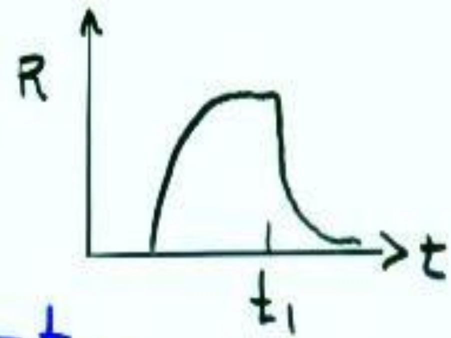
Now can calculate time rate of change:

$$\frac{dn(t)}{dt} = \text{Optical generation rate} \quad (g_{op})$$
$$+ \text{Thermal generation rate} \quad (\alpha_r n_i^2)$$
$$- \text{Recombination rate}$$

$$\frac{dn(t)}{dt} = g_{op} + \alpha_r n_i^2 - \alpha_r n(t)\, p(t)$$



First case: Generate additional electrons and holes with light, then turn light off. $g_{op} = 0$ at $t = t_1$.

In this case, $\dfrac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r (n(t)\, p(t))$

In this case, $\frac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r (n(t)\, p(t))$

$$= \alpha_r n_i^2 - \alpha_r (n_0 + \delta n(t))(p_0 + \delta p(t))$$

$$= \underbrace{\alpha_r n_i^2 - \alpha_r n_0 p_0}_{=0} - \alpha_r (n_0 \delta p(t) + p_0 \delta n(t)) - \alpha_r \delta n(t) \delta p(t)$$

negligible for low light levels ($\delta n, \delta p \ll$ majority carrier concentration)

so $$\frac{dn(t)}{dt} = -\alpha_r (n_0 \delta p(t) + p_0 \delta n(t))$$

Recombination occurs in pairs: $\delta n = \delta p$

so $$\frac{dn(t)}{dt} = -\alpha_r (n_0 + p_0)\, \delta n(t)$$

Since $n = n_0 + \delta n(t)$ and n_0 constant,

$$\frac{dn(t)}{dt} = \frac{d(n_0 + \delta n(t))}{dt} = \frac{d\,\delta n(t)}{dt}$$

Then $$\frac{d\,\delta n(t)}{dt} = -\alpha_r (n_0 + p_0)\,\delta n(t)$$

Change in Excess Carriers

$$\delta n(t) = \Delta n\, e^{-\alpha_r (n_0 + p_0) t}$$

$=$ where

Similarly,

This is the form we've been looking for!

For n-type semiconductors,

$n_o \gg p_o$ and holes are the minority carriers.

$$\tau_p = \frac{1}{\alpha_r (n_o + p_o)} \sim \frac{1}{\alpha_r n_o} = \text{minority carrier lifetime}$$

For p-type semiconductors,

$p_o \gg n_o$ and electrons are the minority carriers

$$\tau_n = \frac{1}{\alpha_r (n_o + p_o)} \sim \frac{1}{\alpha_r p_o} = \text{minority carrier lifetime}$$

Example: Streetman 4-7.

Decay of electrons and holes by recombination

p-type semiconductor with $p_o = 10^{15}\,\frac{\text{acceptors}}{\text{cm}^3}$

$p_o \gg n_o$

Illumination adds 10^{14} electron-hole pairs

$\Delta n = \Delta p = 10^{14}\ \text{EHP/cm}^3$

$= 0.1\, p_o$

$n = n_o + \Delta n$

$= n_o + 0.1\, p_o$

$\simeq 0.1\, p_o$

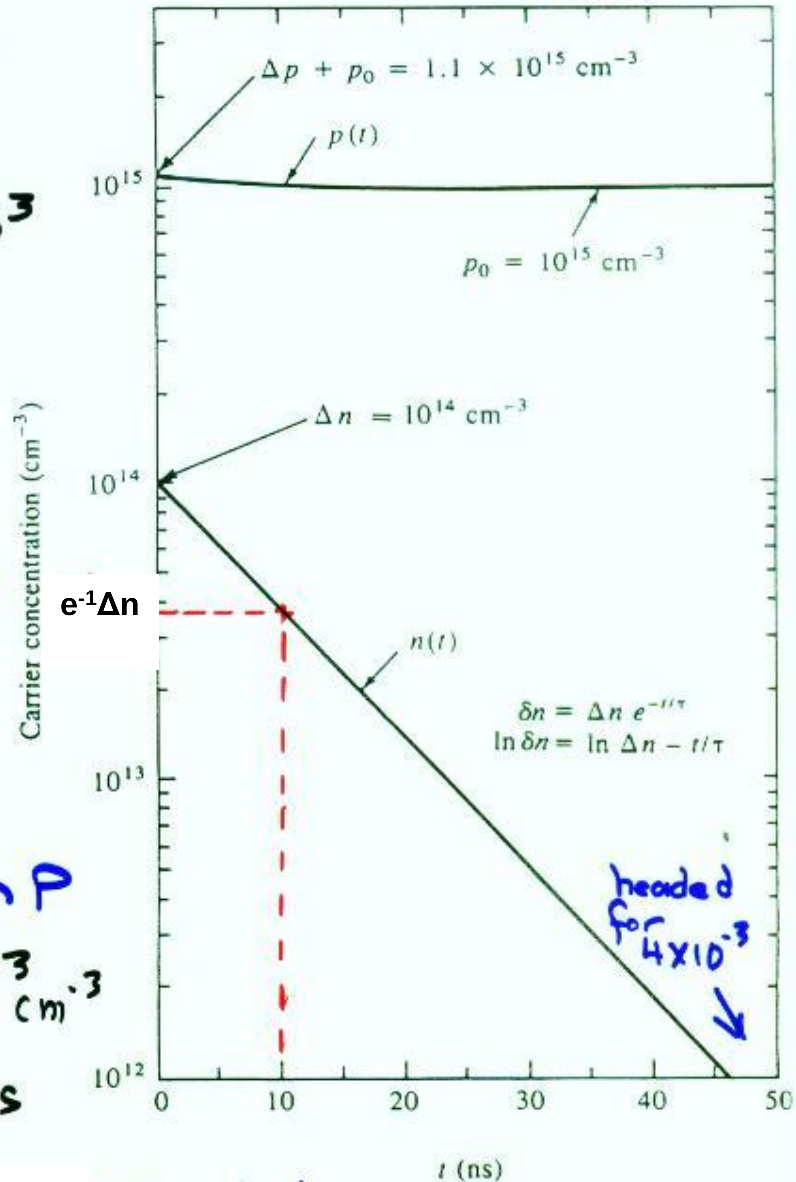
orders of magnitude change in n

$p = p_o + \Delta p$

$= 1.1\, p_o$

Relatively small change in p

$n_o = \frac{n_i^2}{p_o} = \frac{(2\times10^6)^2}{10^{15}} = 4\times10^{-3}\ \text{cm}^{-3}$ for GaAs



$n = n_0 + \Delta n$

$\quad = n_0 + 0.1\, p_0$

$\quad \simeq 0.1\, p_0$

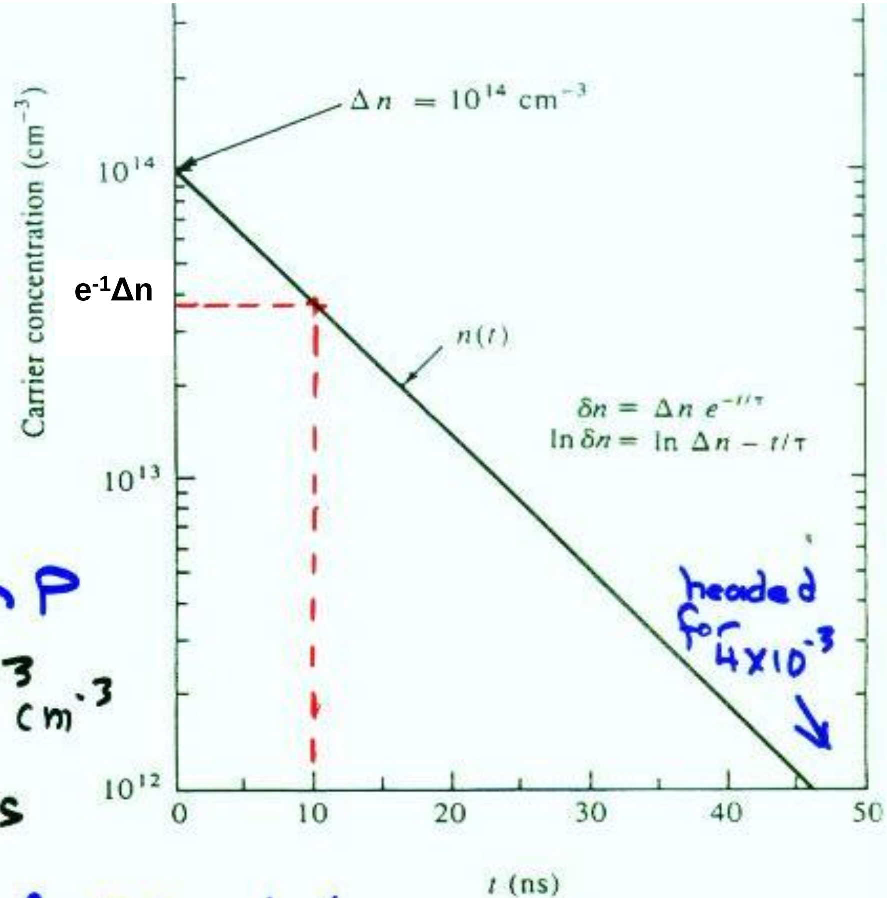
orders of magnitude change in n

$p = p_0 + \Delta p$

$\quad = 1.1\, p_0$

Relatively small change in p

$n_0 = \dfrac{n_i^2}{p_0} = \dfrac{(2\times10^6)^2}{10^{15}} = 4\times10^{-3}\ \text{cm}^{-3}$ for GaAs



on log scale, $\ln \delta n = \ln \Delta n - t/\tau$

and slope of $\ln \delta n$ is $-\frac{1}{\tau}$.

Here $\tau = 10^{-8}$ sec $= 10$ nsec so δn decreases by e^{-1} in 10^{-8} sec.

Can solve for α_r: $\tau_n \cong \dfrac{1}{\alpha_r p_0}$

also, $\tau_n = \tau_p \simeq \dfrac{1}{\alpha_r p_0}$ (pairs)

Can also define a Recombination Rate R in terms of τ.

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

$$\tau = \frac{1}{\alpha_r (n_0 + p_0)}$$

$R =$

Majority carrier: Large and relatively constant

Minority Carrier: Smaller and changing by orders of magnitude

Approximation: for $p_0 >> n_0$ in example just shown
$p(t) = p_0 + \delta p(t)$ and $n(t) \sim \delta n(t)$

Then $R \cong \dfrac{\delta n(t)\, p_0}{\tau_n (n_0 + p_0)} \sim \dfrac{\delta n(t)}{\tau_n} = \dfrac{\#}{time}$

The larger the excess minority carriers, the larger R is.
The smaller the time constant, " " " ".

The larger the excess minority carriers, the larger R is.
The smaller the time constant, " " " ".

When light turned off, $\delta n(t)$ decays $\rightarrow$ R decreases.

Eventually, $R \rightarrow \alpha_r n_o p_o = \alpha_r n_i^2$ = Thermal Recombination Rate

So $\frac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r n_i^2 = g_i - r_i = 0.$

For light not turned off, $\delta n(t) > 0$ and constant

= "steady state"

Continuous and constant carrier generation by external excitation (optical, thermal)

External Excitation changes carrier concentrations

$\longrightarrow$ "Non-Equilibrium"

For No External Excitation, just Thermally generated carriers $\longrightarrow$ "Equilibrium" (A.K.A. Thermal Equilibrium)

"Steady State" is Non equilibrium condition in which all external excitations are constant and balanced.

New Balance:

$$\underbrace{g(T) + g_{op}}_{\text{Generation}} = \alpha_r n p$$

$$= \alpha_r \underbrace{(n_o + \delta n(t))(p_o + \delta p(t))}_{\text{Recombination}}$$

For steady state recombination and no "trapping" (see later)

$$\delta n = \delta p$$

$$\cancel{g(T)} + g_{op} = \alpha_r \cancel{n_o p_o} + \alpha_r \delta n (n_o + p_o) + \alpha_r \delta n^2$$

~ 0

$$g_{op} = \alpha_r \delta n (n_o + p_o)$$

$$= \frac{\delta n}{\tau}$$

same form as R
(match!)

so excess carrier concentration

$$\delta n = \delta p = g_{op} \tau_n \text{ or } g_{op} \tau_p$$

(note: with trapping, $\tau_n \neq \tau_p$ in general)

This means that more free electrons and holes can be generated with the <u>same</u> photon flux but with longer τ_n and τ_p.

Excitation Example:

$g_{op} = 10^{18}$ EHP/cm^3-sec

$\tau_n = 10^{-8}$ sec

so $\delta n = g_{op}\tau = 10^{10}$ excess electrons/cm^3

Recombination Example:

p-type semiconductor with $n_i = 1.5\times10^{10}\,cm^{-3}$
and $p_o = 10^{17}$ acceptors/cm^3.

What is Thermal recombination rate if $\alpha_r = 10^{-7}\,cm^3 sec^{-1}$?

$$R_{thermal} = \alpha_r n_o p_o = \alpha_r n_i^2 = 10^{-7}\frac{cm^3}{sec}\cdot 2.25\times10^{20}\,cm^{-6}$$
$$= \underline{2.25\times10^{13}}\,cm^{-3}sec^{-1}$$

What is recombination rate if $g_{op}\tau = 10^{16}$ EHP/cm^3?

Now $\delta n = \delta p = 10^{16}\,cm^{-3}$

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

$n(t) = n_o + \delta n \sim \delta n = 10^{16}\,cm^{-3}$
$p(t) = p_o + \delta p = 1.1\times10^{17}\,cm^{-3}$
$$R = 10^{-7}\frac{cm^3}{s}(10^{16}\,cm^{-3})(1.1\times10^{17}\,cm^{-3}) = \underline{1.1\times10^{26}\,cm^{-3}sec^{-1}}$$

(Got much larger as n and p grew)

What is τ?

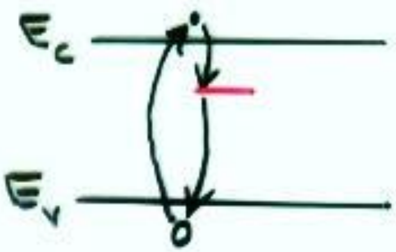
$\tau =$

$R \cong$

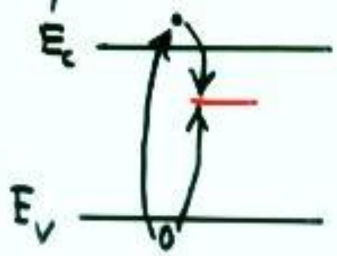
(slightly off since we approximated majority carrier $P(t) = p_0 + \delta n \approx p_0$ in deriving above expression for R)

Indirect Recombination

Traps alter τ_n and τ_p so $\tau_n \neq \tau_p$



same as

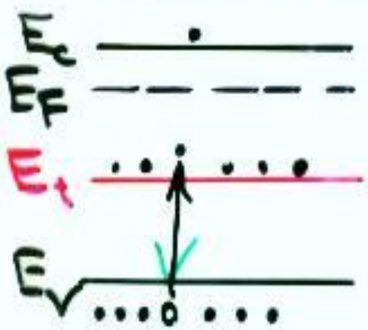


Electron trapped from conduction band, then hole recombines.

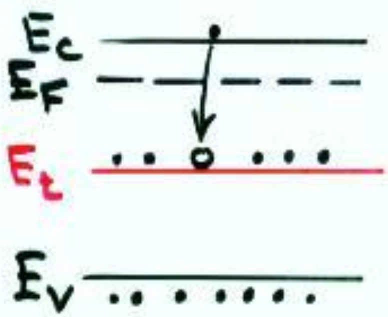
Again, electron trapped first.

▷ If trap is "deep" in band gap, then: Recombination Center

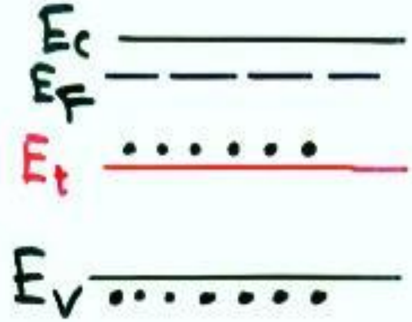
Receive one charge carrier first, then the other.



hole capture

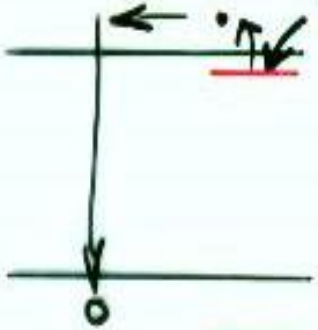


electron capture



annihilation of electron - hole pair

▷ If trap is "shallow", then "temporary trapping" and charge pops out.



Recombination delayed by charge release back to conduction band edge.

In this case, e^- trapped faster than h^+. Released before h^+ can recombine.

Moral: Traps reduce free carrier lifetimes unequally.

Application to Photoconductivity:
Photodetectors, photoswitches, ..

$\sigma =$

$\delta n =$

So $\Delta\sigma =$

Want large μ and τ for large $\Delta\sigma$.

Other design considerations: sensitivity, response time, dark resistance (e.g. shorter drift length → less absorption and lower resistance.)

Steady-State Carrier Generation: Quasi-Fermi Levels

Example 4-3 (Streetman)

10^{13} EHP/cm^3 created optically per 10^{-6} sec

$n_0 = 10^{14} cm^{-3}$ in Si

$\tau_n = \tau_p = 2\ \mu sec = 2 \times 10^{-6}$ sec.

excess e^- and h^+

$$p_0 = \frac{n_i^2}{n_0} = \frac{2.25 \times 10^{20}}{10^{14}} = 2.25 \times 10^{6} cm^{-3}$$

New majority carrier concentration $n = 1.2 \times 10^{14} cm^{-3}$

" minority " " $p \simeq 2 \times 10^{13} cm^{-3}$