Optoelectronic Devices

(Photoelectronic Devices)

Optical Sources

Electrical energy → Light energy

Ex: LED, LASER

Optical detectors (or) Photodetectors

Light energy → Electrical energy

Ex: Photodiode, Solar cell

Optical detectors (or) Photodetectors

→ Photoconductive effect

Ex: Photodiode

- pin
- APD

→ Photovoltaic effect

Ex: Solar cell

Since 1995
ACE

Optical Absorption

* Photon absorption coefficient
* EHP generation rate

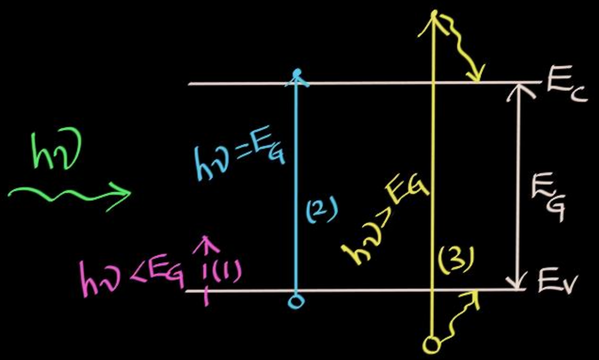
$h\nu \geq E_G \Rightarrow$ EHP generation

(1) Photon interaction with lattice $\longrightarrow$ heat

(2) Photon interaction with acceptor or donor impurities or defects $\longrightarrow$ No EHP generation

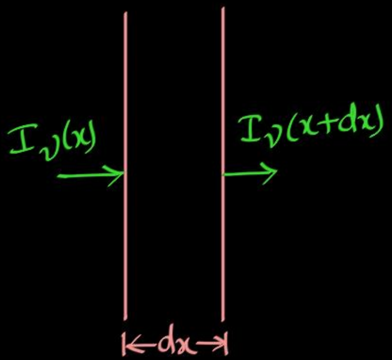
(3) Photon interaction with valance electrons $(h\nu \geq E_G)$ $\longrightarrow$ EHP generation

Photon Absorption coefficient (α)



* If $h\nu < E_G$, the light is transmitted through the semiconductor, it is said to be transparent.

→ The intensity of photon flux − $I_\nu(x)$ (energy/cm^2-s)



* The energy absorbed per unit time in the distance dx is given by

$$\alpha\, I_\nu(x)\, dx$$

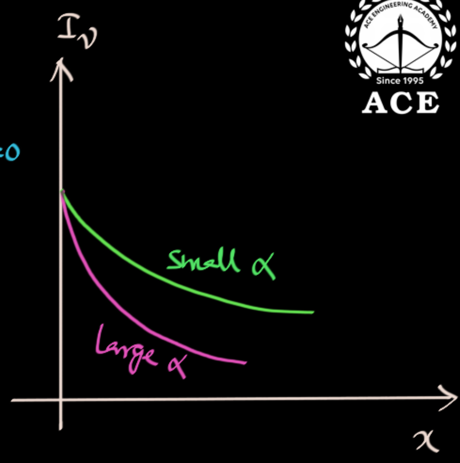
α − the relative number of photons absorbed per unit distance (/cm)

$$I_\nu(x+dx) - I_\nu(x) = \frac{dI_\nu(x)}{dx}\, dx = -\alpha\, I_\nu(x)\, dx \Rightarrow \frac{dI_\nu(x)}{dx} = -\alpha\, I_\nu(x)$$

$$\frac{dI_\nu(x)}{dx} + \alpha\, I_\nu(x) = 0$$

$$\Rightarrow \boxed{I_\nu(x) = I_{\nu 0}\, e^{-\alpha x}} \quad I_{\nu 0} = I_\nu(x)\big|_{x=0}$$

α − Absorption coefficient



* The absorption coefficient is a strong of photon energy ($h\nu$) and energy gap (E_G) of the semiconductor.

→ Calculate the thickness of a semiconductor that will "absorb 90 percent" of the incident photon energy.
(i) $\lambda = 1\mu m$ and (ii) $\lambda = 0.5\mu m$

Assume the semiconductor is silicon, the absorption coefficient $\alpha \simeq 10^2\, cm^{-1}$ for $\lambda = 1\mu m$ and $\alpha \simeq 10^4\, cm^{-1}$ for $\lambda = 0.5\mu m$.

$$I_\nu = I_{\nu 0}\, e^{-\alpha x}$$

At $x = d$, $I_\nu(x = d) = 10\%\, I_{\nu 0} = 0.1\, I_{\nu 0}$

$$I_{\nu 0}\, e^{-\alpha d} = 0.1 I_{\nu 0} \Rightarrow e^{-\alpha d} = 0.1$$

$$d = \frac{1}{\alpha}\ln\left(\frac{1}{0.1}\right)$$

(1) $\lambda = 1\mu m$, $\alpha \simeq 10^2\, cm^{-1}$ $\quad d = \frac{1}{10^2}\ln\left(\frac{1}{0.1}\right) = 0.023\, cm$

(2) $\lambda = 0.5\mu m$, $\alpha \simeq 10^4\, cm^{-1}$ $\quad d = \frac{1}{10^4}\ln\left(\frac{1}{0.1}\right) = 2.3\mu m$

Electron-Hole Pair Generation Rate

$I_\nu(x) \longrightarrow$ energy/cm^2-s

$\alpha\, I_\nu(x) \longrightarrow$ energy/cm^3-s } The rate at which, energy is absorbed per unit volume

α (/cm) $I_\nu(x)$ (energy/cm^2-s)

* Each absorbed photon generates one EHP
* The EHP generation rate is given by

$$\boxed{G' = \frac{\alpha\, I_\nu(x)}{h\nu}} \rightarrow (/\text{cm}^3\text{-s})$$

$$\boxed{\begin{array}{l} \dfrac{I_\nu(x)}{h\nu} = \phi(x) \rightarrow \text{Photon flux} \\ G' = \alpha\, \phi(x) \end{array}}$$

$$G = G_0 + G'$$

→ Calculate the generation rate of EHPs (G') given an incident intensity of photons. Consider GaAs at $T = 300K$. Assume the photon intensity at a particular point is $I_\nu(x) = 0.05\ W/cm^2$ at a wavelength of $\lambda = 0.75\mu m$. The absorption coefficient for GaAs at this wavelength is $\alpha \simeq 0.9 \times 10^4 /cm$ and $\tau = 10^{-7}s$.

Photon energy $E(eV) = \frac{1.24}{\lambda(\mu m)} = \frac{1.24}{0.75} = 1.65 eV$

$$G' = \frac{\alpha I_\nu(x)}{h\nu}$$

$$G' = \frac{0.9 \times 10^4 \times 0.05}{1.65 \times 1.6 \times 10^{-19}} = 1.7 \times 10^{21} / cm^3 - s$$

→ Excess carriers $\delta p = \delta n = \delta$

$$\delta = G'\tau = 1.7 \times 10^{21} \times 10^{-7}$$

$$= 1.7 \times 10^{14} / cm^3$$

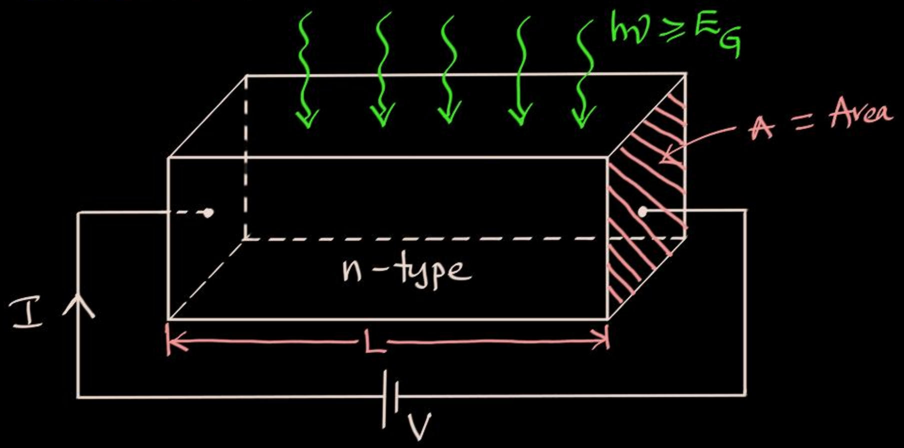
Photodetectors

→ Photoconductor

→ Photodiode → Long photodiode; → pin diode; → APD — Photoconductive effect

→ Solar cell — Photovoltaic effect

Photoconductor → The simplest form of photodetector



Equilibrium $\rightarrow$ $\sigma_0 = n_0 q \mu_n + p_0 q \mu_p$

In the presence of excess carriers $\rightarrow$ $\sigma = n q \mu_n + p q \mu_p$

$n = n_0 + \delta n$ and $p = p_0 + \delta p$ $\quad \delta n = \delta p = \delta$

$$\sigma = n q \mu_n + p q \mu_p = (n_0 + \delta) q \mu_n + (p_0 + \delta) q \mu_p$$

$$= \underbrace{(n_0 q \mu_n + p_0 q \mu_p)}_{\sigma_0} + \underbrace{(\delta q \mu_n + \delta q \mu_p)}_{\Delta\sigma = \sigma_L}$$

$\sigma = \sigma_0 + \Delta\sigma$ (or)

$\sigma = \sigma_0 + \sigma_L$

$$\boxed{\Delta\sigma = \sigma_L = q\delta(\mu_n + \mu_p)}$$

$\rightarrow$ Assume the semiconductor is n-type

$$J = \sigma E = (\sigma_0 + \sigma_L) E = \sigma_0 E + \sigma_L E$$

$J = J_0 + J_L$, J_L – Photocurrent density

$$J_L = \sigma_L E = \Delta\sigma E$$

$$I_L = A J_L = A \sigma_L E = A q \delta (\mu_n + \mu_p) E$$

$$I_L = A q G^1 \tau_p (\mu_n + \mu_p) E \quad (\because \delta = G^1 \tau_p)$$

→ The transit time of the electron, it is the time taken by the electron to travel a distance 'L'

$$t_n = \frac{L}{v_n} = \frac{L}{\mu_n E} \Rightarrow \mu_n E = \frac{L}{t_n}$$

→ Consider $I_L = q G' \tau_p \left(1 + \frac{\mu_p}{\mu_n}\right) \mu_n E A$

$$\Rightarrow \boxed{I_L = q G' \left(\frac{\tau_p}{t_n}\right)\left(1 + \frac{\mu_p}{\mu_n}\right) A L}$$

→ Photoconductor gain – It is the ratio of the rate at which charge is collected by the contacts to the rate at which charge is generated within the photoconductor (Γ_{ph})

$$\boxed{\Gamma_{ph} = \frac{I_L}{q G' A L} = \frac{\tau_p}{t_n}\left(1 + \frac{\mu_p}{\mu_n}\right)}$$

→ Consider an n-type silicon photoconductor with a length $L = 100\,\mu m$, cross-sectional area $A = 10^{-7}\,cm^2$ and minority carrier life time $\tau_p = 10^{-6}\,s$. Let the applied voltage be $V = 10$ volts. Calculate the photoconductor gain. Given that $\mu_n = 1350\,cm^2/V\text{-}s$ and $\mu_p = 480\,cm^2/V\text{-}s$.

$$\Gamma_{ph} = \frac{I_L}{q G' A L} = \frac{\tau_p}{t_n}\left(1 + \frac{\mu_p}{\mu_n}\right)$$

$$t_n = \frac{L}{v_n} = \frac{L}{\mu_n E} = \frac{L}{\mu_n (V/L)} = \frac{L^2}{\mu_n V} \quad \left(\because E = \frac{V}{L}\right)$$

$$= \frac{(100 \times 10^{-4})^2}{1350 \times 10} = 7.41\,ns$$

$$\Gamma_{ph} = \frac{10^{-6}}{7.41 \times 10^{-9}}\left(1 + \frac{480}{1350}\right) = 1.83 \times 10^{2}$$

$$= \underline{\underline{183}}$$