EE 207. LECTURE NOTES

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TOPIC :- GENERATION - RECOMBINATION

Let 'n' and 'p' denote the concentration of electrons and holes in a semiconductor sample. At equilibrium we have

$$np = n_i^2 \qquad \text{(law of mass action)}.$$

where $n_i \propto e^{-E_g/2kT}$.

E_g being the band gap.

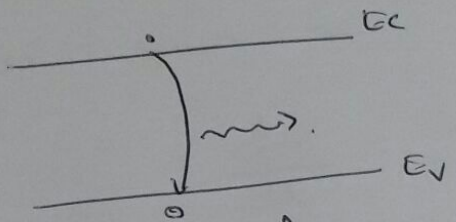
Under such conditions, there is a detailed balance of ~~se~~ between carrier recombination due to various processes and the corresponding generation mechanisms.

Once driven out of equilibrium, if the excitation or perturbation is held constant, the system will reach a "steady state" condition in ~~each~~ which the time rate of change of all parameters will be zero.

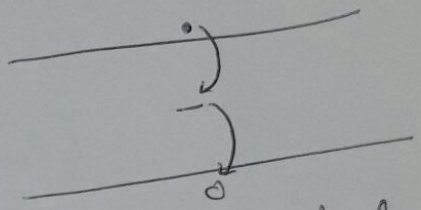
The detailed recombination process will determine how the system reaches steady state or equilibrium condition.

A. Common Recombination Mechanisms

In this course we will consider two recombination mechanisms, viz. Band-Band (radiative) recombination and trap-assisted SRH (non-radiative) recombination mechanism.



Band-Band recombination



trap-assisted recombination

A.1

Band-Band recombination can be represented as

$$\vec{e} + \vec{h} \rightleftharpoons \text{band.}$$

Hence, the rate equation is given as

$$\frac{dp}{dt} = \frac{dn}{dt} = -k\,n\cdot p + G$$

- $-k\,n\cdot p$: recombination (forward reaction)
- $+G$: generation (reverse reaction)
- k: radiative recombination coefficient

the above equation, at equilibrium condition, should result in

$$\left(\frac{\partial n}{\partial t}\right)_{\text{equilibrium}} = 0.$$

or rather

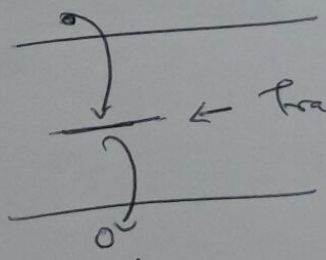
$$G_{equilibrium} = k n_i^2$$

We further assume that the above generation rate remains the same for out of equilibrium condition as well. This indicates that the rate equation is given as

$$\frac{dn}{dt} = -k(np - n_i^2)$$

A.2 Trap-assisted recombination:

For a proper derivation, see the text book ADSF. Here we provide an approximate analysis



We consider near midgap trap states. As all recombinations are pair-wise process we have

$$\frac{dn}{dt} = \frac{dp}{dt}$$

Let N_T be the density of trap states and n_T of them be filled with electrons at any time. The electron capture can be represented as.

free electron + empty traps $\rightleftharpoons$ filled traps.

Neglecting the reverse reaction, we have.

$$\frac{dn}{dt} = -c_n (N_T - n_T) n$$

c_n - electron capture coefficient

Similarly $$\frac{dp}{dt} = -c_p (n_T) p$$

Since $\frac{dn}{dt} = dp/dt$, we find.

$$n_T = \frac{c_n N_T n}{c_n n + c_p p}$$

Accordingly

$$\frac{dn}{dt} = \frac{dp}{dt} = -\frac{c_n c_p N_T n p}{c_n n + c_p p}$$

the above equation needs further modification as (1) the emission process is neglected.

(2) the influence of trap location within

the band gap should be incorporated.

Item (1) can be easily accounted by replacing np with $(np - n_i^2)$. This will ensure that the rate could be zero at equilibrium condition as well.

Item (2) can be accounted by appropriately modifying the rate equations as follows.

$$\frac{dn}{dt} = \frac{dp}{dt} = \frac{-(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

where $\tau_p = \frac{1}{c_p N_T}$

$$\tau_n = \frac{1}{c_n N_T}$$

$$n_1 = n_i e^{(E_i - E_T)/kT}$$

$$p_1 = p_i e^{(E_T - E_i)/kT}$$

Note that n_1 & p_1 ensure that the rate $\rightarrow$ '0' as the trap levels are closer to the conduction and valence band edges.

B. Effective lifetime

Under certain condition, the rate equation could be reduced to the form $\frac{\partial n'}{\partial t} = \frac{n'}{\tau}$, where '$\tau$' could be the effective lifetime of excess carrier.

B1. Effective lifetime in the presence of Band-Band recombination (only).

We have

$$\frac{dn}{dt} = -k(np - n_i^2).$$

As any generation process will lead to pair-wise creation of e-h. we have (thus assumes no spatial variation)

$n = n_0 + \Delta n$
$p = p_0 + \Delta p$

n_0 – } equilibrium
p_0 – } conc.
$n_0 p_0 = n_i^2$

$$\Delta n = \Delta p.$$

Substituting in the rate equation, we have

$$\frac{d}{dt}(n_0 + \Delta n) = -k\left((n_0 + \Delta n)(p_0 + \Delta n) - n_i^2\right)$$

$$\Rightarrow \frac{d}{dt}(\Delta n) = -k\left(\Delta n(n_0 + p_0) + \Delta n^2\right).$$

Assuming low-level injection (ie $\Delta n < n_0$ or p_0 the majority carrier concentration), we have

$$\frac{d(\Delta n)}{dt} = -k\,\Delta n(n_0+p_0)$$

or $$\tau_{radiative} = \frac{1}{k(n_0+p_0)}$$

B2. Effective lifetime for SRH process (only).

Here we have

$$\frac{dn}{dt} = -\frac{(np-n_i^2)}{\tau_n(p+p_1)+\tau_n(n+n_1)}$$

Assume the traps are near mid level. (ie. $n_1 = p_1 = n_i$) and the sample is P-type doped. (ie $p_0 \gg n_0$).

Following the analysis in previous section, we have

$$\frac{d(n_0+\Delta n)}{dt} = -\frac{(n_0+\Delta n)(p_0+\Delta n)-n_i^2)}{\tau_n(p_0+\Delta n+n_i)+\tau_p(n_0+\Delta n+n_i)}$$

Assume low level injection ($\Delta n = \Delta p \ll p_0$), the term that dominates the denominator is $\tau_n p_0$.

$$\Rightarrow \frac{d\Delta p}{dt} = \frac{d\Delta n}{dt} = -\frac{\Delta n}{\tau_{n_0}} = -\frac{\Delta p}{\tau_{n_0}}$$

or rather the minority carrier effective lifetime $\tau_{SRH} = \tau_{n_0}$.

* Note that the above analysis could lead to different expressions depending on the specific values of n_0 & p_0. For example for intrinsic semiconductor, low level injection assumption will not hold, and the τ_{SRH} will be different.

B.3: Effective lifetime in the presence of both radiative and SRH. processes (low level injection)

Here we have:

$$\frac{dn}{dt} = \frac{dp}{dt} = -k N_A \Delta n - \frac{\Delta n}{\tau_{n_0}}$$

$$= \frac{-\Delta n}{\tau_{eff}}$$

$$\Rightarrow \frac{1}{\tau_{eff}} = k N_A + \frac{1}{\tau_{n_0}}$$

C. Carrier Concentrations in steady state.

In the presence of external perturbation like generation due to an optical source the rate equation becomes. (low level injection)

$$\frac{dn}{dt} = \frac{dp}{dt} = -\frac{\Delta n}{\tau_{eff}} + G_{ex}$$

G_{ex} – Generation due to external source

At steady state, we have

$$\frac{dn}{dt} = \frac{dp}{dt} = 0 \Rightarrow$$

$$\boxed{\Delta n = G_{ex} \tau_{eff}}$$

Hence $n = n_0 + \Delta n$

$p = p_0 + \Delta n$

Note $np \neq n_i^2$.

So, it is convenient to use quasi-Fermi levels as defined below.

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

$$p = n_i e^{(E_i - E_{Fp})/kT}$$

Sample Problems

1* Assuming low level injection, find the effective carrier life. (Sample doped with $N_A = 10^{17}\ cm^{-3}$)

(a) In the presence of Band-Band recombination only ($b = 10^{-11}\ cm^3/s$.

0.01s

(b) In the presence of SRH recombination only ($\tau_n = \tau_p = 100\ ns$).

10^4

(c) In the presence of both SRH & band-band recombination

2* The above sample ~~in~~ (i.e. as specified in part c) is subjected to optical illumination which leads to $G_{ex} = 10^{18}\ cm^{-3}/s$.

* Assuming low level injection, what would be the steady state carrier density.

10^17

10^1

* Is the assumption of low level injection valid?

* If $G_{ex} = 10^{21}\ cm^{-3}/s$, comment on the assumption of low level injection. If not valid, what would be the carrier density?

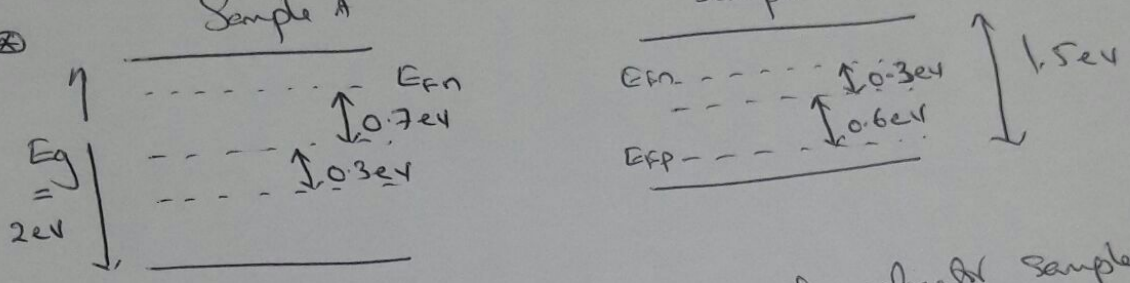
yes as delta n << n

2.6*10^17

(Hint - You might have to start from the basic rate equation of B-B & SRH processes).

3 ⊛ Find E_{Fn} & E_{Fp} for the two cases discussed in Question (2).

4 ⊛



Consider the above two semiconductor samples (A) & (B). Assume the same N_c, N_v for them to be the same as that of Si and (at T = 300K) and that they are temperature independent.

⊛ Find the carrier densities in both the samples.

⊛ Find the doping densities in both the samples.

⊛ Which of them is under higher intensity of illumination?

5 ⊛ Without using calculator or any calculations, figure out whether the below sample is under low level illumination?

low level as efp and efn are not equally separated from ei