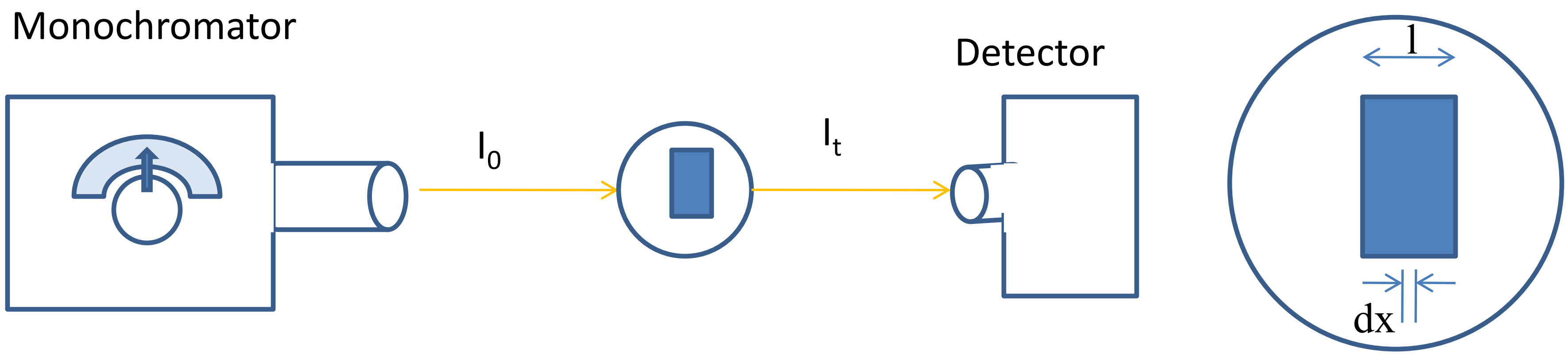
Optical absorption

A photon with energy less than E_g is unable to excite an electron from the valence band to the conduction band. Thus in a pure semiconductor ,there is negligible absorption of photons with $h\nu<E_g$ This explains why some materials are transparent in certain wavelength ranges. We are able to see through certain insulators such as good NaCl crystal because a large energy gap containing no electron states exist the material. If the band gap is about 2 eV wide ,only wavelengths (infrared) and red part of the visible spectra are transmitted. On the other hand ,a band of about 3 eV allows infrared and the entire visible spectrum to be transmitted.

If the beam of photons with $h\nu>E_g$ falls on a semiconductor there will be some predictable amount of absorption determined by the properties of the material. We would expect the ratio of transmitted to incident light intensity to depend on photon wavelength and thickness of the sample.

Optical absorption



Let us assume that a photon beam of intensity I_0 (photons/cm^2-s) is directed at a sample thickness *l*. The beam contains only photons of wavelength λ,selected by a monochromator .As the beam passes through the sample ,its intensity at a distance x from the surface can be calculated by considering the probability of absorption within any increment dx,

Optical absorption

Consider a layer(x.x+dx) through which light passes the amount of energy absorbed in the layer dx and be proportional to the layer width and the energy reaching the layer x.x+dx , I(x) . Denoting the proportionality factor between the absorbed energy and the incident energy , we may write

$$-dI(x)=\alpha I(x)dx$$

Hence α is the amount of energy absorbed a beam of unit intensity in a layer of unit width.

$$-dI(x)=\alpha I(x)dx$$

$$-\frac{dI(x)}{I(x)}=\alpha dx$$

$$-\int\frac{dI(x)}{I(x)}=\alpha\int dx$$

$$-\log I(x)=\alpha x+const$$

At $x=0, I(x)=I_0$

$$-\log I_0(x)=const$$

$$\log I(x)-\log I_0=-\alpha x$$

$$\log\frac{I}{I_0}=-\alpha x$$

$$I=I_0e^{-\alpha x}$$

Hence intensity at a length *l* $\quad I=I_0e^{-\alpha l}$

Photoconductivity

Photoconductivity is associated with semiconductors and it is the induced conductivity due to incident of light . This phenomena is not observed in metals or insulators .Thus Change of conductivity in certain semiconductors with incident of light it termed as photoconductivity

Equation of continuity gives

$$\frac{d\rho}{dt} = \frac{\delta\rho}{\delta t} + divJ$$

$$0 = e\frac{\delta n}{\delta t} + divJ$$

It should be

$$\frac{\delta n}{\delta t} = -div\frac{J}{e}$$

This equation means that volume charge density may change only as a result of the current divergence.

Now electron or hole concentration n(r,t) not equal to the their equilibrium values $n_o(r)$ are termed non equilibrium concentration. The quantity

$$\Delta n(r,t)=n(r,t)-n_0(r)$$

Now we have to take account the concentration variation due to generation and recombination. Hence we have to write equation of continuity taking account generation and recombination.

Photoconductivity

$$\frac{\delta n}{\delta t} = -div\frac{J}{e} + G - R$$

If we assume current is small

$$\frac{\delta n}{\delta t} = G - R$$

$$\frac{\delta(n_0 + \Delta n)}{\delta t} = G - R$$

Now amount of light falling per unit area per second is the Intensity

Let the intensity of light falling on the material is I_0 then the intensity transmitted after crossing the thickness x of the material

Then $I=I_0e^{-\alpha x}$

Amount of light absorbed $\Delta I=I_0-I=(I_0-I_0e^{-\alpha x})$

$\Delta I=(I_0-I_0e^{-\alpha x})=I_0\alpha x$ [if $\alpha x<<1$]

$\Delta I=I_0\alpha x$ $\quad\quad$ $I=Nh\nu$ $I_o=N_0h\nu$

Again , $\Delta I=\Delta Nh\nu$ ΔN is the no of photons involved

$\Delta Nh\nu=I_0\alpha x$

$\Delta Nh\nu/x=I_0\alpha$

Now quantum efficiency β is defined by

Photoconductivity

$$\beta = \frac{No\ of\ \ pairs\ \ produced / vol / time}{No\ of\ \ photons\ \ absorbed / vol / time}$$

No of pairs produced/vol/time = β x No of photon absorbed /vol/time

$$= \beta \times \frac{\Delta n}{x}$$

$$= \beta \times \frac{I_0 \alpha}{h\nu} \qquad k = \frac{\alpha}{h\nu}$$

$$= I_0 k \beta$$

Where the generation rate $G = kI_0\beta$

Also simultaneously recombination is taking place. Now the rate of production of carrier

$$\frac{\delta n}{\delta t} = \frac{\delta}{\delta t}(n_0 + \Delta n)$$

$$= \frac{\delta}{\delta t}(\Delta n)$$

Hence considering the generation and recombination simultaneously

$$\frac{\delta(\Delta n)}{\delta t} = \underbrace{kI_0\beta}_{\mathbf{G}} - r_n \underbrace{(np - n_0 p_0)}_{\mathbf{R}}$$

Photoconductivity

$$R \propto (np - n_0 p_0)$$ = No of excess carriers for electron in the conduction band

$$\propto \{(n_0 + \Delta n)(p_0 + \Delta p)\} - n_0 p_0$$

$$\propto \{n_0 p_0 + n_0 \Delta p + \Delta n p_0 + \Delta n \Delta p\} - n_0 p_0$$

$$\propto \{n_0 \Delta p + p_0 \Delta n + \Delta n \Delta p\}$$

Now Δn=Δp, it obvious due to charge neutrality

$$R \propto (n_0 + p_0)\Delta n + \Delta n^2$$

If the sample is n type $n_0 >> p_0$

Also $n_0 >> \Delta n$ for low level injection

$\Delta n >> n_0$ for high level injection

We consider the case of low level injection

$$R \propto n_0 \Delta n$$

$$R = r_n n_0 \Delta n$$

r_n=transition probability constant

Hence

$$\frac{\delta(\Delta n)}{\delta t} = k I_0 \beta - r_n n_0 \Delta n$$

Photoconductivity

in steady state condition
$$\frac{\delta(\Delta n)}{\delta t}=0$$

$$\frac{\delta(\Delta n)}{\delta t}=kI_0\beta-\frac{\Delta n}{\tau_n}$$

$$=0$$

τ_n =life time of carriers=1/n_0r_n

Hence
$$\frac{\Delta n}{\tau}=kI_0\beta$$

$$\Delta n=kI_0\beta\tau$$

Hence no of pairs in the steady state =no of pairs generated x life time

In non steady state condition

$$\int\frac{\delta(\Delta n)}{kI_0\beta\tau-\Delta n}=\int\frac{\delta t}{\tau}$$

$$\int\frac{\delta(kI_0\beta\tau-\Delta n)}{kI_0\beta\tau-\Delta n}=-\int\frac{\delta t}{\tau}$$

$$\log(kI_0\beta\tau-\Delta n)=-\frac{t}{\tau}+const$$

Since at t=0 Δn=0
c= $\log kI_0\beta\tau$

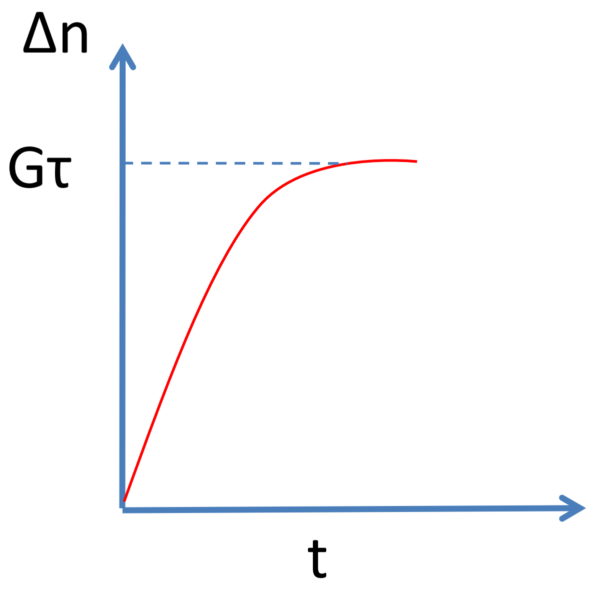
$$\log(kI_0\beta\tau-\Delta n)=-\frac{t}{\tau}+\log kI_0\beta\tau$$

$$\log\frac{kI_0\beta\tau-\Delta n}{kI_0\beta\tau}=-\frac{t}{\tau}$$

$$\frac{kI_0\beta\tau-\Delta n}{kI_0\beta\tau}=e^{-\frac{t}{\tau}}$$

$$\Delta n=kI_0\beta\tau(1-e^{-\frac{t}{\tau}})=G\tau(1-e^{-\frac{t}{\tau}})$$

When the intensity of external influence is kept constant ,the concentration of excess carriers initially grows fast and then slows down because of the increased rate of recombination. It finally comes to a steady state value

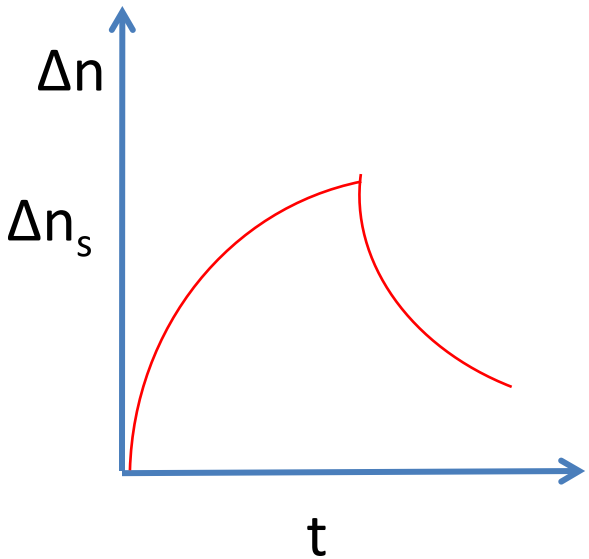


$$\frac{\delta(\Delta n)}{\delta t}=0 \qquad kI_0\beta-\frac{\Delta n}{\tau}=0$$

$$\Delta n=kI_0\beta\tau=G\tau$$

Photoconductivity

If now light is switched off $I_0=0$ there $G=0$,$kI_o\beta=0$ Now the equation becomes



$$\frac{\delta(\Delta n)}{\delta t} = 0 - \frac{\Delta n}{\tau}$$

$$\frac{\delta(\Delta n)}{\Delta n} = -\frac{\delta t}{\tau}$$

$$\log \Delta n = -\frac{t}{\tau} + \log(\Delta n_s)$$

$$\Delta n = \Delta n_s e^{-\frac{t}{\tau}}$$

Determination of τ

Now the dark current is given by $J_d = \sigma\varepsilon$

$$= q(n_n\mu_n + n_p\mu_p)\varepsilon$$

Similarly photocurrent

$$J_{ph} = q\{(n_0 + \Delta n)\mu_n + (p_0 + \Delta p)\mu_p\}\varepsilon$$

Photoconductivity

Now the photocurrent change at a certain time t is given by

$$\Delta J_{ph}\Big|_t = J_{ph}\Big|_t - J_d = q\{\Delta n\mu_n + \Delta p\mu_p\}\varepsilon$$

$$= q\Delta n(\mu_n + \mu_p)\varepsilon$$

Also photocurrent change at steady state the condition

$$\Delta J_{ph}\Big|_s = J_{ph}\Big|_s - J_d = q\{\Delta n_s\mu_n + \Delta p_s\mu_p\}\varepsilon$$

$$= q\Delta n_s(\mu_n + \mu_p)\varepsilon$$

Since Δn=Δp

$$\Delta J_{ph}\Big|_t = q\Delta n_t(\mu_n + \mu_p)\varepsilon$$

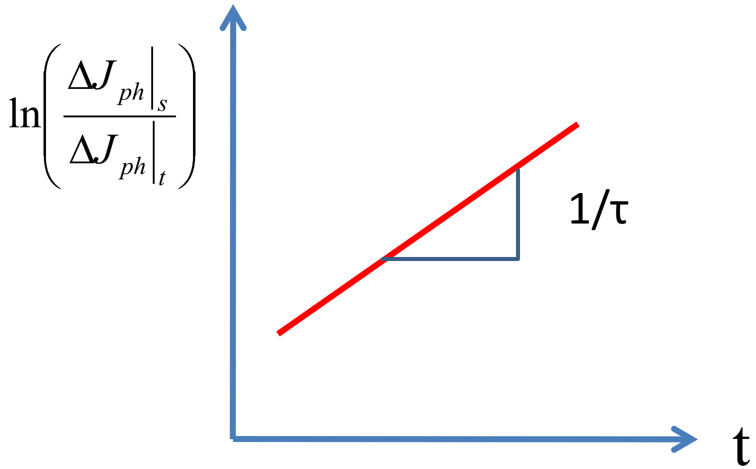
$$= q\Delta n_t e^{-t/\tau}(\mu_n + \mu_p)\varepsilon$$

$$\frac{\Delta J_{ph}\Big|_s}{\Delta J_{ph}\Big|_t} = \frac{1}{e^{-t/\tau}} = \frac{\Delta n_s}{\Delta n}$$

$$\ln\left(\frac{\Delta J_{ph}\Big|_s}{\Delta J_{ph}\Big|_t}\right) = t/\tau$$

Photoconductivity

If we plot $\ln\left(\frac{\Delta J_{ph}\big|_s}{\Delta J_{ph}\big|_t}\right)$ vs t we get a straight line. The slope of line will give the value of 1/τ.Hence decay curve is used to find the mean life time of the carrier.

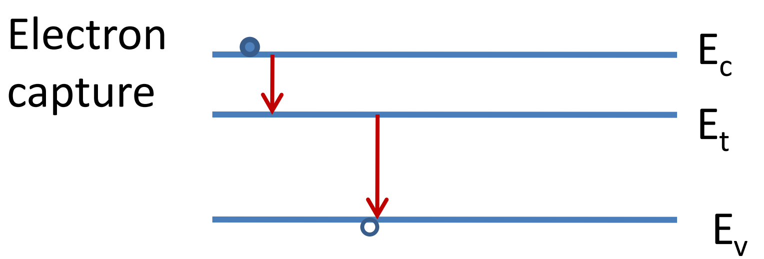


For a good detector τ should be very small. This gives good resolution. For solar cell τ should be large. In some sample τ is such that we can store information for a long time and can be used as a memory circuit.
The recombination which are considered is nothing but direct interband recombination .But in presence of traps the recombination is different. This is called indirect recombination. The calculation and experiment shows that interband radiation recombination can be rather significant in narrow band gap semiconductor.

For wide band gap semiconductor however the main mechanism responsible for the recombination is of non radiation type, where the recombination occurs via impurity levels.

Localized levels in the band gap of a semiconductor can be effective recombination centers and are often called traps.
The process in which an electron leaves the conduction band and falls into a trap is known as electron capture by the trap. Probabilility of capture of an electron by a trap in unit time is given by

$$P_n = A_n N_{tv} v_n$$



N_t concentration of trap
N_{tv} concentration of vacant traps
V_n electron velocity
A_n cross section of electron capture

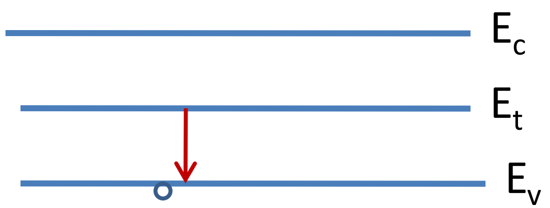
Here as regard electron capture we can see each trap to a sphere of radius r as it runs into this sphere ,an electron undergoes a collision which results in its capture by the trap. The area A_n is refer to as the cross section of the electron capture. By analogy the transfer of an electron from its trap to a vacant level in the valence band, thus letting the trap level free, is called the hole capture by trap.

Photoconductivity

But the above phenomenon takes lace only when the trap is away from the middle of the band gap . This type of trap is called shallow trap

If we have a single trap in the middle of the gap .we get deep trap. This type of trap is not able to capture electrons from the conduction band ,but they can give up electrons to valence band i.e able to capture holes (denoted by solid line) .As a trap becomes empty one of the conduction electrons will immediately fall into the trap and so the recombination event will be completed .

Hole capture



Quadratic recombination (when intensity of light is very strong)

When the intensity of light is very strong ,then then $n_0 << \Delta n$, $p_0 << \Delta n$, thus corresponds to high level injection

$$
\begin{aligned}
R &= r(np - n_0 p_0) \\
&= r\{(n_0 + \Delta n)(p_0 + \Delta p)\} - n_0 p_0 \\
&= r\{n_0 p_0 + n_0 \Delta p + \Delta n p_0 + \Delta n \Delta p\} - n_0 p_0 \\
&= r\{n_0 \Delta p + p_0 \Delta n + \Delta n \Delta p\} \\
&= r\{n_0 \Delta n + p_0 \Delta n + (\Delta n)^2\} \\
&= r \Delta n\{n_0 + p_0 + \Delta n\} \\
&\cong r(\Delta n)^2
\end{aligned}
$$

$$
\begin{aligned}
\frac{\delta n}{\delta t} &= \frac{\delta(n_0 + \Delta n)}{\delta t} \\
&= \frac{\delta(\Delta n)}{\delta t}
\end{aligned}
$$

$$\frac{\delta(\Delta n)}{\delta t} = G - R$$

Since the light is made off G=0

$$\frac{\delta(\Delta n)}{\delta t} = -r(\Delta n)^2$$

$$\frac{\delta(\Delta n)}{(\Delta n)^2} = -r\delta t$$

Integrating

$$\delta n(t) = \frac{\delta n(0)}{1 + r\delta n(0)\delta t}$$

Hence in case of quadratic recombination excess carrier concentration decreases hyperbolically