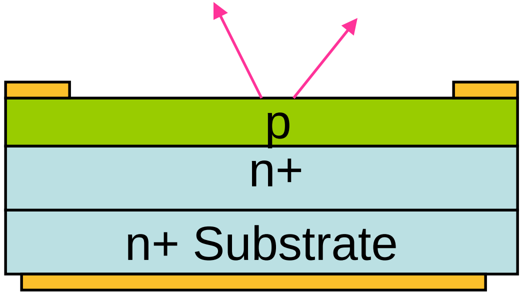
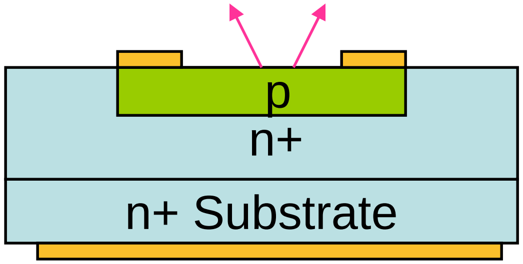
Structure, Material and process

1. LED structure

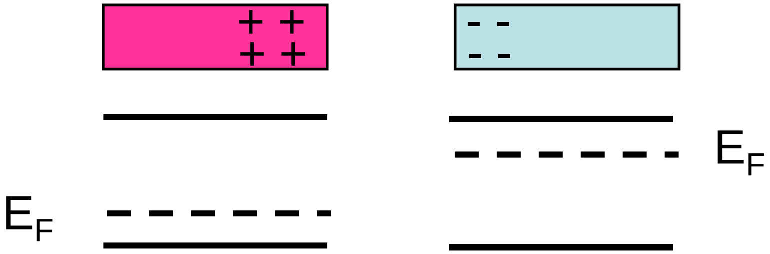


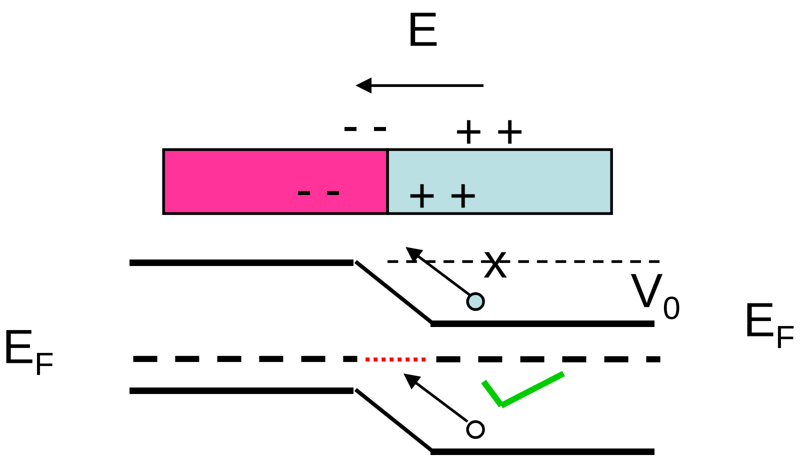
Epitaxial LED



Diffusion LED

Band diagram

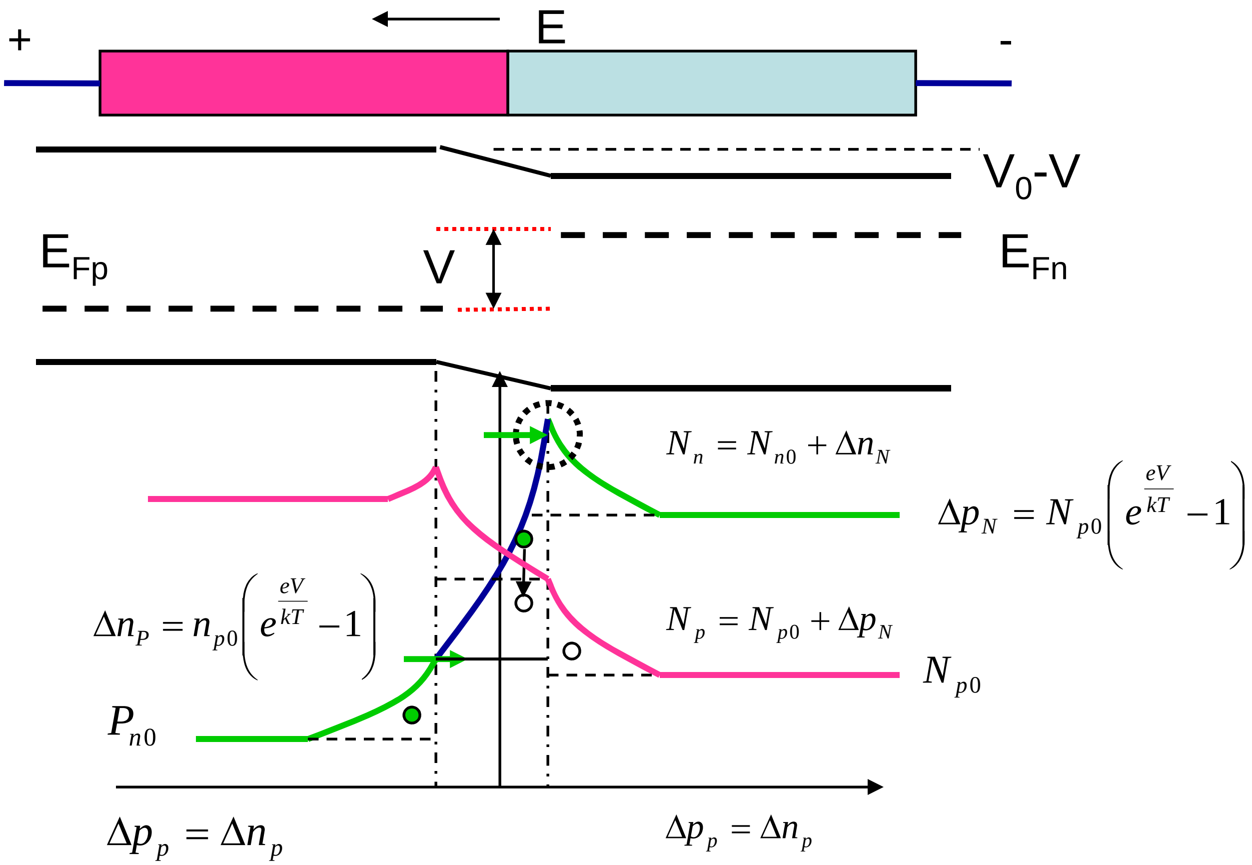


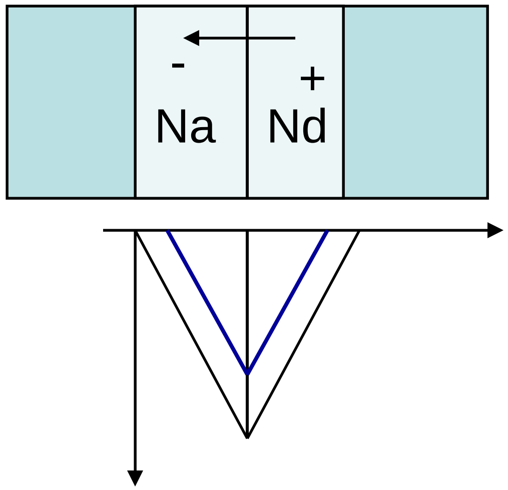


$$E_F - E_i = -\frac{kT}{q}\ln\left(\frac{n_i}{N_D}\right) \qquad E_i - E_F = \frac{kT}{q}\ln\left(\frac{n_i}{N_A}\right)$$

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

Non-equilibrium





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

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

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

Materials

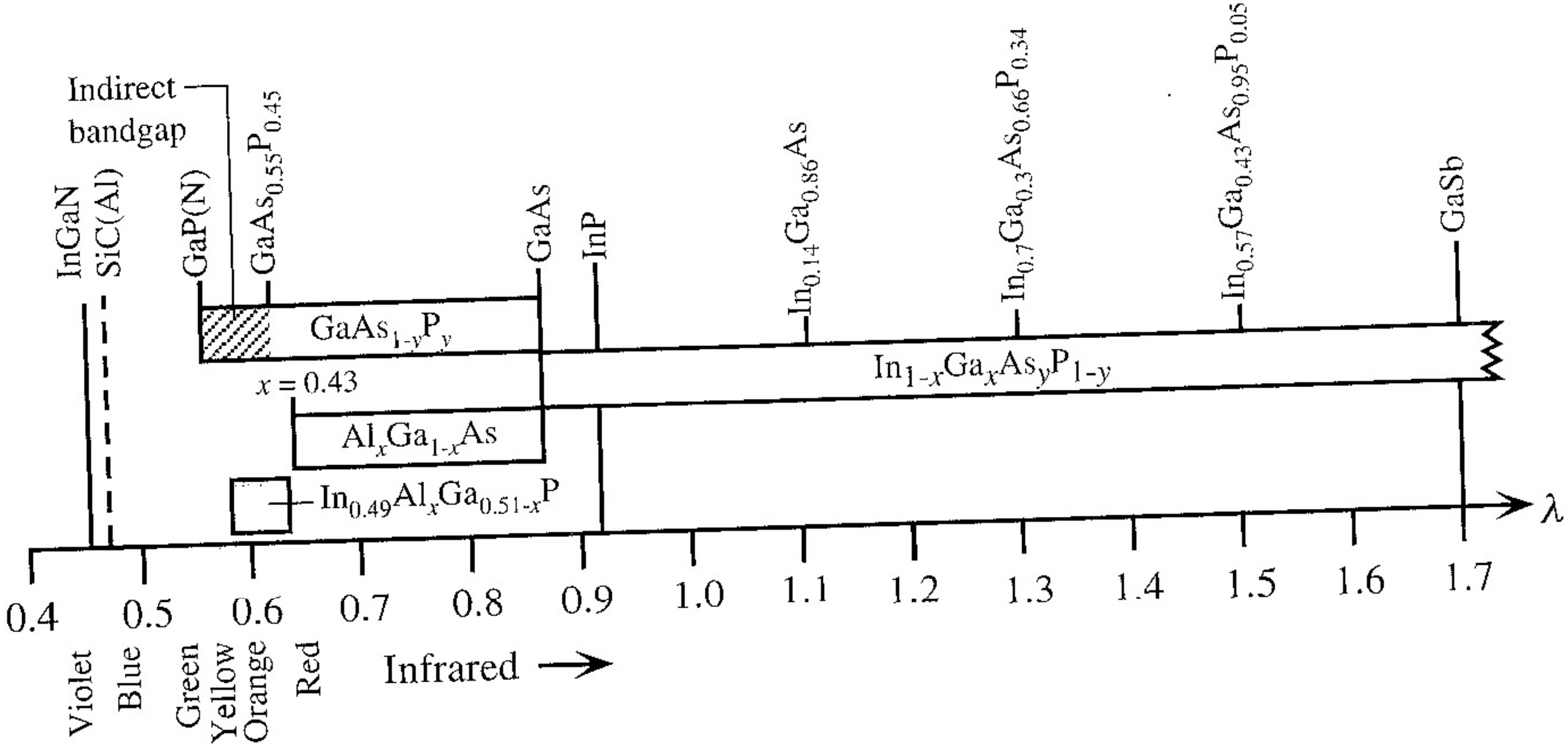
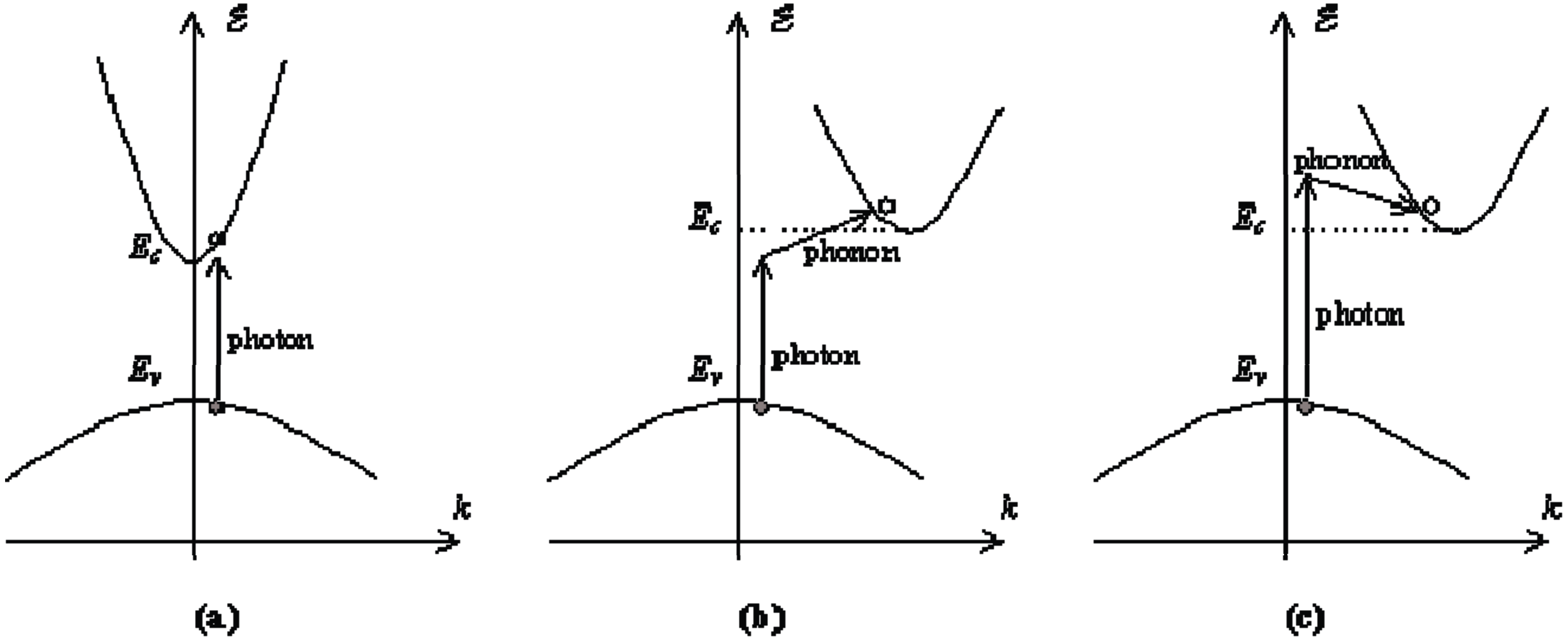
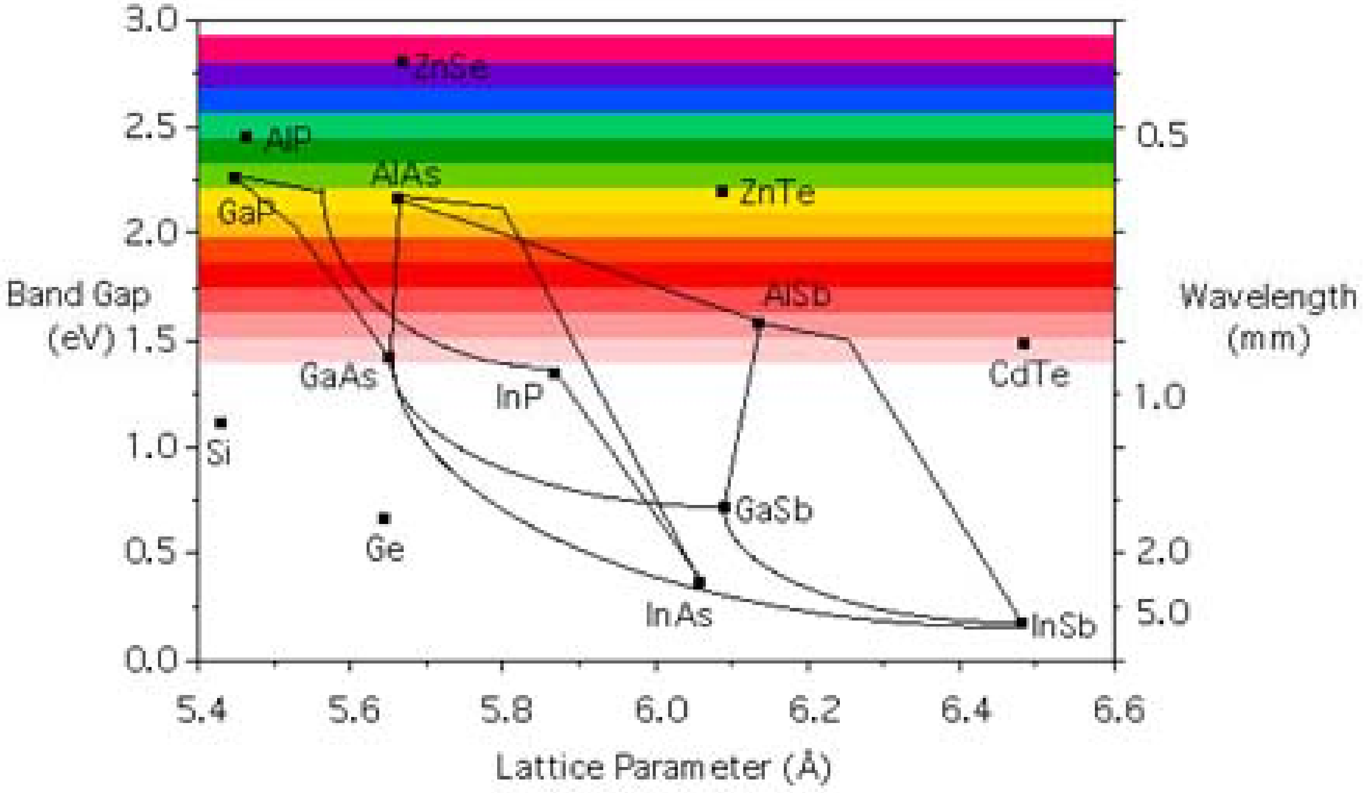


FIGURE 3.25 Free space wavelength coverage by different LED materials from the visible spectrum to the infrared including wavelengths used in optical communications. Hatched region and dashed lines are indirect E_g materials.

Materials



Band Gap *versus* Lattice Parameter for IV, III-V, and II-VI Semiconductors



Display LED

2. LED Materials

III-V ternay alloys, $GaAs_{1-y}P_y$, $y > 0.45$ indirect bandgap

- $GaAs_{0.55}P_{0.45}$ → 630 nm, red

  $GaAs$ → 870 nm, Infrared

- N doped $GaAs_{1-y}P_y$ ← indirect bandgap

  N forms electron traps, which attract holes in Its vicinity and eventually recombined gives light

  Nitrogen doped $GaAs_{1-y}P_y$ is widely used in green, yellow, & orange LED

3. blue LED

- SiC

  Indirect bandgap $E_g \sim 2.86$ eV

  Luminous efficiency $\eta \sim 0.04$ lm/W, $\eta_{ext} = 0.02\%$

  Research to find good isoelectronic trap to increase η

Display LED

- II – VI compounds

ZnCdSe/ ZnSe, ← material system Not Mature

issues: a). No Lattice-Matched substrate
b). Degradation.

- GaN ← best one

Two historical problems solved by Nichia Corp.

1). GaN is usually n-type as grown (probably N vacancies

1st n-type GaN was doped with Mg and annealed in a N_2 atmosphere ⇒ p-type GaN

Now, Zn has also been used

2). No Lattice-Matched substrates

use sapphire (Al_2O_3), but lattice Match is poor.

lattice mismatch ~ 15%.

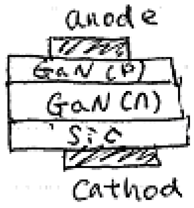
⇒ Breakthrough poly crystalline GaN buffer.

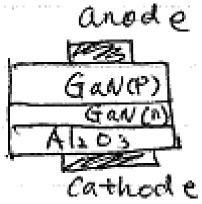
Luminous Intensity ~ 1 cd

$P_{out} \cong 1500\,\mu W$. $\eta_{ext} = 2.7\%$.

$\lambda \simeq 450nm$, $\Delta\lambda \simeq 70nm$.

- SiC substrates





SiC substrates

① better lattice match to GaN

② better thermal conductivity

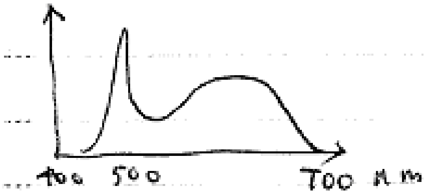
③ better thermal expansion match.

However, High substrate cost, ~ \$2,000 each

sapphire ~ \$200 each.

4. White LED

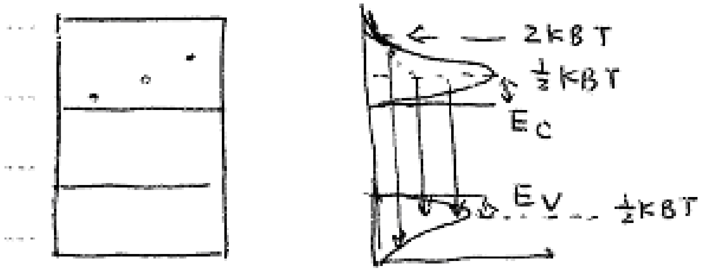
place blue LED chip inside phospher-coate package



← emission spectrum

$\eta \sim 10$ lumens/W

2. Emission spectra

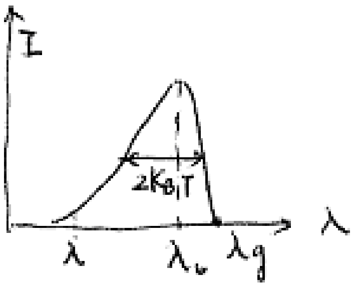


** electron & hole peaks

at $\frac{1}{2}k_BT + E_c$

& $-\frac{1}{2}k_BT + E_v$

width ~ $2k_BT$



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

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

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

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

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

Communication LED

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

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

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

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

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

- $\Delta\lambda$ increases with N_a
- $\Delta\lambda$ increase as injection level increase

Communication LED

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

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

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

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

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

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

Communication LED

3. <u>Bandwidth</u>, (Modulation Bandwidth)

wide bandwidth ⇒ require shorter carrier lifetime
why?

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

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

⇒ 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

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

at high injection:

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

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

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

4. Bandwidth ⟷ output power trade off

a) at low injection:

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

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

e.g. @ $N_a \sim 2\times 10^{19}/cm^3$, $\tau_r = 1\,ns$, $\tau_{nr} \simeq 1\,ns$

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

Communication LED

b). <u>at high injection</u>

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

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

Excess carrier recombination

1. Radiative combination → Emit light

2. non-radiative combination → Emit heat

On P side:

$n_P = n_{P0} + \Delta n_P$ ← Minority carriers

$p_P = p_{P0} + \Delta p_P$ ← Majority carriers

$$\frac{\partial n_P}{\partial t} = -Bn_P p_P + G_{thermal}$$

B is recombination coefficient, G is regeneration rate

$$= -B(n_{P0} + \Delta n_P)(p_{P0} + \Delta p_P) + Bn_{P0} p_{P0}$$

$$= -Bn_{P0}\Delta p_P - Bp_{P0}\Delta n_P - B\Delta n_P \Delta p_P$$

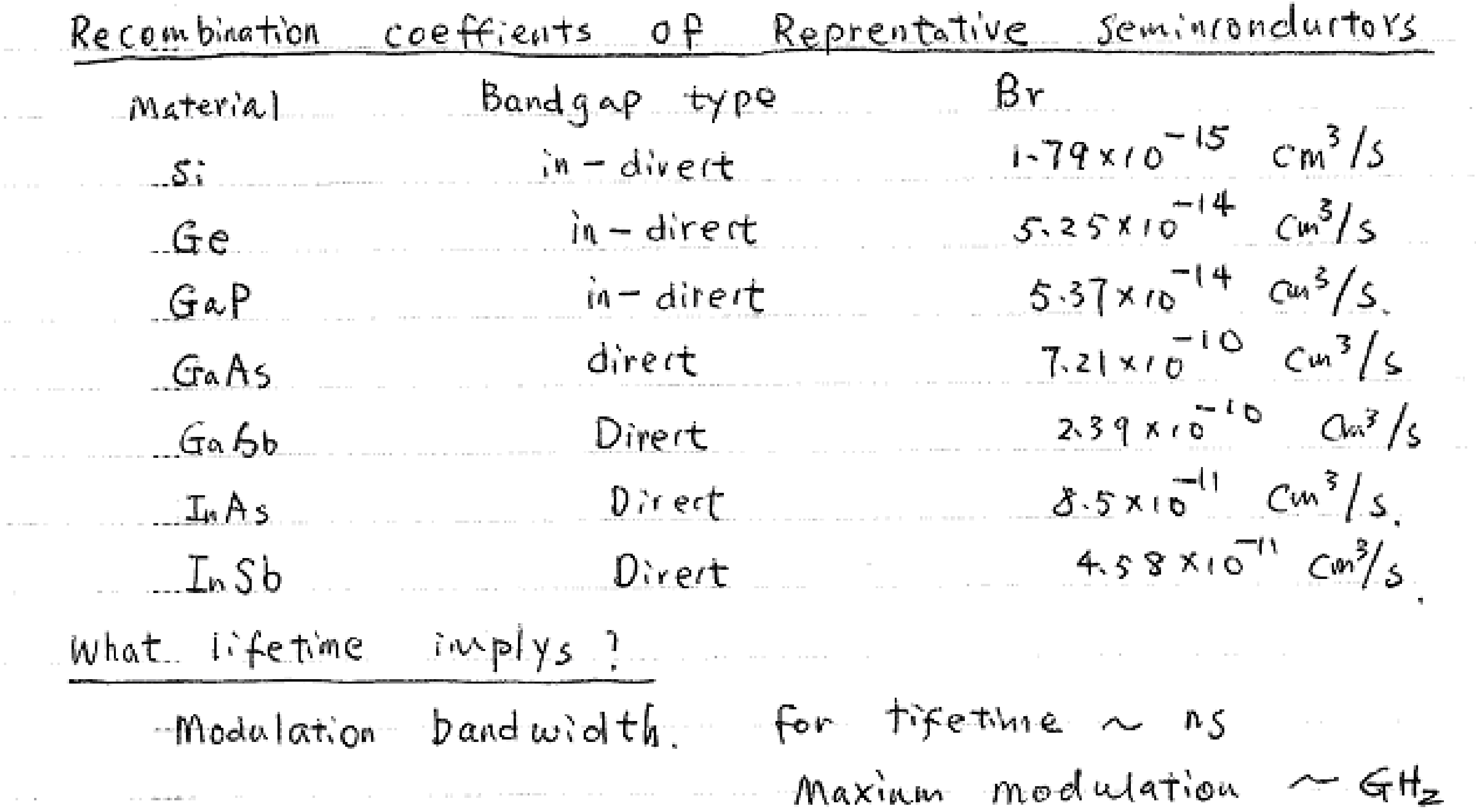
At low injection level: $\Delta n_P << p_{P0} = N_A$

$$\frac{\partial n_P}{\partial t} \cong -Bp_{P0}\Delta n_P = -BN_A \Delta n_P \qquad \frac{\partial \Delta n_P}{\partial t} = -\frac{\Delta n_P}{\tau_e} \qquad \tau_e = \frac{1}{BN_A}$$

At high injection level: $\Delta n_P >> p_{P0} = N_A$

$$\frac{\partial n_P}{\partial t} \cong -B\Delta p_P \Delta n_P = -BN_A (\Delta n_P)^2 \qquad \frac{\partial \Delta n_P}{\partial t} = -\frac{\Delta n_P}{\tau_e} \qquad \tau_e = \frac{1}{B\Delta n_P}$$

Excess carrier recombination



Recombination coeffients of Reprentative semiconductors

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

What lifetime implys ?

Modulation bandwidth. for lifetime ~ ns

Maxinum modulation ~ GHz

Excess carrier recombination

Example : calculate radiative lifetime of GaAs & Si

1). GaAs , assuming low level injection :

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

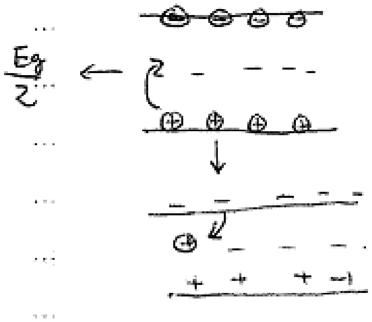
$$\tau_r = \frac{1}{B_r P} = \frac{1}{B_r N_a} = \frac{1}{7.2\times10^{-10}\cdot10^{18}} = 1.4\,\mathrm{ns}.$$

2). Si ,

$P \sim 10^{18}\ \mathrm{cm}^{-3} \leftarrow N_a$

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

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.

Excess carrier recombination

the Non-radiative recombination rate in spare charge region

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

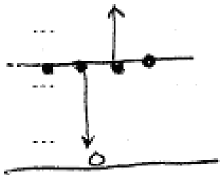
σ_t : $= \sigma_p = \sigma_n \equiv$ hole & electron capature cross sertor

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

V_{th}: thermal velociey.

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.

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

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

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

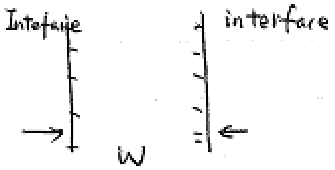
InGaAsP , $\delta = 10^{-28}$ cm^6/s .

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 Engrgy 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 ~ 500 cm/s

recently reduced t.

0.25 cm/s

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

Quantum Efficiency

Quantum Efficiency (QE)

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

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

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

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

Example: η_i for GaAs & Si

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

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

$\eta_i \sim 97\%$

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

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

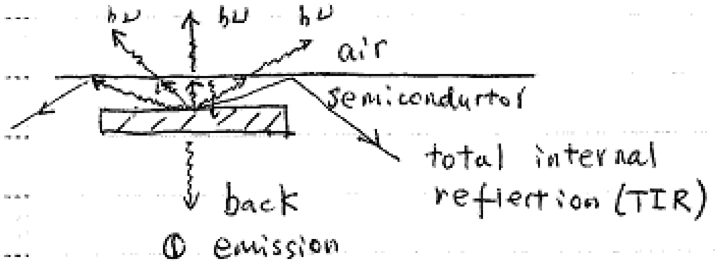
Conclusion: ① τ_r needs to be small enough.

② Si is not a good Light emitter.

Quantum Efficiency

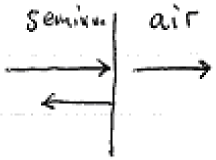
External Quantum Efficiency

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



① back emission ~ 50% Loss through back

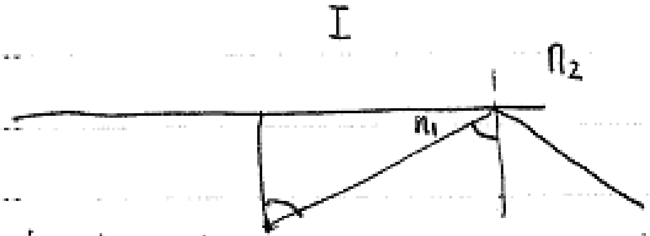
② Fresnel Reflection:



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

③ Reabsorption:

④ total interal reflertion



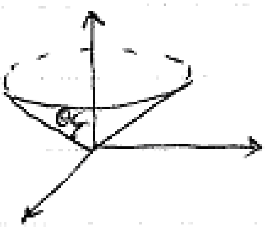
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

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

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

$= \frac{1}{3.5} \Rightarrow \theta_c \sim 16°$

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



efficiency due to TIR

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

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

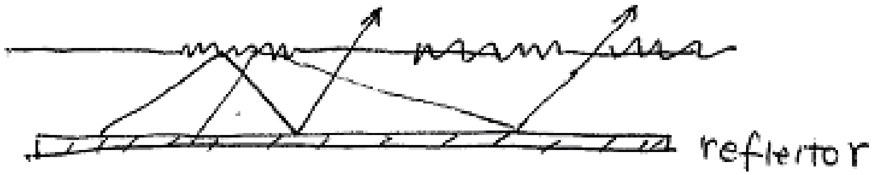
include Fresnel reflections:

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

↑ fundmental Problem of LED for 35 years.

Solution:

- textured structure

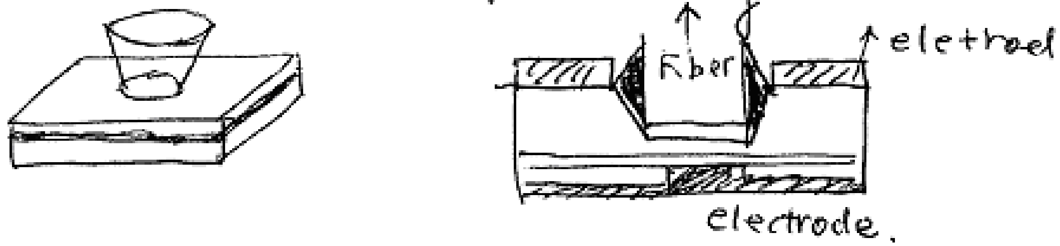


- Grating

Communication LED

Communication LEDs

1. Structure : a). surface emitting



b). edge emitting

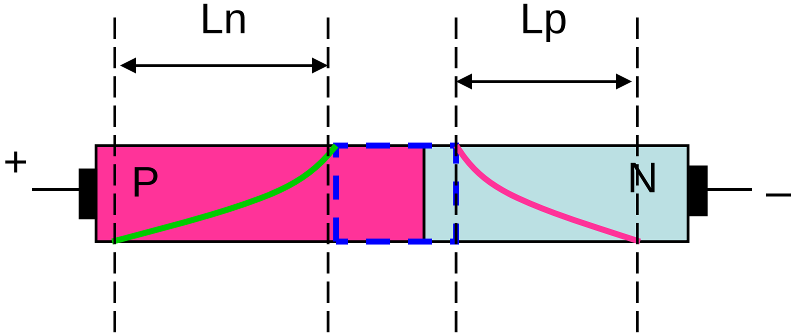
- high coupling efficiency
- Very thin active layer

⇒ much of the light extends to cladding layer. ⟹ Low reabsorption

- AR coating front facet
- HR coating back facet.

2. emission Spectra

Homo-junction

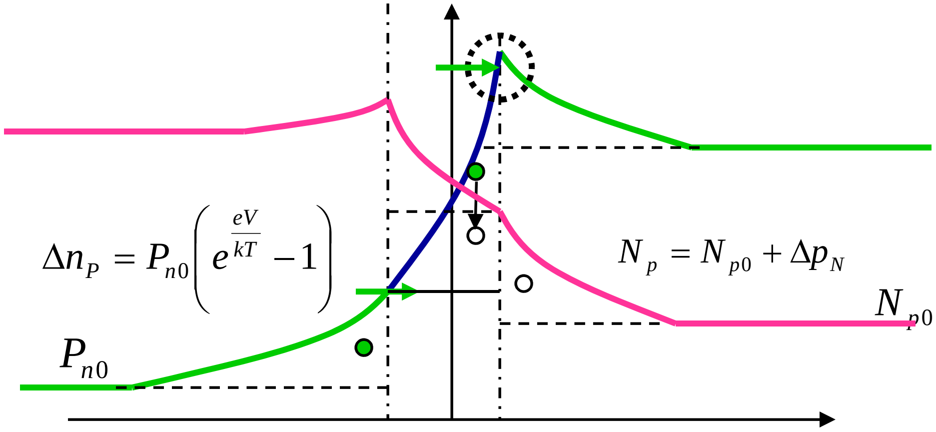


Example 3.3.1:

$$L_n = \sqrt{D_n \tau_n} \approx 13\mu m$$

$$L_p = \sqrt{D_p \tau_p} \approx 3\mu m$$

Minimum LED size? why?



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

$$N_p = N_{p0} + \Delta p_N$$

$$P_{n0}$$

$$N_{p0}$$

$$\Delta p_p = \Delta n_p$$

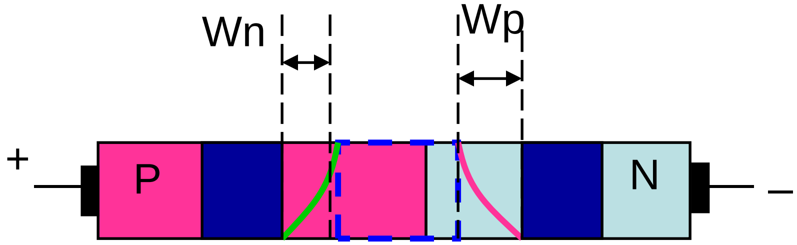
$$\Delta p_p = \Delta n_p$$

$$\Delta p_N = N_{p0}\left(e^{\frac{eV}{kT}} - 1\right) \qquad J_p = \frac{qD_p}{L_p}\frac{n_i^2}{N_D}(e^{\frac{qV}{kT}} - 1)$$

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

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

Hetero-junction



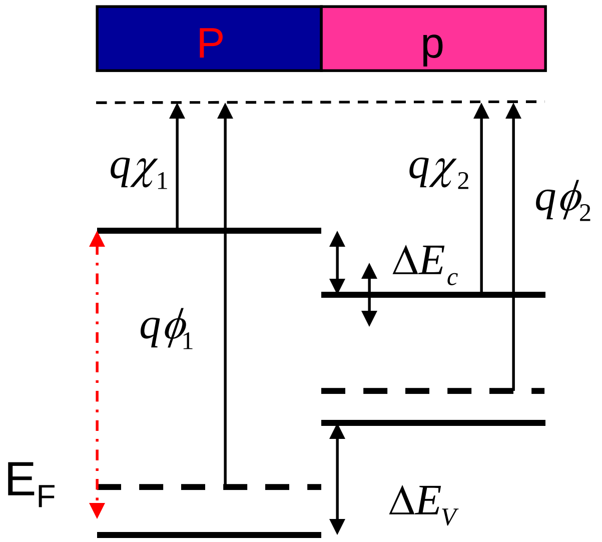
Carrier confinement

$$W_n << L_n = \sqrt{D_n \tau_n} \approx 13 \mu m$$

$$W_p << L_p = \sqrt{D_p \tau_p} \approx 3 \mu m$$

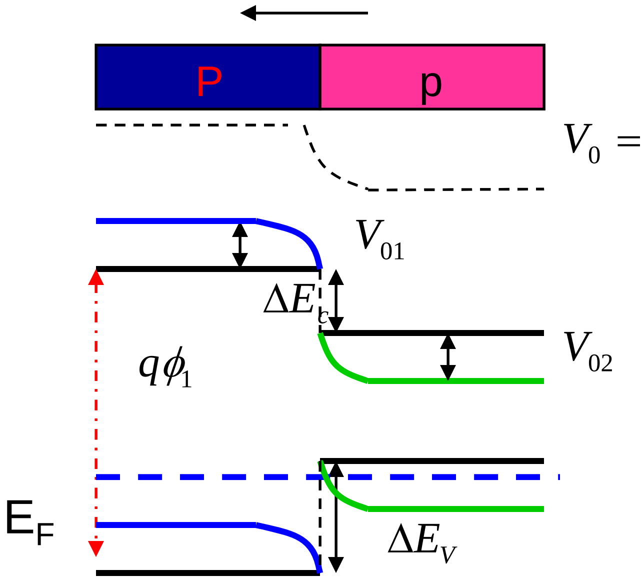
Better light emitting efficiency

Band diagram



$$\Delta E_g = \Delta E_c + \Delta E_V$$

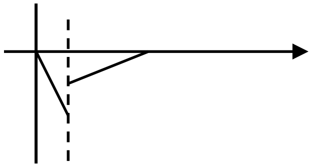
$$\Delta E_c = q\chi_2 - q\chi_1$$



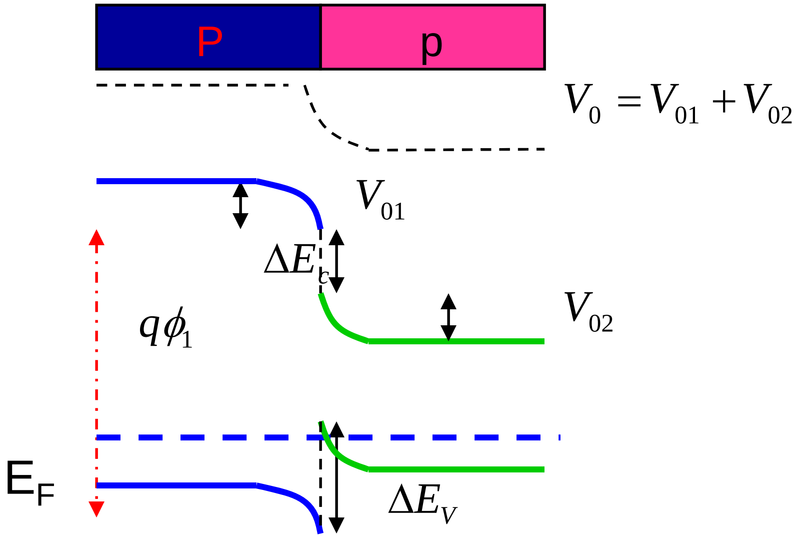
$$V_0 = V_{01} + V_{02}$$

$$\frac{V_{01}}{V_{02}} = \frac{\varepsilon_2 N_{A2}}{\varepsilon_1 N_{A1}}$$

$$\varepsilon_1 E_1 = \varepsilon_2 E_2$$



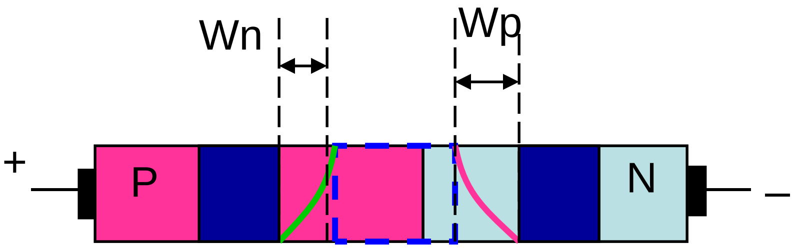
Hetero-junction



$$V_0 = V_{01} + V_{02}$$

$$n_1 = n_2 e^{-\frac{q(V_0+\Delta E_C)}{kT}}$$

Carrier confinement:

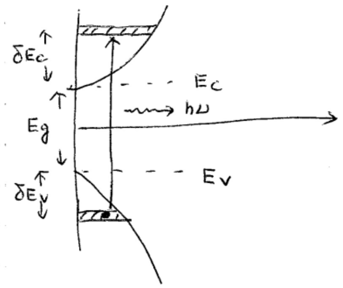


Reading Ch. 4.1-4.6, 4.9

Reduced density of States

⑧

6. Gain in a semiconductor



$$E_2 - E_c = \frac{\hbar^2 k_c^2}{2m_e^*}$$

$$E_v - E_1 = \frac{\hbar^2 k_v^2}{2m_h^*}$$

$k_c = k_v = k$ no − photon transitions.

$$\Rightarrow \quad E_2 - E_c = \frac{m_h^*}{m_e^*}(E_v - E_1)$$

$$h\nu = E_2 - E_1$$

$$\Rightarrow \quad E_2 - E_c = E_2 - E_1 + E_1 - E_v + E_v - E_c$$

$$= h\nu - (E_v - E_1) - E_g$$

$$= h\nu - E_g - (E_v - E_1)$$

$$\Rightarrow \quad E_2 - E_c = \frac{1}{1+\frac{m_e^*}{m_h^*}}(h\nu - E_g) = \frac{m_h^*}{m_e^* + m_h^*}(h\nu - E_g)$$

$$E_v - E_1 = \frac{1}{1+\frac{m_h^*}{m_e^*}}(h\nu - E_g) = \frac{m_e^*}{m_e^* + m_h^*}(h\nu - E_g)$$

$$\because \quad E_2 - E_c = \frac{m_h^*}{m_e^*}(E_v - E_1)$$

$$\Rightarrow \quad dE_2 = -\frac{m_h^*}{m_e^*}\,dE_1$$

Reduced density of states

$$\rho(h\nu)\,dE = \cancel{\rho(E_2 - E_1)}\ \rho(h\nu)\,d(E_2 - E_1) = \rho(h\nu)(dE_2 - dE_1)$$

$$dE = \hbar^2\left(\frac{1}{m_e^*} + \frac{1}{m_h^*}\right)k\,dk$$

$$\Rightarrow \quad \frac{dk}{dE} = \frac{1}{\hbar^2\left[\frac{1}{m_e^*} + \frac{1}{m_h^*}\right]k}$$

Reduced density of States

$$\Rightarrow \rho(h\nu) = \frac{4\pi k^2}{(2\pi)^3}\cdot\frac{dk}{dE} = \frac{1}{2\pi^2\hbar^2}\overbrace{\frac{m_e^* m_h^*}{(m_e^*+m_h^*)}}^{\uparrow\, m_r^*} k$$

$$\hbar k = \left[2m_e^*\left(E - E_c\right)\right]^{1/2}$$

$$\Rightarrow \rho(h\nu) = \frac{1}{4\pi^2}\left(\frac{2m_r^*}{\hbar^2}\right)^{\frac{3}{2}}(h\nu - E_g)$$

$$m_r^* = \frac{m_e^* m_h^*}{m_e^* + m_h^*}$$

$\rho(h\nu)$ ← reduced density of States, and reflects the fact the condition are placed on the recombination.