velocity is a rate constant

For low-level injection in the bulk,

$$\boxed{S_{bulk}(LLI) = N_T k_p = \frac{1}{\tau_p}} \quad \text{for n-type}$$

$$U = S\Delta p \qquad \& \qquad U = -\frac{\partial \Delta n}{\partial t} = -\frac{\partial \Delta p}{\partial t}$$

$$-\frac{\partial \Delta p}{\partial t} = S\Delta p \quad \Rightarrow \quad -\frac{\partial \Delta p}{\Delta p} = S\partial t$$

$$\Delta p = p_0 \exp(-St) = p_0 \exp(-t/\tau_p)$$

Bulk Recombination: under High Level Injection

For n-type bulk,

High-level injection

$\Delta n = \Delta p \gg n_{b,0} = N_D \gg p_{b,0}$

$$U_{bulk}(HLI) = N_T \frac{k_n \cdot k_p \cdot [(N_D + \Delta n) \cdot (p_{b,0} + \Delta p) - n_i^2)]}{k_n \cdot (N_D + \Delta n + n_1) + k_p \cdot (p_{b,0} + \Delta p + p_1)}$$

$$U_{bulk}(HLI) = N_T \frac{k_n \cdot k_p \cdot \Delta n \cdot \Delta p}{k_n \cdot (\Delta n) + k_p \cdot (\Delta p)}$$

But $\Delta n = \Delta p$

$$\boxed{U_{bulk}(HLI) = N_T \frac{k_n \cdot k_p}{k_n + k_p} \Delta p}$$

Now $S_{bulk}(HLI) = N_T \frac{k_n \cdot k_p}{k_n + k_p} = \frac{1}{\frac{1}{N_T k_p} + \frac{1}{N_T k_n}}$

$$\boxed{S_{bulk}(HLI) = \frac{1}{\tau_n + \tau_p}}$$

$\Rightarrow$ **The carrier with the longer life time determines the recombination velocigy**

Bulk Recombination: under High Level Injection

Finally, if $k_n \approx k_p$, then $\tau_n \approx \tau_p \equiv \tau_{bulk}$

$$S_{bulk}(HLI) = \frac{1}{\tau_n + \tau_p} = \frac{1}{2\tau_{bulk}} = \frac{1}{2\tau_p}$$

$$S_{bulk}(LLI) = \frac{1}{\tau_p}$$

This results show that $S_{bulk}(HLI) = \frac{1}{2} S_{bulk}(LLI)$

Under low level injection, we only have to wait for the photogenerated holes,Δp to relax.

This is because $n = N_D + \Delta n \cong N_D$.

The perturbed electron concentration is essentially zero.

But for high level injection, we have to wait for both electrons(Δn) and holes(Δp) to relax.

This will take twice as long if $\tau_n \approx \tau_p$. (or else it will take $\tau_n + \tau_p$)