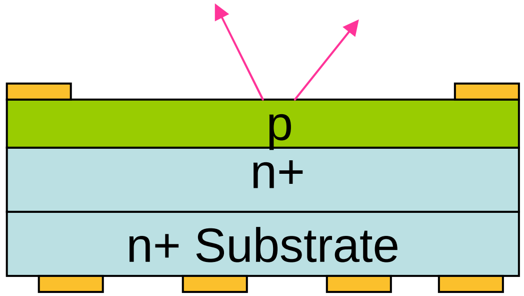
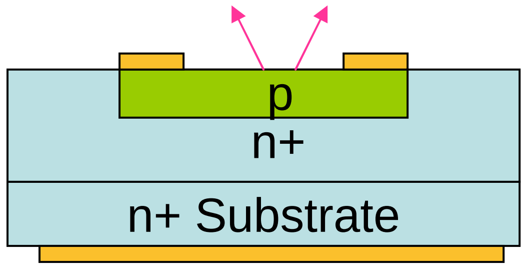
LED structure

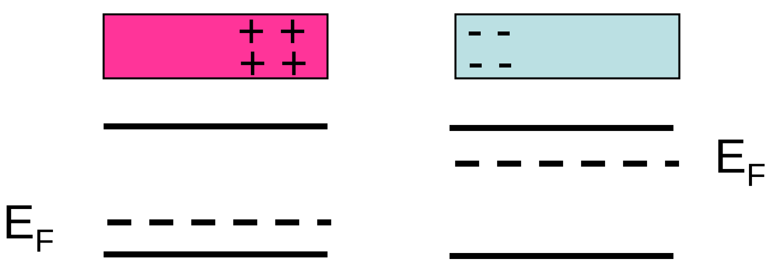


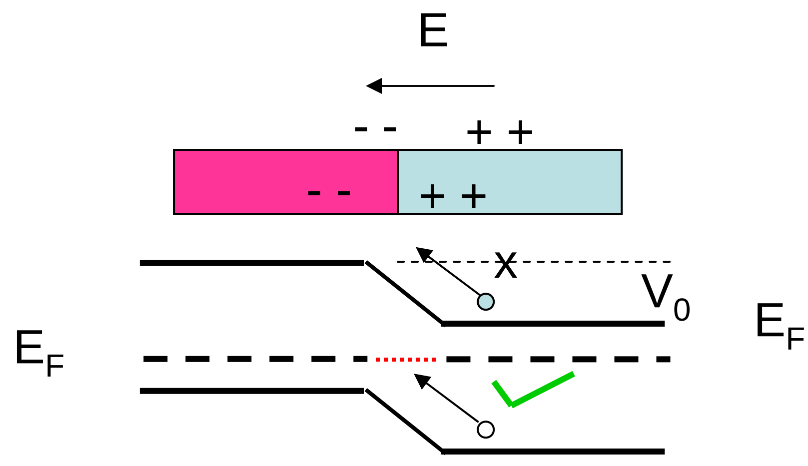
Epitaxial LED



Diffusion LED

Band diagram



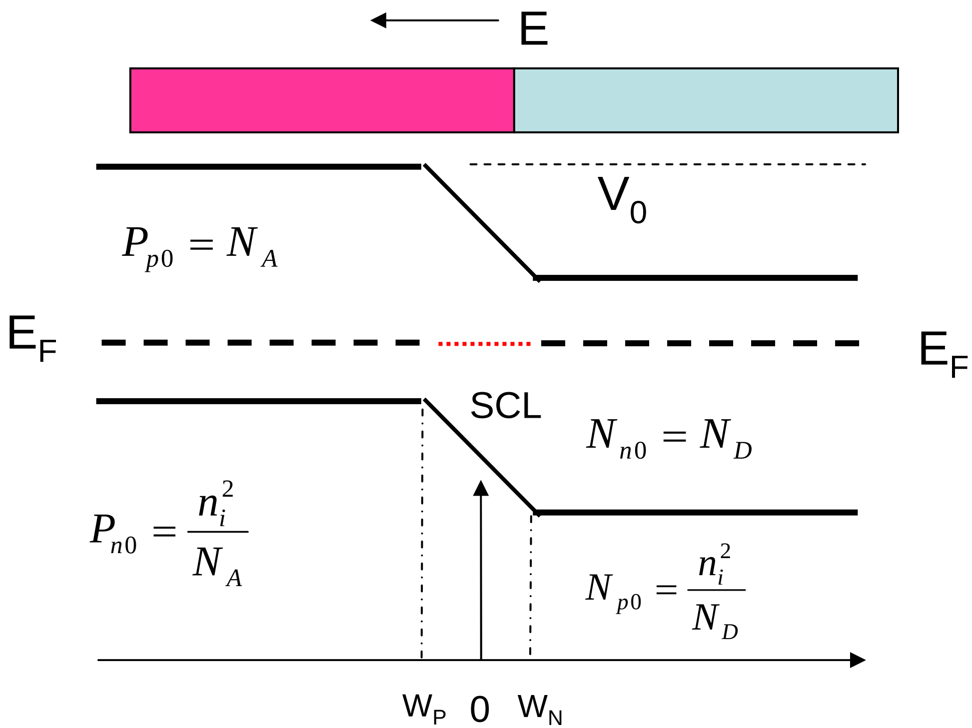


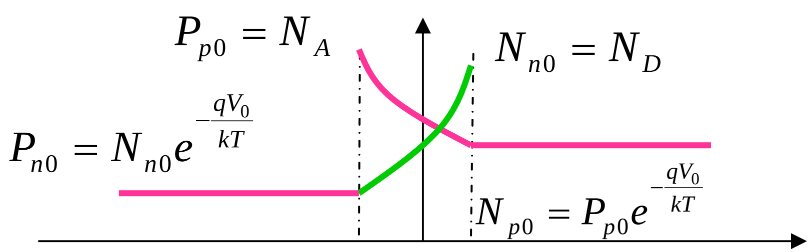
$$E_F - E_i = -\frac{kT}{q}\ln\left(\frac{n_i}{N_D}\right) \qquad E_i - E_F = \frac{kT}{q}\ln\left(\frac{n_i}{N_A}\right)$$

$$V_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Light emitting diode (LED)

Carrier concentration





Doping

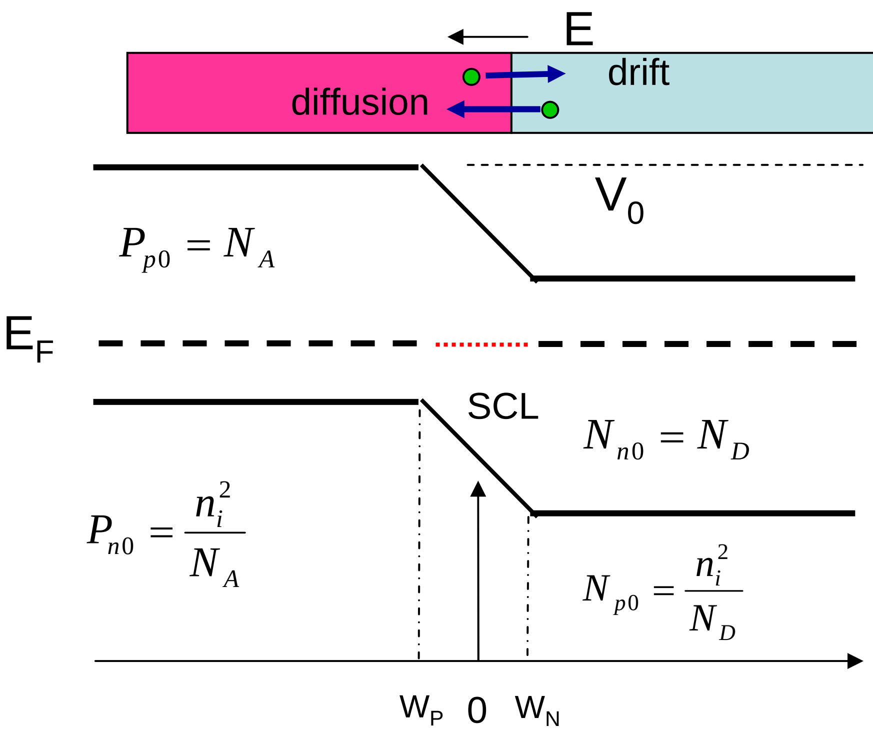
Spatial distribution

$$P_{p0}(x)$$

Carrier type

Thermal equilibrium

$$V_0 = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$



$$J_{diffusion} = eD\frac{\partial n_0}{\partial x}$$

$$J_{drift} = n_0 \mu_e E$$

$$J_{drift} = J_{diffusion} \Rightarrow n_0 \mu_e E = D_e \frac{\partial n_0}{\partial x}$$

$$\Rightarrow \frac{dn_0}{n_0} = (\mu_e / D_e) E dx$$

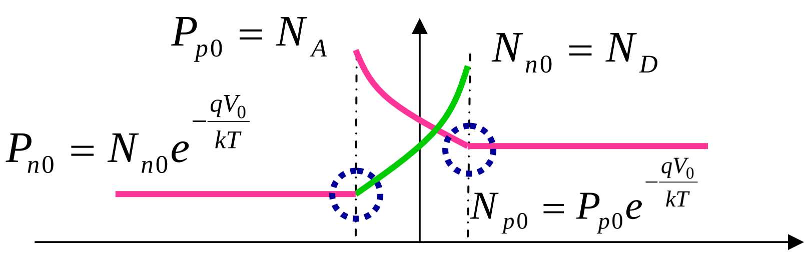
$$\Rightarrow d\ln(n) = -(\mu_e / D_e) dV$$

$$\Rightarrow \ln(n / n(0)) = -[V(W) - V(0)] = -V_0$$

$$\Rightarrow n(W) = n(0) e^{-\frac{qV_0}{kT}}$$

$$\Rightarrow n(x) = n(0) e^{-\frac{qV(x)}{kT}}$$

$$p(x) = p(0) e^{-\frac{qV(x)}{kT}}$$



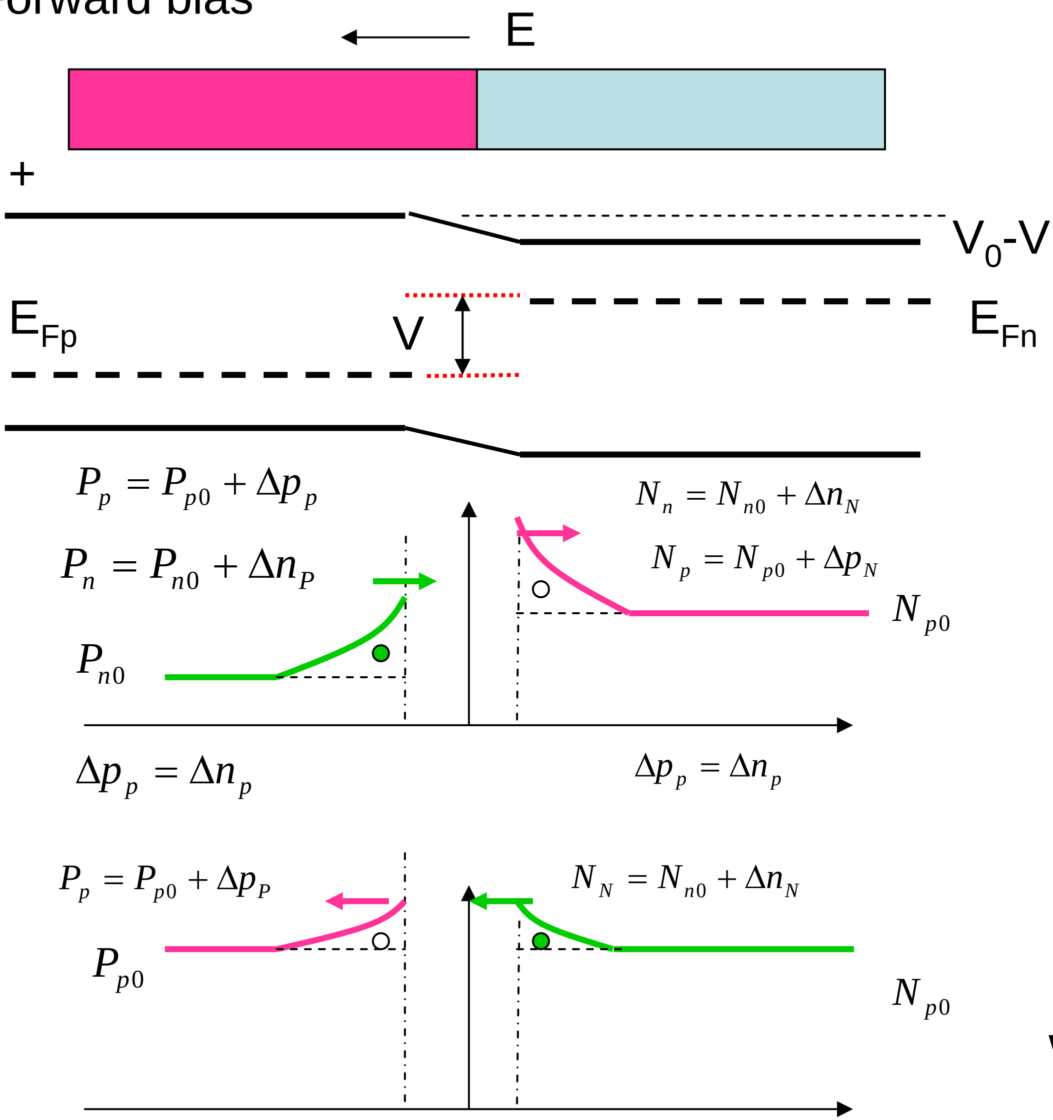
Net J out and in = 0

$$J_{drift} = n_0 \mu_e E = 0$$

$$J_{diffusiont} = 0$$ Why?

Non-equilibrium

Forward bias



Δp_p Excess hole on the P side

$$n(x) = n(0)e^{\frac{qV(x)}{kT}} \quad n(x) = n(0)e^{\frac{q(V_0 - V)}{kT}}$$

$$P_n = n(0) = N_n e^{-\frac{qV_0}{kT}} e^{\frac{qV}{kT}}$$

$$P_{n0} = N_{n0} e^{-\frac{qV_0}{kT}}$$

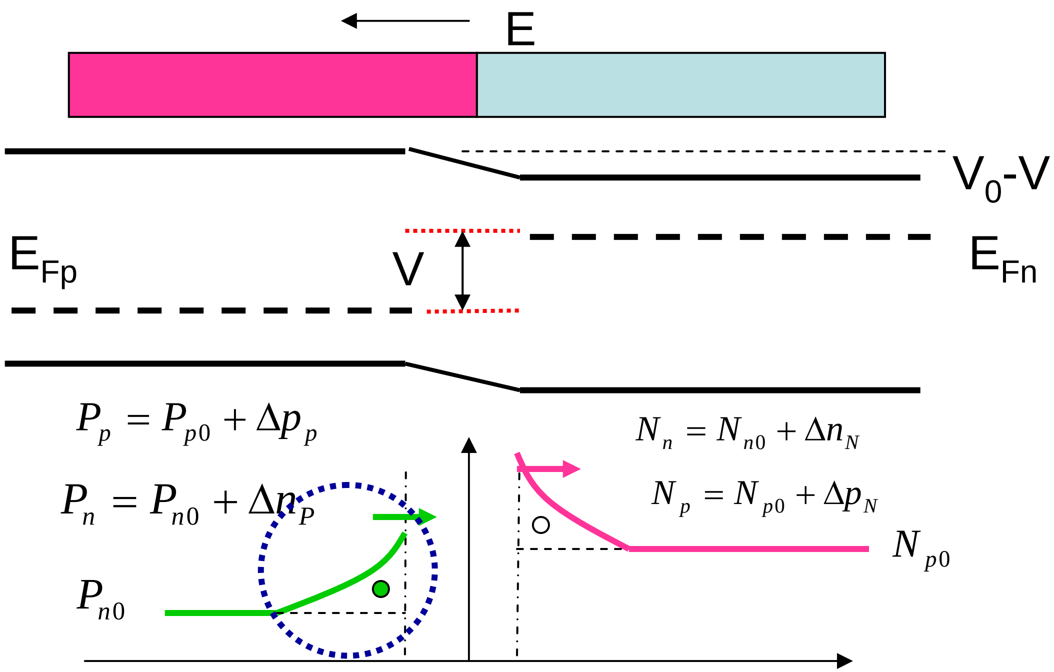
$$\Delta n_P = P_{n0}\left(e^{\frac{qV}{kT}} - 1\right)$$

$$\Delta p_N = N_{p0}\left(e^{\frac{qV}{kT}} - 1\right)$$

Weak injection $\Delta p_P = \Delta n_P = P_{n0} e^{\frac{qV}{kT}} << P_{p0}$

Strong injection $\Delta p_p = \Delta n_p = P_{n0} e^{\frac{qV}{kT}} \sim P_{p0}$

Ignore majority carrier diffusion at weak injection, why?



$\Delta p_p = \Delta n_p$ $\qquad$ $\Delta p_p = \Delta n_p$

$$\nabla \cdot \vec{J} = -q \frac{\partial \Delta n}{\partial t}$$

No drift current, why?

$$\frac{\partial J}{\partial x} = -q \frac{\partial \Delta n}{\partial t} \qquad J_{diffusion} = qD \frac{\partial \Delta n}{\partial x}$$

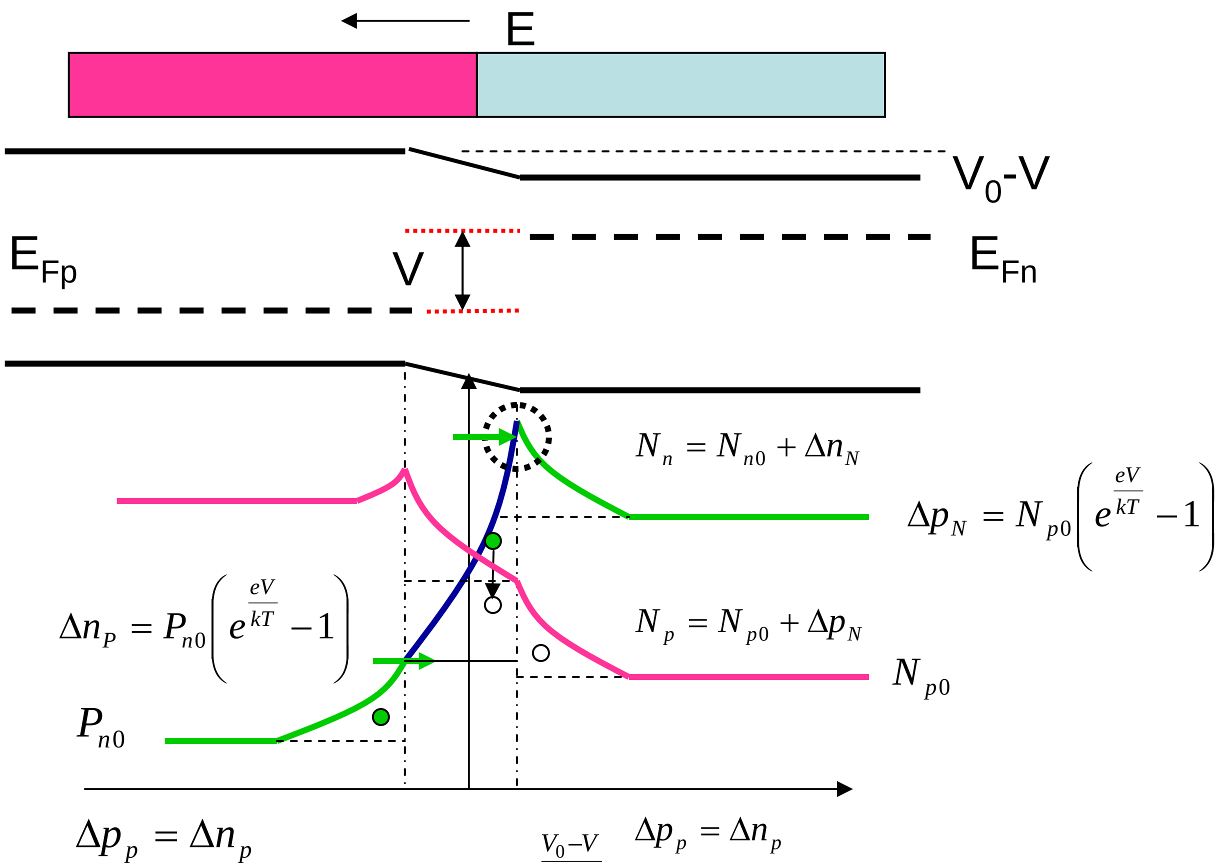
$$D \frac{\partial^2 \Delta n}{\partial x^2} = \frac{\Delta n}{\tau_p}$$

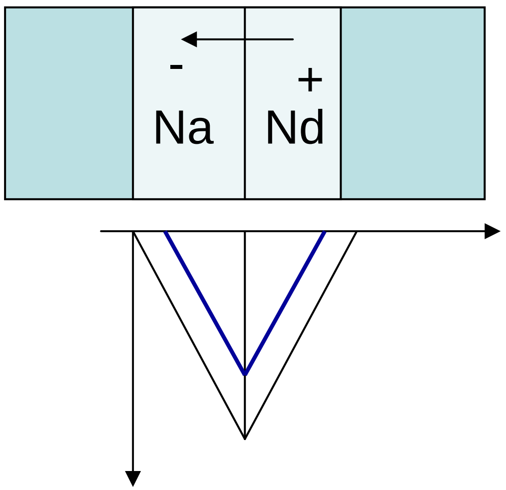
$$\Delta n(x,t) = \Delta n(x = -W_p, t) e^{x/L_n} \qquad L_n = \sqrt{D_n \tau_n}$$

$$\Delta p(x,t) = \Delta p(x = W_n, t) e^{-x/L_p} \qquad L_p = \sqrt{D_p \tau_p}$$

$$J_n |_{x=-W_P} = qD_n \frac{d\Delta n}{dx} |_{x=-W_P} = \frac{qD_n}{L_n} n_{p,0} (e^{\frac{qV}{kT}} - 1) = \frac{qD_n}{L_n} \frac{n_i^2}{N_A} (e^{-\frac{qV}{kT}} - 1)$$

$$J_p |_{x=W_n} = qD_p \frac{d\Delta p}{dx} |_{x=W_n} = \frac{qD_p}{L_p} N_{p,0} (e^{\frac{qV}{kT}} - 1) = \frac{qD_p}{L_p} \frac{n_i^2}{N_D} (e^{\frac{qV}{kT}} - 1)$$





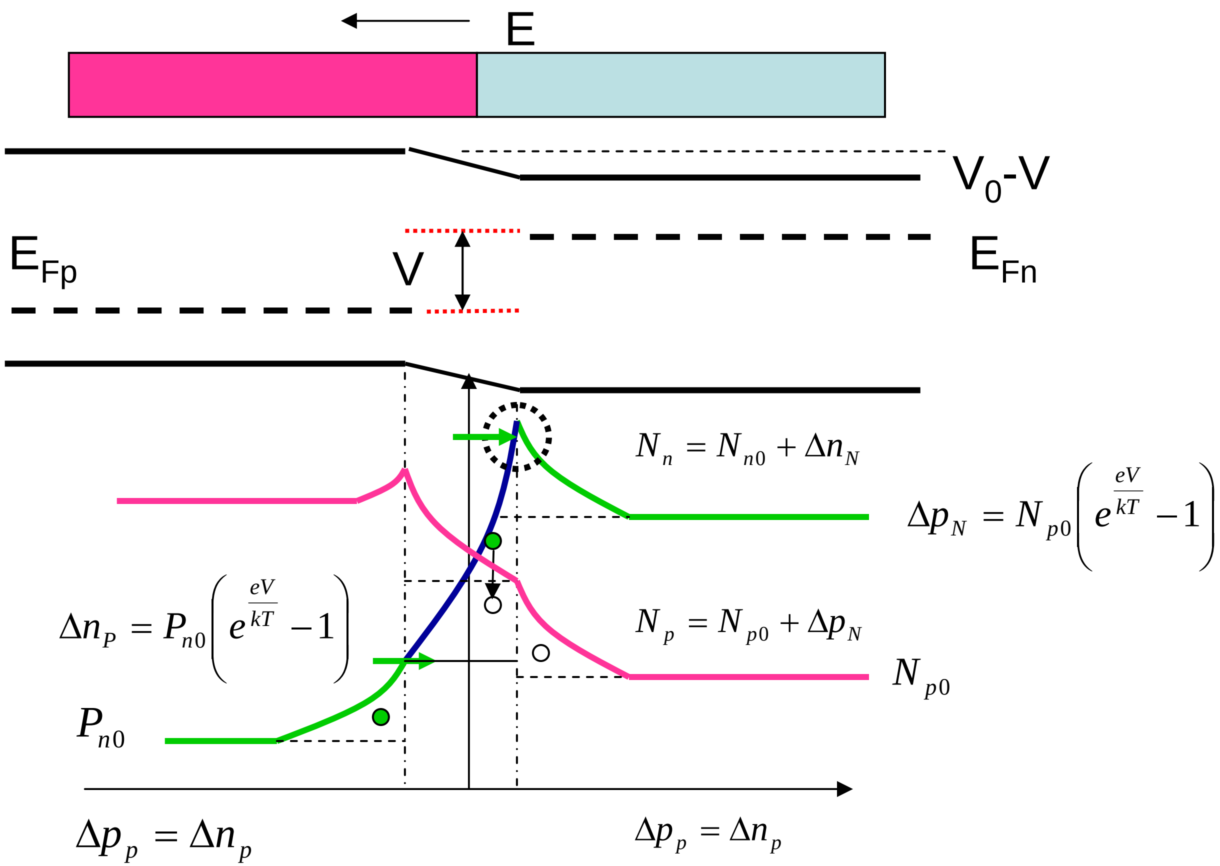
$$n(x) = n(0)e^{\frac{V_0 - V}{kT}}$$

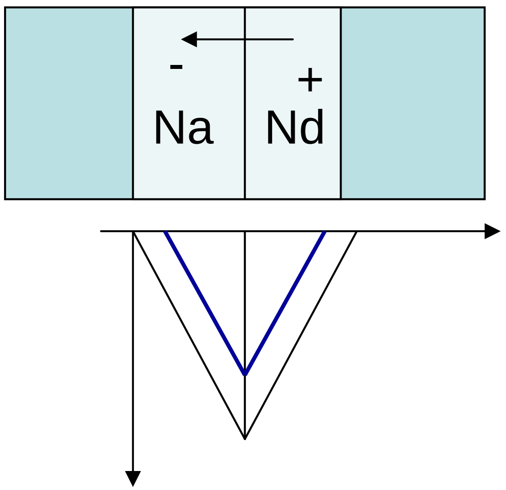
$$J_r = \left(\frac{qn_iW}{2\tau_n} + \frac{qn_iW}{2\tau_p}\right)\left(e^{\frac{qV}{2kT}} - 1\right)$$

$$n = \frac{n(0)e^{\frac{V_0 - V}{2kT}}W}{2}$$

$$\Delta n = \frac{N_{n0}W}{2}\left(e^{-q\frac{V_0 - V}{2kT}} - 1\right) \approx \frac{n_iW}{2}\left(e^{\frac{qV}{2kT}} - 1\right)$$

Non-equilibrium



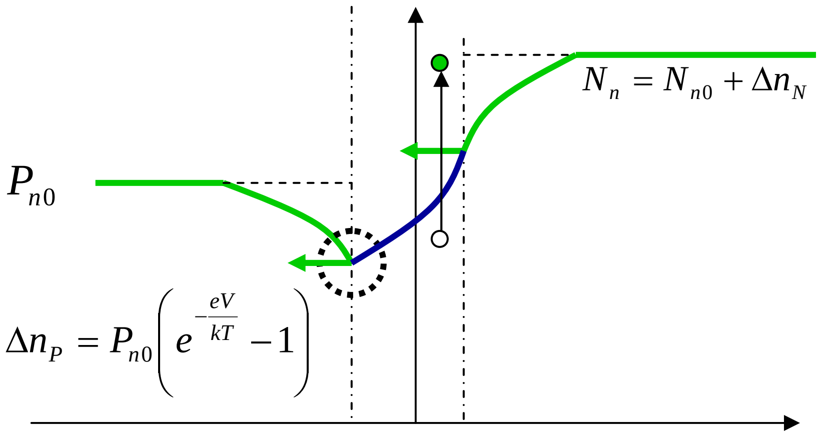


$$J_n = \frac{qD_n}{L_n}\frac{n_i^2}{N_A}(e^{-\frac{qV}{kT}} - 1)$$

$$J_r = \left(\frac{qn_iW}{2\tau_n} + \frac{qn_iW}{2\tau_p}\right)\left(e^{\frac{V}{\eta kT}} - 1\right)$$

$$J_p = \frac{qD_p}{L_p}\frac{n_i^2}{N_D}(e^{\frac{qV}{kT}} - 1)$$

Reverse bias



$$J_n = \frac{qD_n}{L_n}\frac{n_i^2}{N_A}(e^{-\frac{qV}{kT}} - 1) \approx -\frac{qD_n}{L_n}\frac{n_i^2}{N_A}$$

$$J_p = -\frac{qD_p}{L_p}\frac{n_i^2}{N_D}$$

$$J_r = -\frac{qn_iW}{\tau_g}$$

1. Radiative combination $\longrightarrow$ Emit light

2. non-radiative combination $\longrightarrow$ Emit heat

on P side: $n_p = n_{p0} + \Delta n_p$ ← instantaneous minority carriers

$P_p = P_{p0} + \Delta P_p$ ← majority carriers

$$\frac{\partial n_p}{\partial t} = -B\, n_p P_p + G_{thermal}$$ B is direct recombination coefficient

$$= -B(n_p P_p - n_{p0} P_{p0})$$

$$= -B(n_{p0} + \Delta n_p)(P_{p0} + \Delta P_p) + B\, n_{p0} P_{p0}.$$

at low injection level: $\Delta n_p \ll P_{p0}$ $\cong -B\,\Delta n_p P_{p0} = -B\,\Delta n_p \cdot N_a$

$$\frac{\partial \Delta n_p}{\partial t} = -\frac{n_p}{\tau_e} \Rightarrow \tau_e = \frac{1}{B N_a} \sim ns$$

at high injection Level: $\Delta n_p \gg P_{p0}$

$$\frac{\partial \Delta n_p}{\partial t} = -B\,\Delta n_p \cdot \Delta P_p = -B(\Delta n_p)^2$$

$$\tau_e = \frac{1}{B\,\Delta n_p}$$

Recombination coeffients of Reprentative semiinconductors

Material	Bandgap type	Br
Si	in-dirert	1.79×10^{-15} cm^3/s
Ge	in-direct	5.25×10^{-14} cm^3/s
GaP	in-dirert	5.37×10^{-14} cm^3/s.
GaAs	direct	7.21×10^{-10} cm^3/s
GaSb	Dirert	2.39×10^{-10} cm^3/s
InAs	Direct	8.5×10^{-11} cm^3/s.
InSb	Dirert	4.58×10^{-11} cm^3/s.

What lifetime implys ?

Modulation bandwidth. for lifetime ~ ns

Maxium modulation ~ GHz

Example: calculate radiative lifetime of GaAs & Si

1). GaAs, assuming low level injection:

$p \sim 10^{18}\,cm^{-3} \leftarrow N_A$

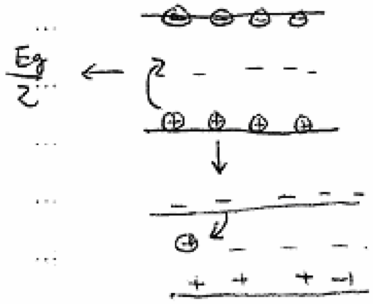
$$\tau_r = \frac{1}{B_r p} = \frac{1}{B_r N_A} = \frac{1}{7.2\times10^{-10}\cdot10^{18}} = 1.4\,ns.$$

2). Si,

$p \sim 10^{18}\,cm^{-3} \leftarrow N_a$

$$\tau_r = \frac{1}{B_r N_a} = \frac{1}{1.8\times10^{-15}\cdot10^{18}} = 0.6\,ms$$

non-radiative combination



1). electron-hole pairs "recombine" through traps in the forbidden gap, which emit heat or multi-phonons

also called spare-charge recombination, which is a two-step process.

the Non-radiative recombination rate in spare charge region

$$R = \frac{n_i}{2\tau} e^{qV/2kT} , \qquad \tau = \frac{1}{\sigma_t V_{th} N_t}$$

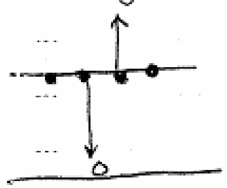
σ_t : $= \sigma_p = \sigma_n \equiv$ hole & electron capature cross sertor

$\sigma_p = \sigma_n$, since trap is at roughly $\frac{E_g}{2}$.

V_{th} : thermal velocity.

N_t : density of traps

2) Auger recombination



. Collision of two electrons which knocks one electrons down to Valanre band and the other to a higher energy state in CB.

$$\tau_A = \frac{1}{C n_0^2} , \qquad R_A = C N^3$$

Auger recombination is important only at high injection level, C is material dependent

example . GaAs, $C = 5\times10^{-30}\ cm^6/s$. –

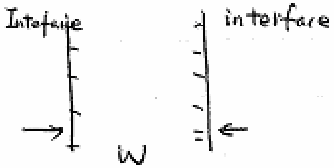
InGaAsP, $C = 10^{-28}\ cm^6/s$.

For $n_0 = 5\times10^{17}\ cm^{-3}$, GaAs $\tau_A = \frac{1}{5\times10^{-30} \cdot (5\times10^{17})^2} = 8\ \mu s$

InGaAsP $\tau_A = \frac{1}{10^{-28} \cdot (5\times10^{17})^2} \simeq 40\ (ns)$.

3) Inteface Recombination

- dangling bonds at surface and material Interface which forms miniband in Engngy gap



$$\tau_s = \frac{W}{2S}$$

$S \equiv$ interface recombination velocity

typical value of S:

GaAs $\sim 10^6$ cm/s

InP $\sim 10^3$ cm/s

heterojunction interface

Si/SiO$_2$ $\sim$ 10 cm/s

GaAs/AlGaAs $\sim$ 500 cm/s
recently reduced to 0.25 cm/s

InP/InGaAsP $\sim 10^3 - 10^4$

Quantum Efficiency (QE)

1. internal QE. $\eta_i = \dfrac{\text{\# of Photons generated}}{\text{\# electron - hole injected}}$

$$\eta_i = \frac{R_r}{R_{total}} = \frac{\frac{\Delta n}{\tau_r}}{\frac{\Delta n}{\tau_r} + \frac{\Delta n}{\tau_{nr}}} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}$$

$$R_{total} = R_r + R_{nr} = R_r + R_t + R_A + R_S$$

$$= \underbrace{\frac{1}{B_r N}}_{\tau_r} \Delta n + \frac{1}{\underbrace{\sigma_t V_{th} N_t}_{\tau_t}} \Delta n + \frac{\Delta \tau}{C n_0^2} + \frac{\Delta n}{\frac{W}{2s}}$$

Example: η_i for GaAs & Si

GaAs: $\tau_r \sim 1$ ns, Assuming Interface recombination dominates.

$S = 500$ cm/s, $W \sim 0.3 \times 10^{-4}\ \mu m$, $\Rightarrow \tau_{nr} = 30$ ns

$\eta_i \sim 97\%$

For Si: $\tau_r = 2 \times 10^{-4}$ s, $\tau_{nr} \simeq 100$ ns.

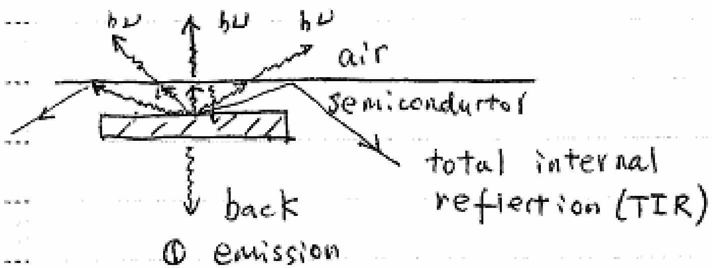
$\eta_i \sim 5 \times 10^{-4}$

Conclusion: ① τ_r needs to be small enough.

② Si is not a good Light emitter.

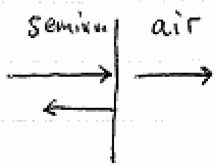
External Quantum Efficiency

$$\eta_e = \frac{\#\ \text{photons emitted}}{\#\ \text{eHP injected}}$$ ← depends on η_i and device structure



① back emission ~ 50% Loss through back

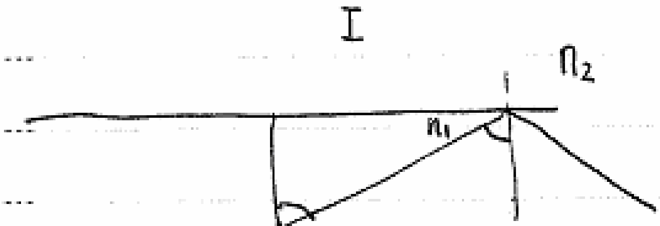
② Fresnel Reflection:



$$r = \frac{n_1 - n_2}{n_1 + n_2} = \frac{3.5 - 1}{3.5 + 1} \approx \frac{2.5}{4.5} = 40\%$$

③ Reabsorption:

④ total interal reflection



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\Rightarrow \sin\theta_c = \frac{n_2}{n_1}\sin\theta_2 \Big|_{\theta_2 = 90^\circ}$$

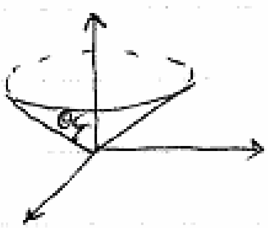
$$= \frac{1}{3.5}$$

- Lambert Law: Light measured will vary as the cosine of the angle off normal

$$\Rightarrow \theta_c \sim 16^\circ$$

any light generated in the active region that larger than $\theta_c = 16^\circ$, will not be emitted

efficiency due to TIR



$$\frac{P_{out}}{P_{in}} = \frac{\int_0^{\theta_c} \sin\theta \, d\theta \cos\theta \, 2\pi}{\int_0^{\pi/2} \sin\theta \, d\theta \cos\theta \, 2\pi} = \frac{1}{2}\sin^2\theta_c$$

$$= \frac{1}{2}\left(\frac{n_2}{n_1}\right)^2$$

include Fresnel reflections:

$$\frac{P_{out}}{P_{in}} = (1-R)\cdot\frac{1}{2}\sin^2\theta_c \approx 3\%. \quad \leftarrow \text{Low Quantum efficien}$$

↑ fundmental Problem of LED for 35 years.

Solution:

- textured structure

- Grating

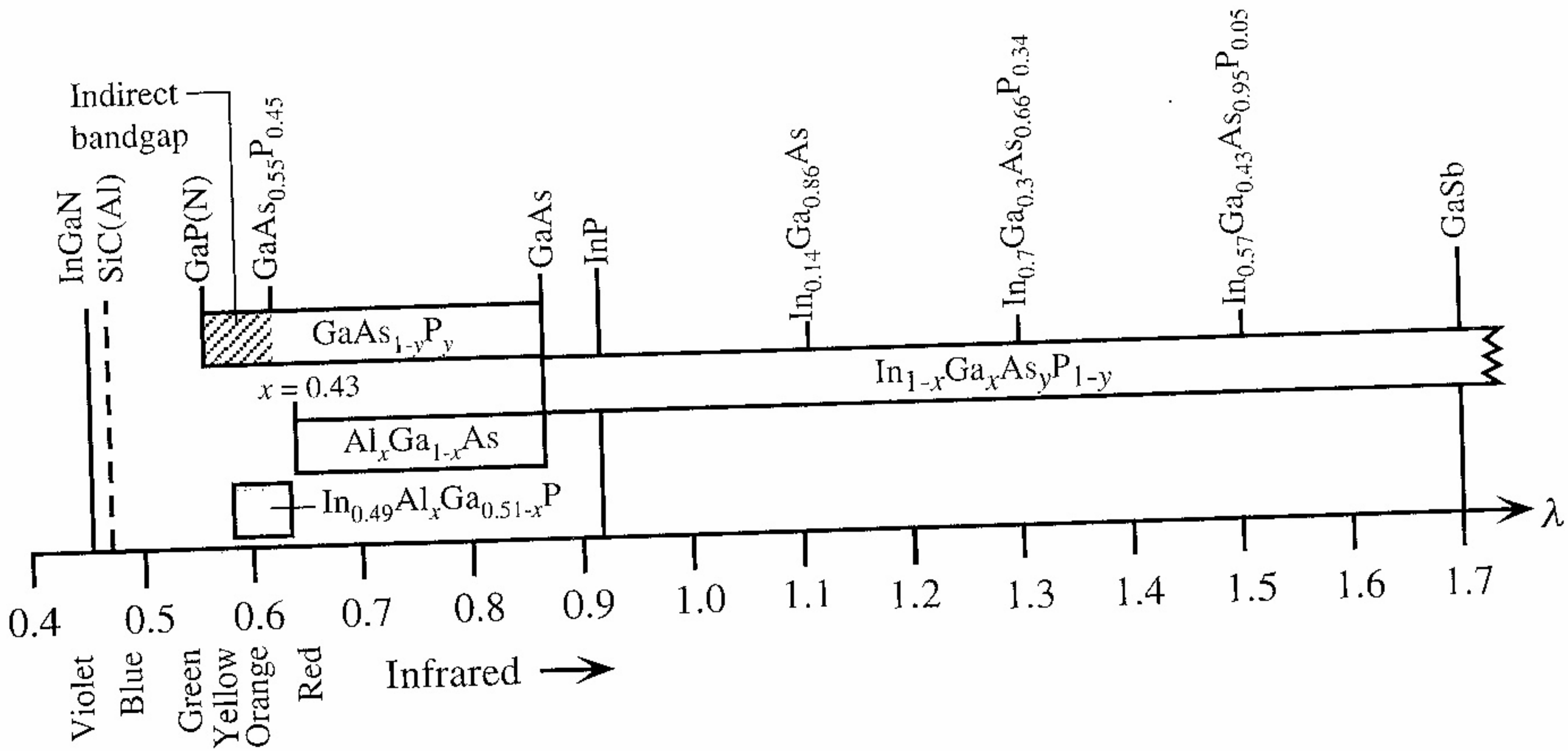
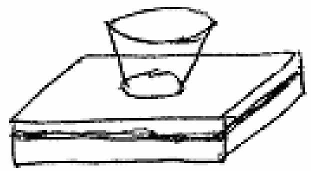
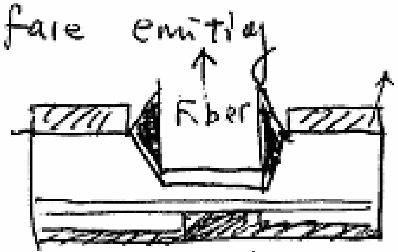


FIGURE 3.25 Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials.

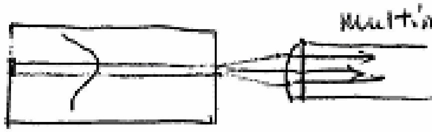
Communication LEDs

1. Structure: a). surface emitting





b). edge emitting

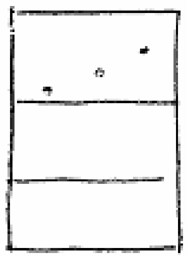


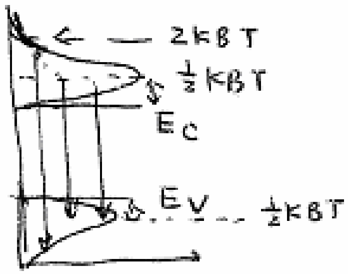
- high coupling efficiency
- Very thin active layer
  ⇒ much of the light extends to cladding layer. ⇒ Low reabsorption

- AR coating front facet
- HR coating back facet.

2. emission Spectra

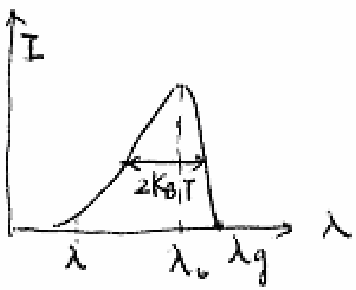
2. Emission spectra





- electron & hole peaks at $\frac{1}{2}K_BT + E_c$ & $-\frac{1}{2}K_BT + E_v$

width $\sim 2K_BT$



$$\lambda \cdot \nu = \frac{c}{n},$$

- $(h\nu)_{peak} = E_g + K_BT$
- $\Delta h\nu = 2K_BT$

$$\lambda = \frac{c}{\nu n}$$

$$\Rightarrow \quad \Delta\lambda = \frac{c}{-\nu^2 n}\Delta\nu = -\frac{\lambda_0^2}{hc/n}\Delta(h\nu)$$

$$= -\frac{\lambda^2}{hc/n}\cdot 2K_BT$$

- $\Delta\lambda \propto \lambda_0^2$

$$\frac{\Delta\lambda\, InGaAs\ (\sim \lambda \sim 1.3\mu m)}{\Delta\lambda\, GaAs\ (\lambda \sim 0.85\mu m)} \doteq 2.3$$

a). GaAs $\lambda_0 \sim 0.85\,\mu m$, $\Delta\lambda = 300\,\text{Å} = 30\,nm$

b). InGaAsP $\lambda_0 \sim 1.08\mu m$, $\Delta\lambda \simeq 500\,\text{Å}$

c). InGaAsP, $\lambda \sim 1.3\mu m$, $\Delta\lambda \simeq 700\,\text{Å}$

- $\Delta\lambda$ increases with N_a

- $\Delta\lambda$ increase as injection level increase

Examples :

1. LED output wavelength variations

Consider, GaAs LED, $E_g = 1.42\,eV$ @ 300K.

$$\frac{dE_g}{dT} = -4.5\times10^{-4}\ eV/K. \quad \text{find } \frac{d\lambda}{dT}.$$

$$(h\nu)_{peak} = E_g + k_BT \quad \Rightarrow \quad h\cdot\frac{c}{n\lambda} = E_g + k_BT$$

$$\Rightarrow \quad \frac{hc}{n(E_g+k_BT)} = \lambda \quad \Rightarrow \quad \frac{d\lambda}{dT} = -\frac{hc}{n}\cdot\frac{dE_g/dT}{(E_g+k_BT)^2}$$

$$= 2.8\times10^{-10}\,m/K = 0.28\ nm/K$$

2. The ternary alloy $In_{1-x}Ga_xAs_yP_{1-y}$

to avoid lattice mismatch, $y \simeq 2.2x$.

$$E_g = 1.35 - 0.72y + 0.12y^2, \quad 0 \le x \le 0.47$$

Calculate the composition of InGaAsP to make the emission peak at 1.3 μm

$$(h\nu)_{peak} = E_g + k_BT \quad \Rightarrow \quad \frac{hc}{n\lambda} = E_g + k_BT$$

$$\lambda = 1.3\ \mu m$$

$$\Rightarrow \quad E_g = 0.928\ eV = 1.35 - 0.72y + 0.12y^2$$

$$\Rightarrow \quad y = 0.66 \quad \Rightarrow \quad x = \frac{y}{2.2} = 0.3$$

$In_{0.7}Ga_{0.3}As_{0.66}P_{0.34}$

3. Bandwidth, (Modulation Bandwidth)

wide bandwidth $\Rightarrow$ require shorter carrier lifetime
why?

$I(\omega) = \dfrac{I_{dc}}{\sqrt{1+(\omega\tau)^2}}$, $P \propto I^2(\omega)$

$P_{3dB} = \dfrac{P_{dc}}{2}$ $\Rightarrow$ $\omega\tau = 1$, $f_{3B} = \dfrac{1}{2\pi\tau}$

$\Rightarrow$ short τ_r.

$\dfrac{1}{\tau} = \dfrac{1}{\tau_r} + \dfrac{1}{\tau_{nr}}$, $\tau_r = \dfrac{1}{N_a B_r}$ at low injection

$\Rightarrow f_{3B} = \dfrac{B_r N_a}{2\pi}$, independent of current at low injection.

at high injection:

$\tau_r = \dfrac{1}{B_r \Delta n_p}$, $J = \dfrac{qW\Delta n}{\tau}$ $\Rightarrow$ $\Delta n = J\tau/qW$

$\Rightarrow (\tau_r)^{-1} = \left(\dfrac{B_r J}{qW}\right)^{1/2}$

$\Rightarrow f_{3B} = \dfrac{1}{2\pi}\left(\dfrac{B_r J}{qW}\right)^{1/2}$

4. Bandwidth $\longleftrightarrow$ output Power trade off

a) at low injection:

$f_{3B} = \dfrac{B_r N_a}{2\pi}$. $N_a \uparrow \Rightarrow f_{3B}\uparrow$

however, heavy Doping ($> 10^{18} cm^{3}$) forms
Nonradiative recombination centers, $\tau_{nr} \downarrow$

e.g. @ $N_a \sim 2\times10^{19}/cm^3$, $\tau_r = 1\,ns$, $\tau_{nr} \simeq 1\,ns$

$\eta_i = \dfrac{1}{1+\tau_r/\tau_{nr}} = 50\%$

b). at high injection

$$f_{3B} = \frac{1}{2\pi}\left(\frac{B_r J}{q W}\right)^{1/2}$$

reduce W, can increase f_{3B}

but increase interface recombination

e.g. GaAs

$\tau_r = 10$ ns, $S = 300$ cm/s, $W = 2\,\mu m$

$$\tau_{nr} = \frac{W}{2S} \simeq 200\ \text{ns}.$$

$\Rightarrow \tau = 9.5$ ns $\Rightarrow f_{3B} = 37$ MHz, $\eta_i \simeq 100\%$

if $w = 0.1\,\mu m$

$\tau_{nr} = 10$ ns, $\tau = 5$ ns, $f_{3dB} = 200$ MHz

$\eta_i = 50\%$.

5. applications of Communication LED

a). Surface emitters

- large volume, Low-cost arrays
- on wafer testing
- Chip-to-Chip optical Interconnects

b). Edge emitters

Short distance fiber optic communication.

hw: 3.5, 3.7, 3.8