Lecture #02

Semiconductor Lasers : Device structure

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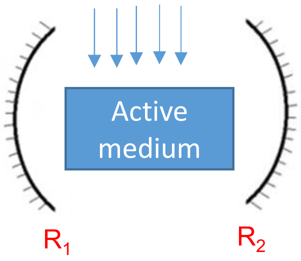
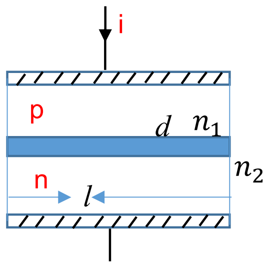
Summary of Lecture #01



Bulk laser

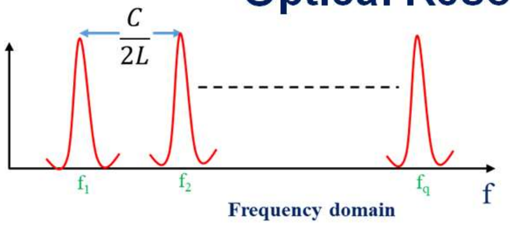


Semiconductor laser

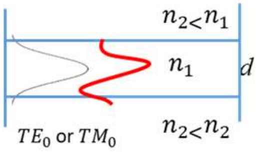
Optical Resonator

$$\lambda_q = \frac{2L}{q}$$

$$f_q = q\frac{c}{2L}$$



Longitudinal mode



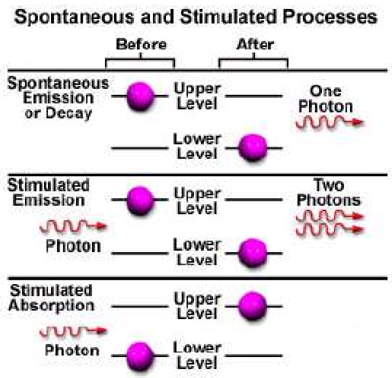
$$V = \frac{2\pi}{\lambda} d\sqrt{n_1^2 - n_2^2}$$

Transverse mode

So in general 3 components of laser are

- Optical feedback- optical resonator: Longitudinal and Transverse mode
- gain medium --- active device – stimulated emission, gain>loss;
- Pump or power supply: excite for holes and electrons recombination and generate photon

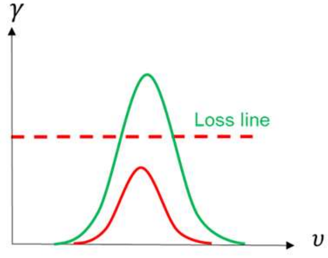
Active Media

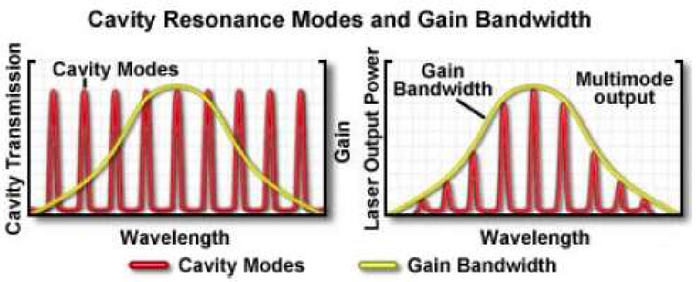


Spontaneous & stimulated emission

Gain = Loss

$$\alpha_r = \alpha_s + \frac{1}{2L} ln\left(\frac{1}{R_1 R_2}\right)$$





OUTLINES

I. Importance of Semiconductor Laser

II. Semiconductor

   a. Types of Semiconductor
   b. pn Junction

III. Homojunction & Heterojunction

IV. Guided Structures

Semiconductor Lasers

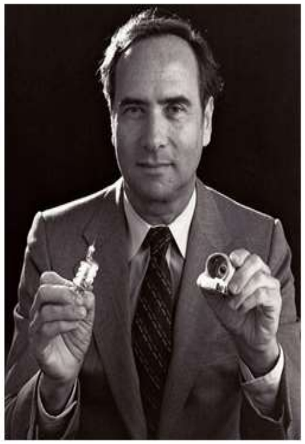
Invention by four groups simultaneously in 1962

- **Compact**
- **Efficient**
- **Direct Modulation**
- **Optoelectronic Integration**

Theodore H. Maiman at Hughes Research Laboratories

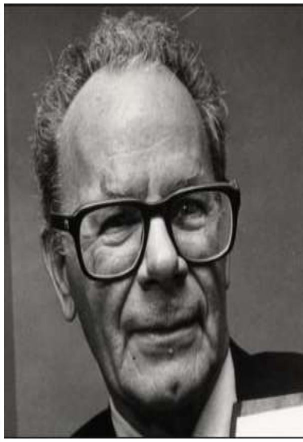
Theoretical work by Charles Hard Townes and Arthur Leonard Schawlow

Gould working for Technical research group at 1959 first patent


Theodore Maiman


Charles Townes

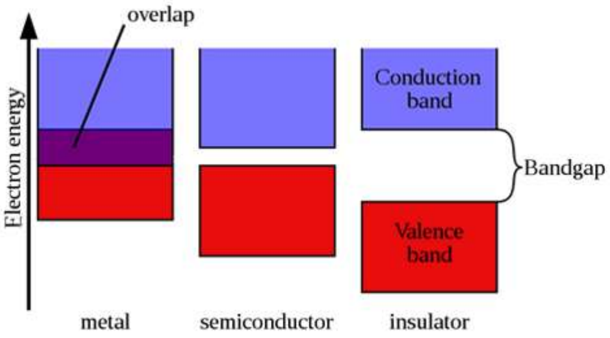

Arthur Schawlow



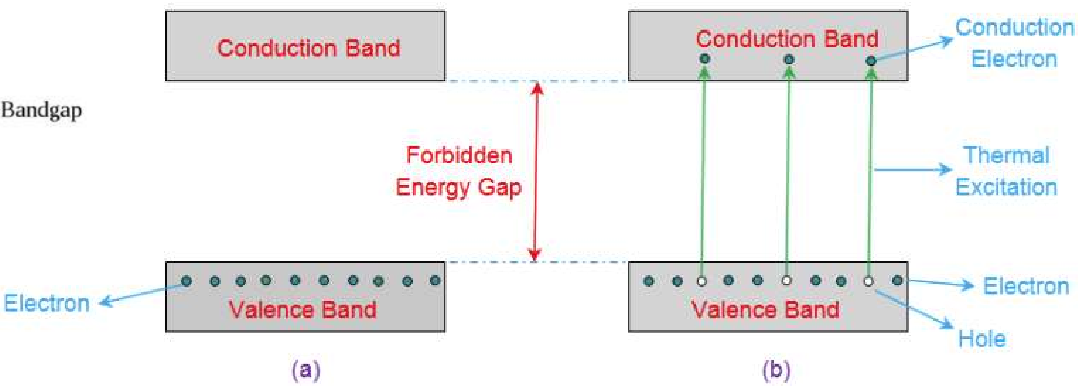
Basics of Semiconductor: Intrinsic

Energy Band Gap (E_g) :

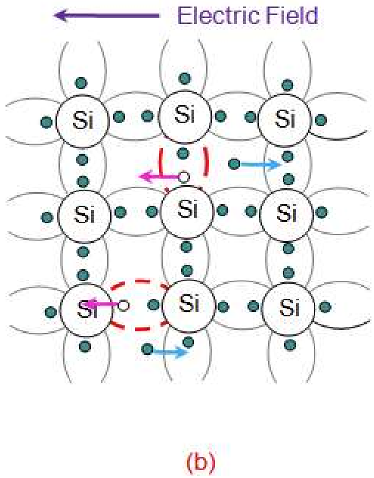
- One of the most important characteristics of a semiconductor (**about 1eV**), distinguishing it from metals and insulators
- Determinant of the wavelengths of the light absorbed or emitted by the semiconductor



Intrinsic semiconductor

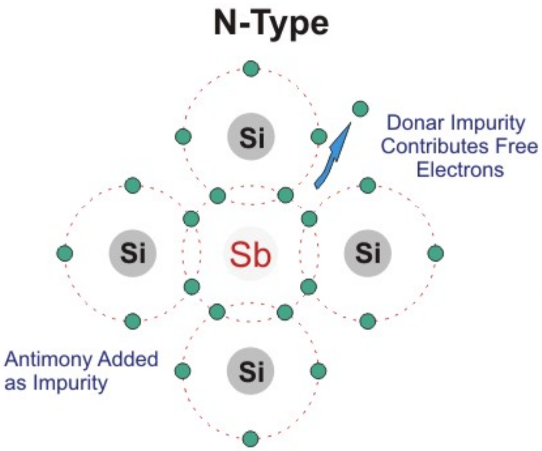


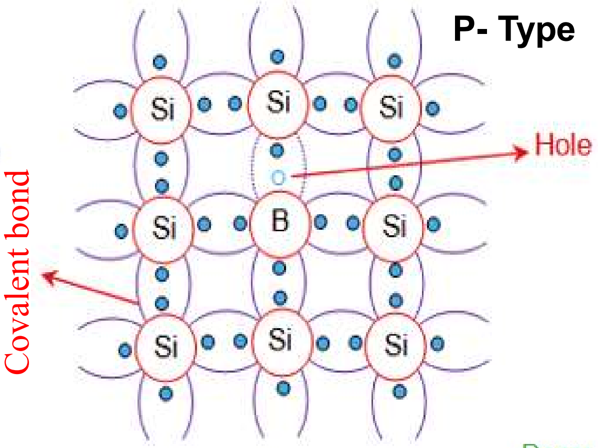
Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K



Conduction Mechanism in case of Intrinsic Semiconductors in the (a) Absence of Electric Field (b) Presence of Electric Field

Basics of semiconductor : Extrinsic

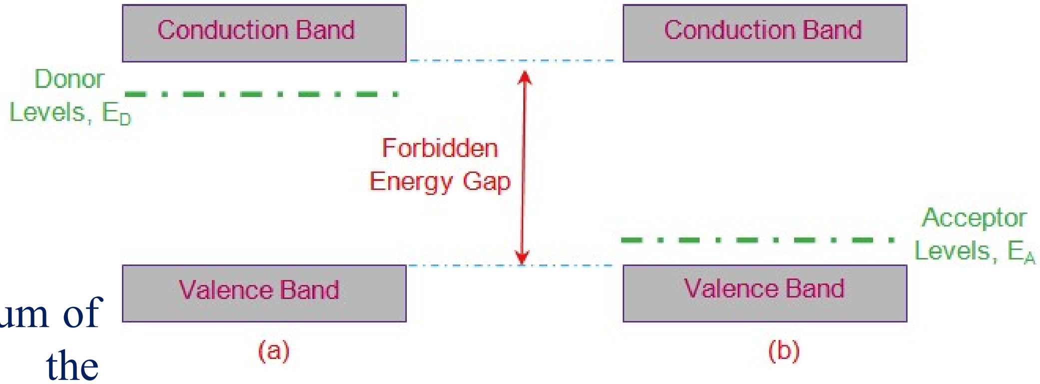




- Pure semiconductors like Silicon (Si) or Germanium (Ge) are tetravalent - Group IV of the periodic table
- n-type doped with pentavalent – **P, As, Sb, Bi, Li**
- p-type doped with Trivalent – **Al, N, Ga, In**

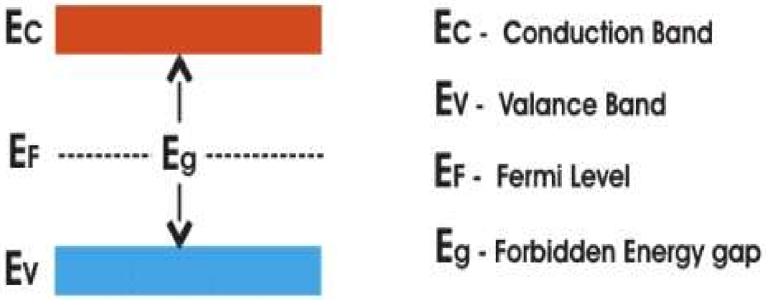
- **Donor elements– Antimony, Sb**
- **Acceptor elements– Boron, B**

The total number of holes/electrons will be equal to the sum of the holes/electrons induced due to doping and the holes/electrons generated due to the thermal excitation process in p-type/n-type semiconductor

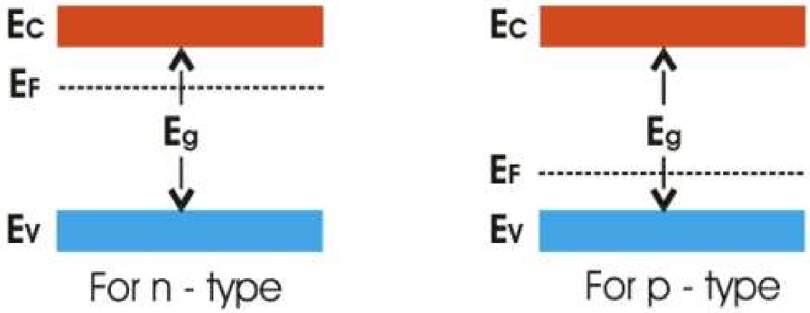


Energy Band Diagram of (a) *n*-type Extrinsic Semiconductor
(b) *p*-type Extrinsic Semiconductor

Basics of semiconductor : Energy band gap



Energy band diagram for Intrinsic

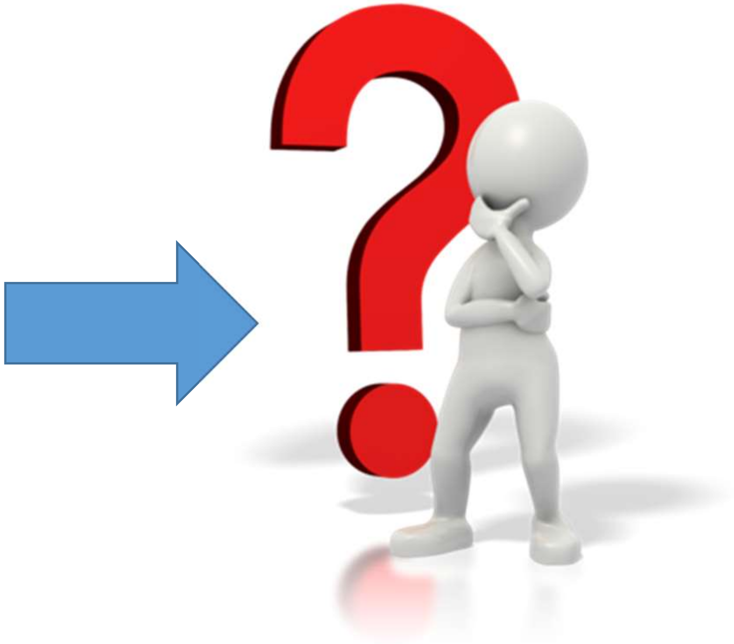


Energy band diagram for Extrinsic

- **Intrinsic silicon:** the Fermi level lies in the middle of the gap
- **n-type:** Fermi level moves higher i.e. closer to the conduction band
- **p-type:** Fermi level moves towards valance band

Basics of semiconductor : Extrinsic

Number of holes in n-type
& electrons in p-type



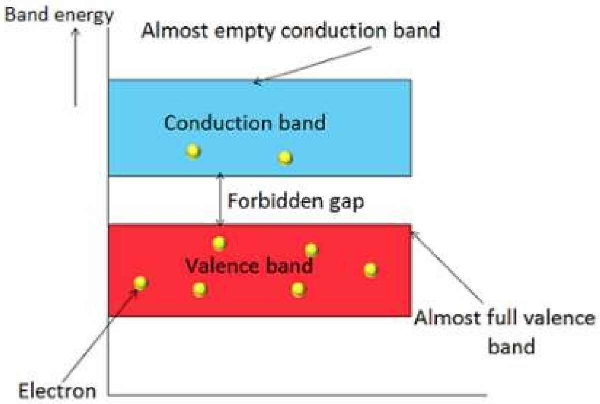
Basics of semiconductor : Heat & light effect

At absolute zero temperature, all the valence electrons are revolving around the nucleus of an atom. Hence, there are no free electrons present in the conduction band. Therefore, the semiconductor behaves as a **perfect insulator at absolute zero temperature.**

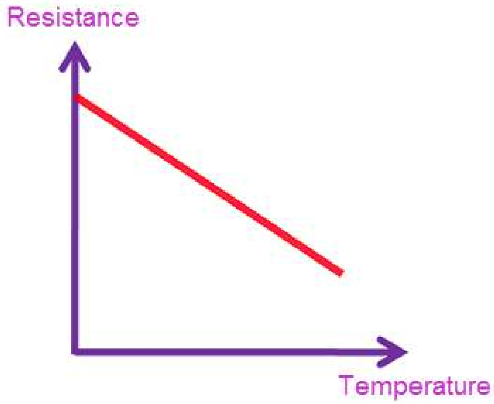
When the temperature is increased valence electrons gain enough energy in the form of heat to break the bonding with the parent atom and they jumps into the conduction band. These conduction band electrons are called as free electrons.

When the electron leaves the valence band and jumps into the conduction band, a vacancy is created at the electron position in the valence band. This vacancy is called as hole. Thus, both the free electrons in the conduction and holes in the valence band are generated at the same time. The free electrons carry the negative charge or electric current from one place to another place in the conduction band whereas the holes (vacancies) carry the positive charge or electric current from one place to another place in the valence band.

If the temperature or heat energy applied on the semiconductor is further increased then even more number of valence electrons gains enough energy to break the bonding with the parent atom and they jump into the conduction band. This results in increase in number of free electrons in the conduction band. If more number of electrons leaves the valence band and jumps into the conduction band then more number of holes (vacancies) are created in the valence band at the electrons position. Thus, a small increase in heat generates more number of charge carriers (electrons and holes).

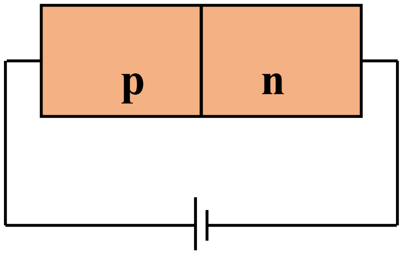


0^0K

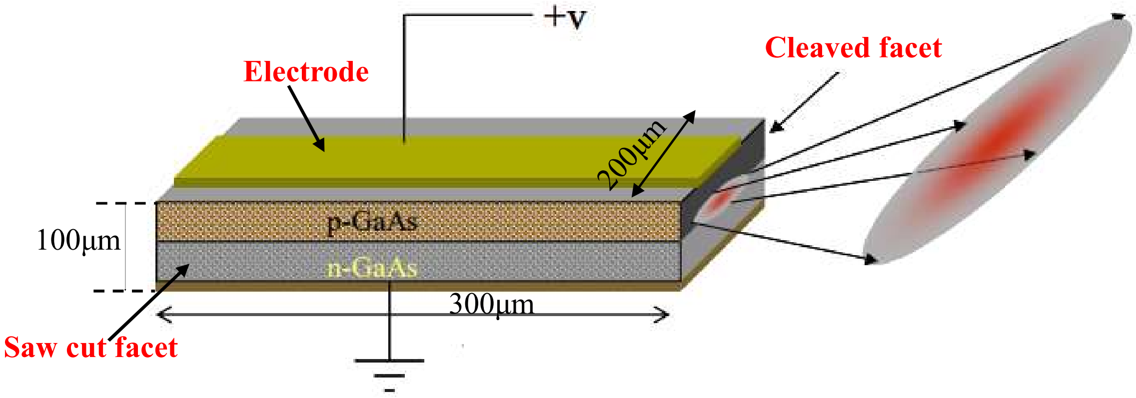


Resistance with temperature

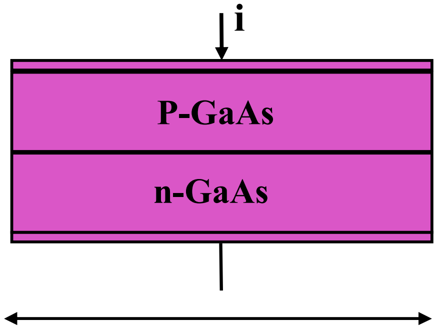
Basic Structure: pn junction



- Forward biased p-n junction
- Of a direct bandgap material and of same bandgap
- e.g., GaAs, InP

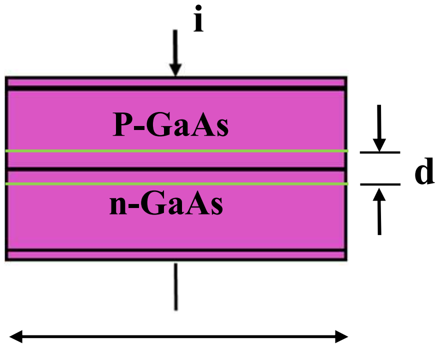


Basic Structure: Homojunction lasers



L= 300µm

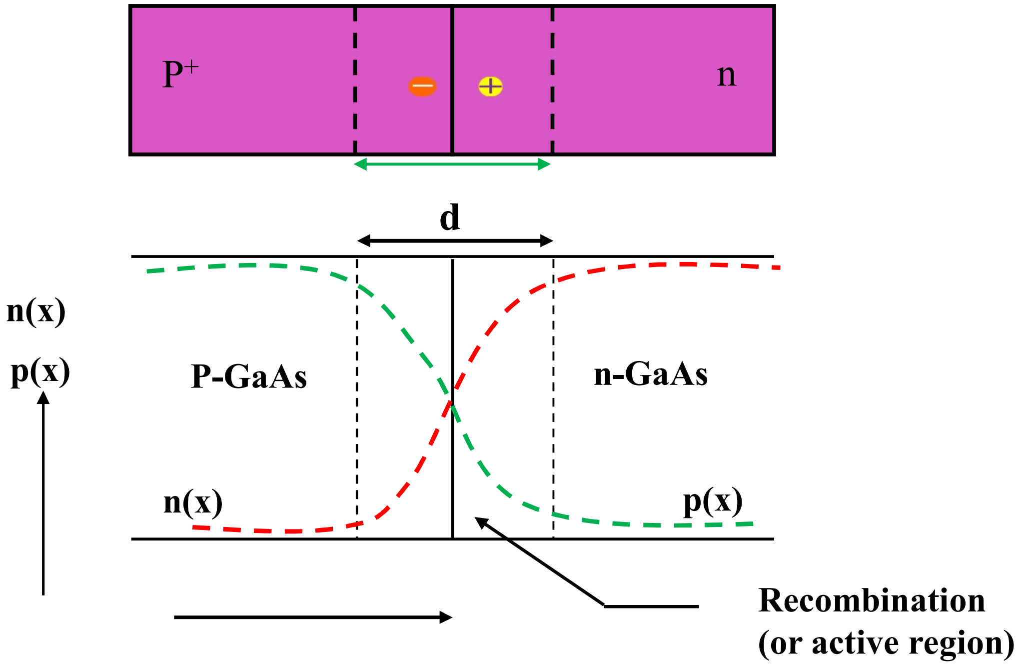
(Side view)



W= 200µm

(Front view)

Structure : Homojunction

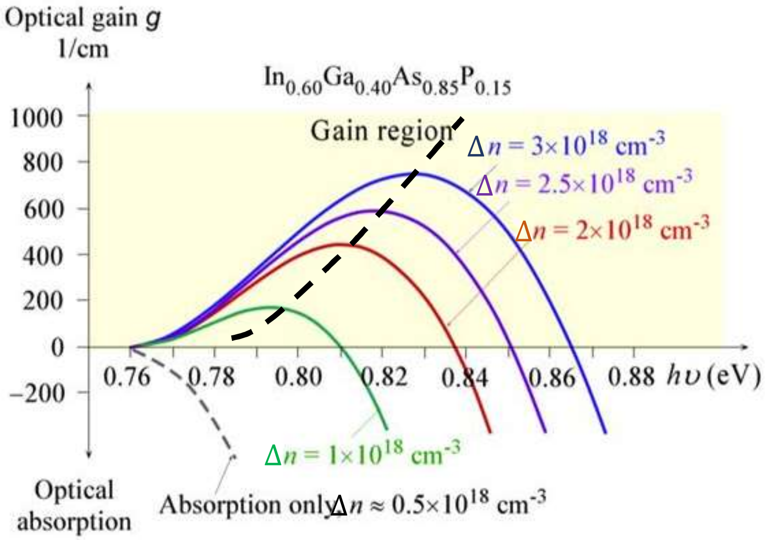


Carrier Distribution across a Homojunction

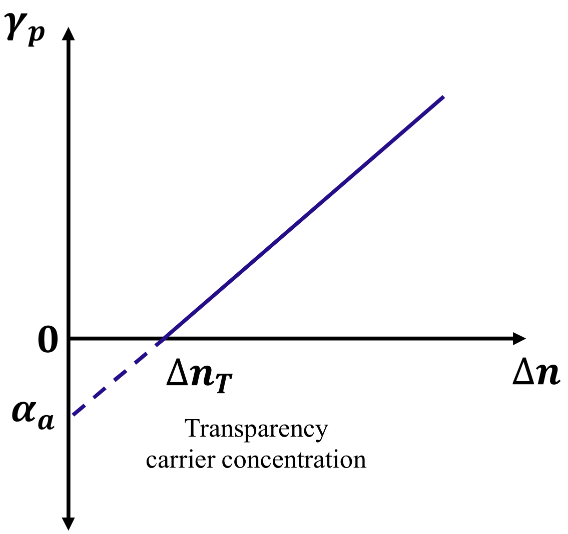
Basic Structure: Gain Co-efficient

Gain coefficient:

$$\gamma(\upsilon) = \frac{(c/n)^2}{8\pi\upsilon^2}\,\frac{1}{h^2\tau}\,(h\upsilon - E_g)^{\frac{1}{2}}[f_c(E_2) - f_v(E_1)]$$



Peak Gain coefficient: $\gamma_p = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right)$



Variation of Peak Gain coefficient with excess carrier concentration

Basic Structure: Gain Co-efficient & current

$$\gamma_p = \alpha_a\left(\frac{\Delta n}{\Delta n_T} - 1\right)$$

$$\Delta n = \frac{\left(\frac{i}{e}\right)\tau}{l \times w \times d} = \frac{J\tau}{ed}$$

$$\Delta n_T = \frac{J_T\tau}{ed}$$

$$\frac{\Delta n}{\Delta n_T} = \frac{J}{J_T} = \frac{i}{i_T}$$

J – current density
τ – recombination time
e – electronic charge
Δn – excess carrier concentration

$$\gamma_p = \alpha_a\left(\frac{J}{J_T} - 1\right)$$

Basic Structure: Example

$In_{0.7}Ga_{0.3}As_{0.7}P_{0.4}$ Laser Amplifier

$$J_T = \frac{ed}{\eta_i \tau_r}\Delta n_T$$

η_i – internal quantum efficiency

$\eta_i = 0.5$

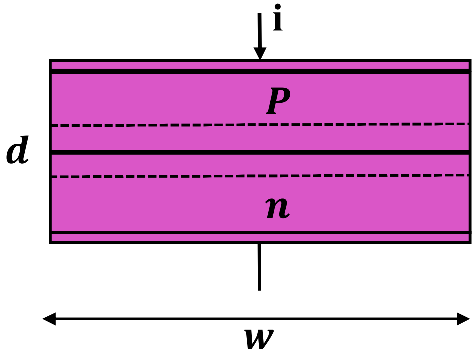
$\tau_r = 2.0\ ns$

$\alpha_a = 600 cm^{-1}$

$d = 2.0 \mu m$

$\Delta n_T \approx 1.2 \times 10^{18} cm^{-3} ns$

$e = 1.602 \times 10^{-1}\ C$



It Gives:-

$J_T \approx 40KA/Cm^2$

$$\therefore I_T = J_T A = J_T wl$$
$$= J_T \times 300 \times 200 \times 10^{-8}\ KA$$
$$= 24\ A!$$

Basic Structure: Example contd....

$let\ w\ be\ reduced\ to\ 10\mu m$

$$\rightarrow i_T = 1.2\ A$$

$further\ if\ d\ is\ reduced\ to\ 0.2\ \mu m$

$$\rightarrow i_T = 120\ mA$$

How to reduce d

How to reduce w

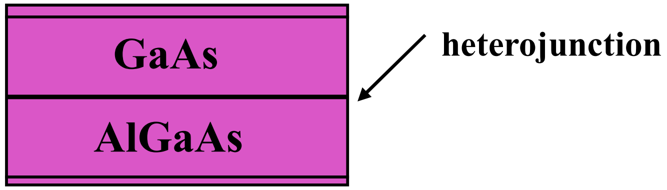
↓

Heterojunctions

Nobel Prize 2000: Z. Alferov & H. Kroemer

Basic Structure: Heterojunction Lasers

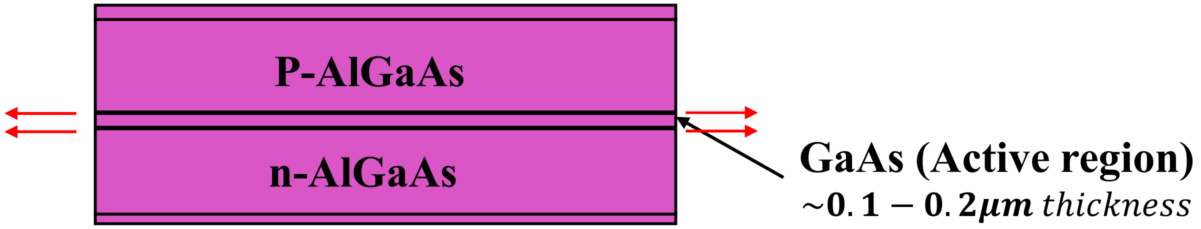
Heterojunction: junction between dissimilar semiconductors



Advantages:

- Carrier confinement
- Optical confinement
- Lower Losses
- Design flexibility
- And more

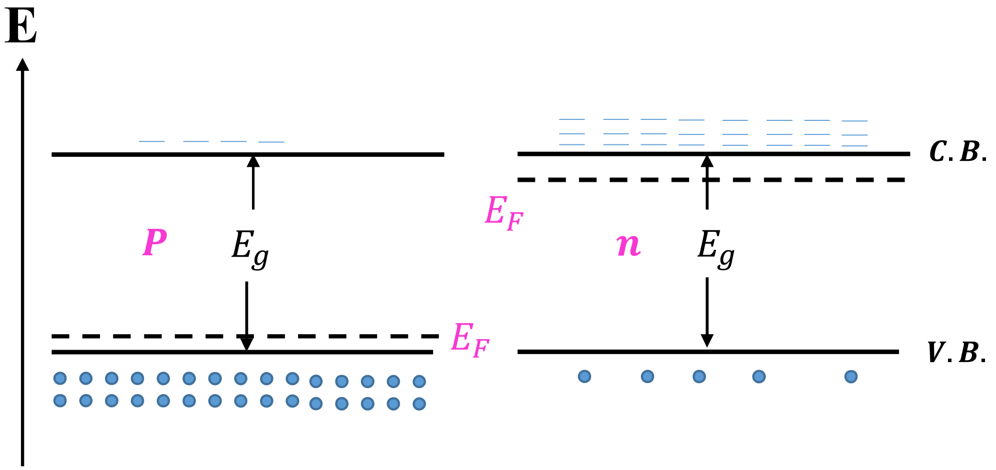
Double Heterostructure Lasers:



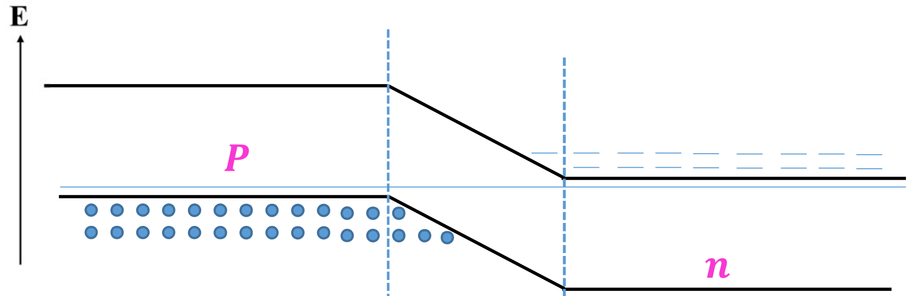
$\sim 0.1 - 0.2\mu m$ *thickness*

pn junction: Homojunction lasers

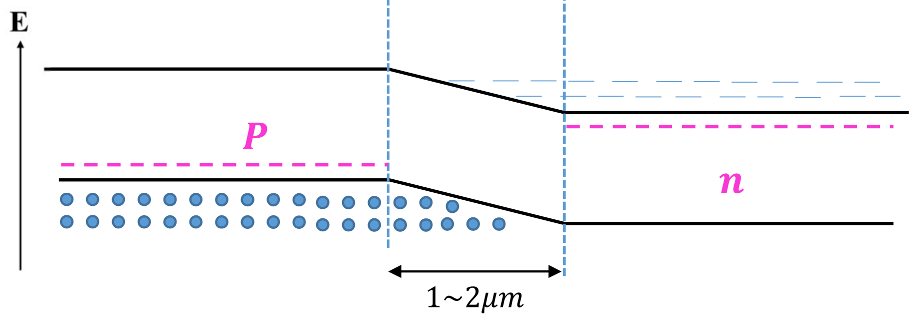
Before contact:



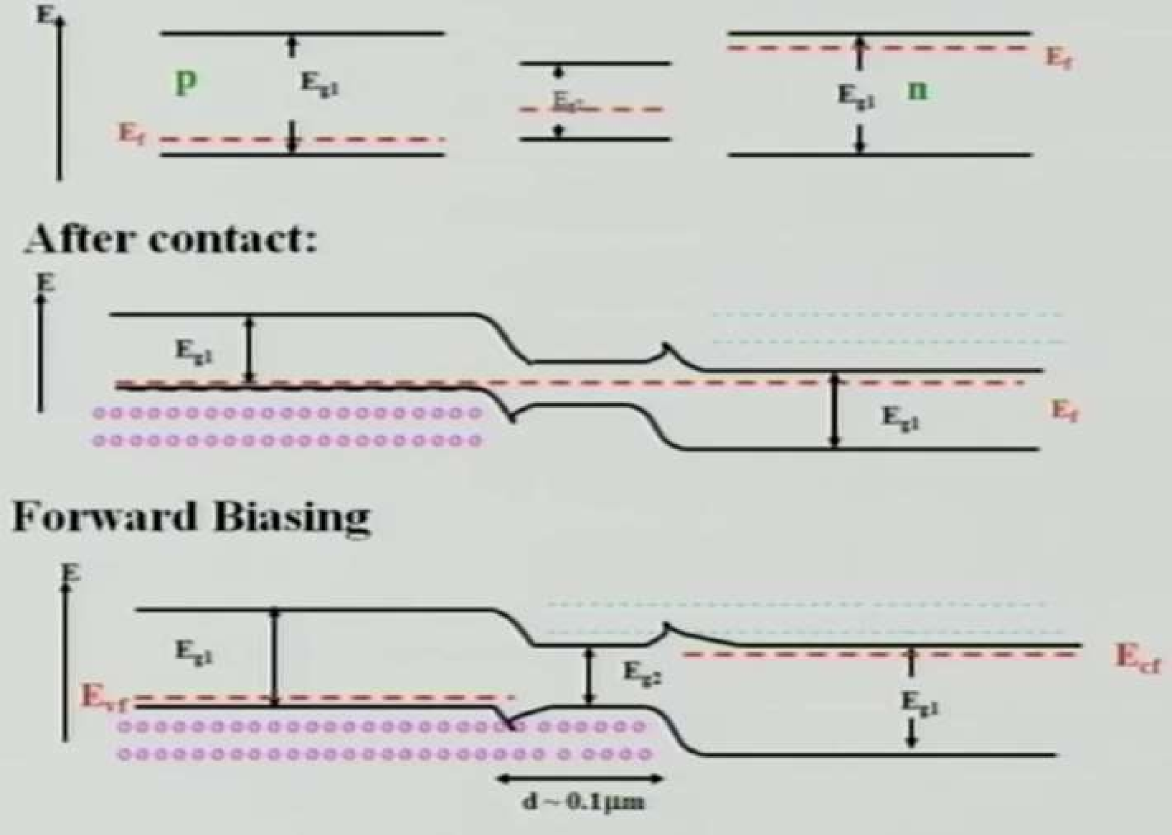
After contact:



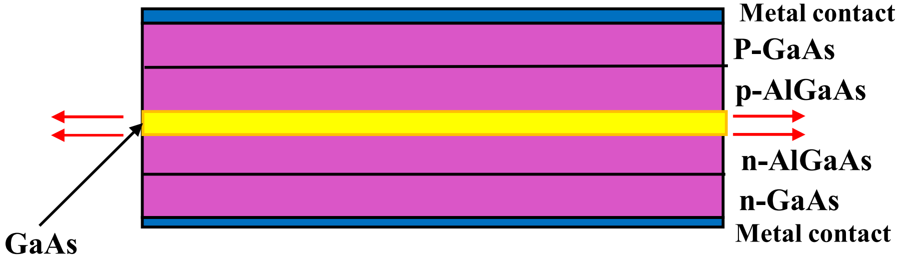
Forward biasing:



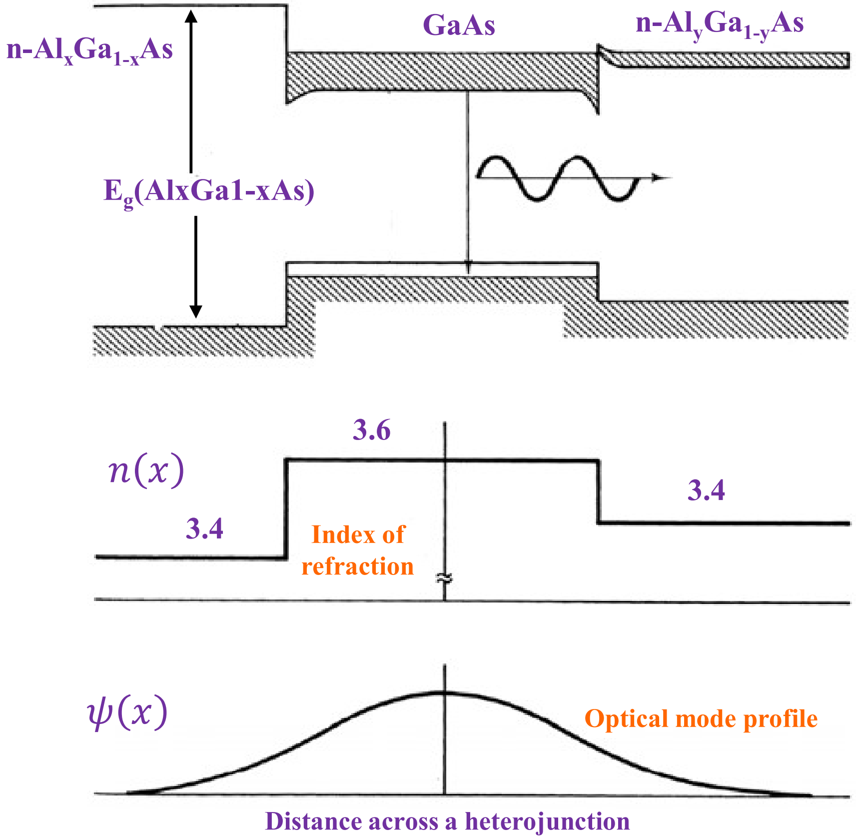
pn junction:Heterojunction lasers carrier confinement



Heterostructure: optical confinement



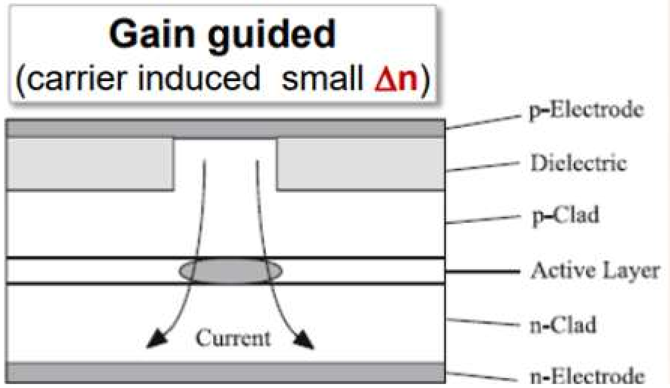
Longitudinal cross-section of DH laser

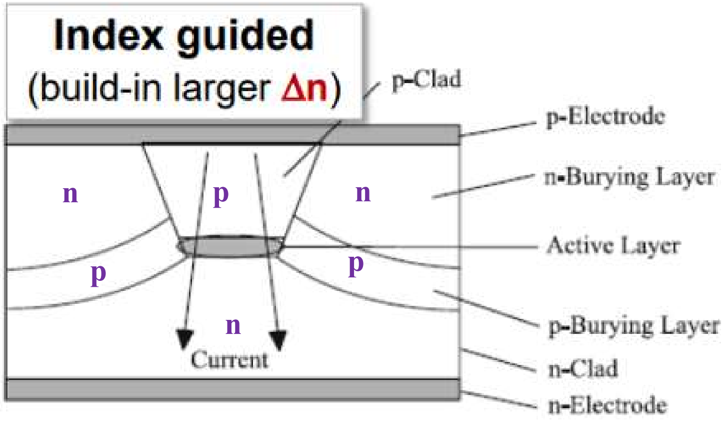


FP lasers

To further reduce the threshold

Improve the confinement of photons and carriers via a built-in lateral waveguide





One-dimensional guidance by refractive index, other transverse direction by gain

Guidance in both transverse direction due to refractive index

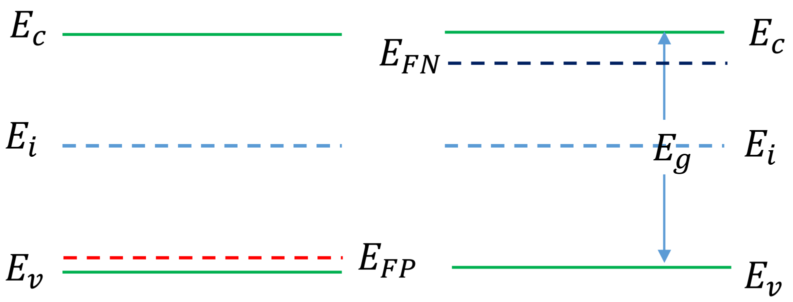
Fabrication : LPE, MBE, VPE (MOCVD)

Any Queries

Appendices

Basics of semiconductor : pn junction

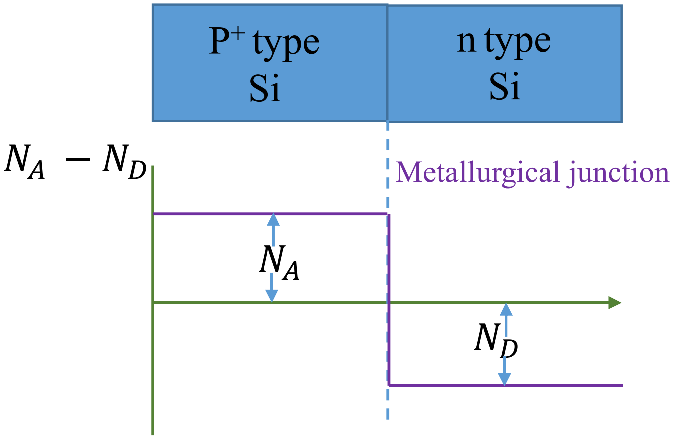
	P^+ type Si	n type Si
Doping concentration	N_A	N_D
Majority hole concentration	$P_{P0} = N_A$	$n_{n0} = N_D$
Minority electron concentration	$n_{P0} = \frac{n_i^2}{N_A}$	$P_{n0} = \frac{n_i^2}{N_D}$



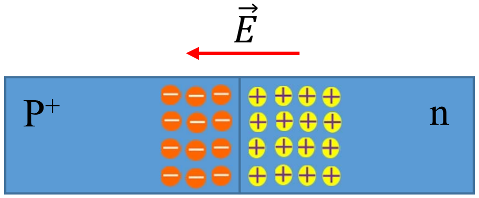
$$P_{p0} = n_i e^{(E_i - E_{FP})/kT}$$

$$(E_i - E_{FP}) = kT \ln\left(\frac{P_{p0}}{n_i}\right)$$

Abrupt pn junction



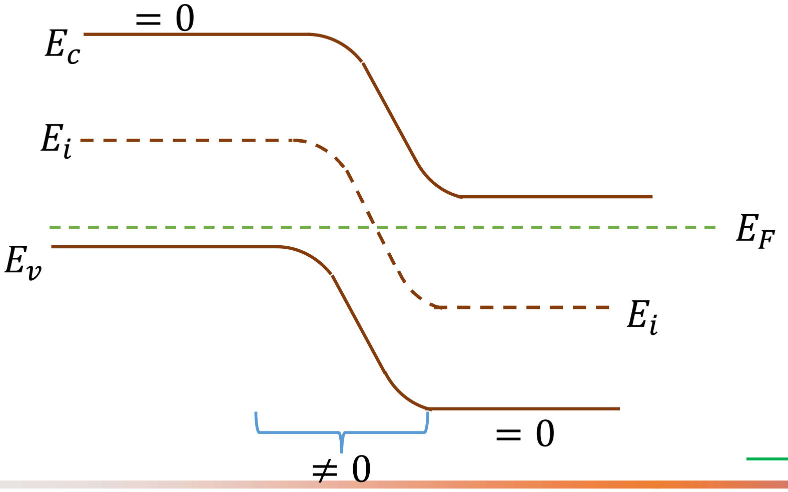
Basics of semiconductor : pn junction Energy band

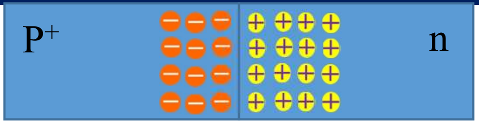


$P_{P0} \gg P_{n0}$ $\quad n_{P0} \ll n_{n0}$

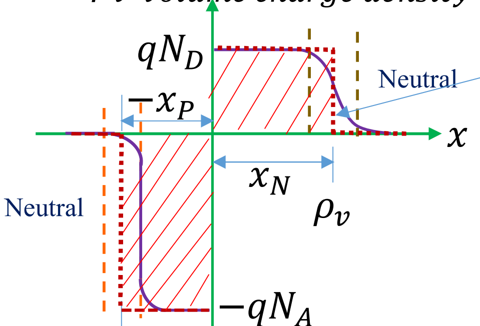
h $\quad$ e$^-$

Equilibrium condition





ρ_v volume charge density

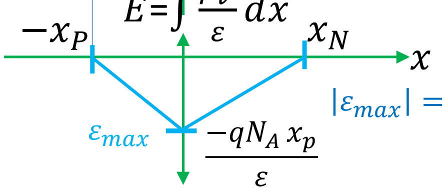


$$qN_D x_N = qN_A x_p$$

$$N_D x_N = N_A x_p$$

Depletion Approximation

$$E = \int \frac{\rho_v}{\varepsilon} dx$$



$$|\varepsilon_{max}| = \frac{qN_A x_p}{\varepsilon}$$

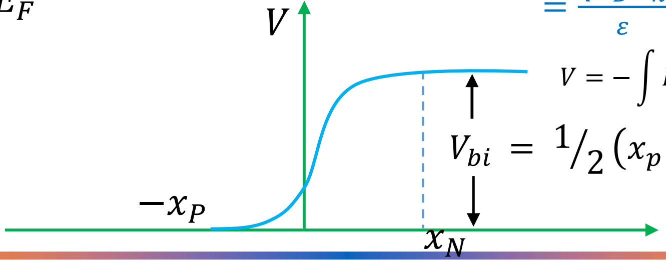
$$= \frac{qN_D x_n}{\varepsilon}$$

$$W = x_p + x_n = \frac{N_D x_N}{N_A} + x_n$$

$$x_n = W\left(\frac{N_A}{N_A + N_D}\right)$$

What happen if p side is highly doped?

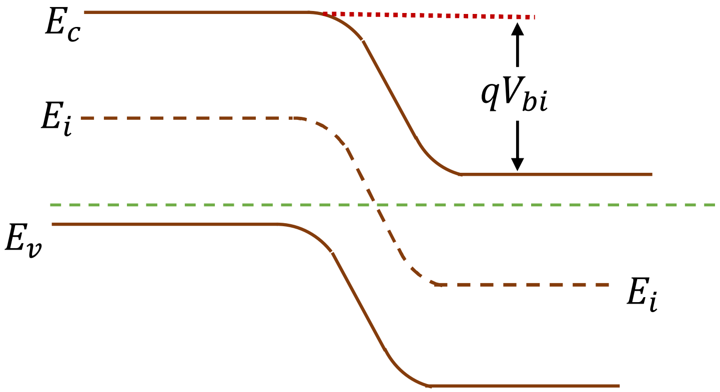
$$\boxed{W = \left[\frac{2\varepsilon_0 \varepsilon_r}{q} V_{bi}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2}}$$



$$V = -\int E\, dx$$

$$V_{bi} = {}^1/_2\,(x_p + x_n)\,\frac{qN_D x_n}{\varepsilon}$$

Basics of semiconductor : pn junction Energy band

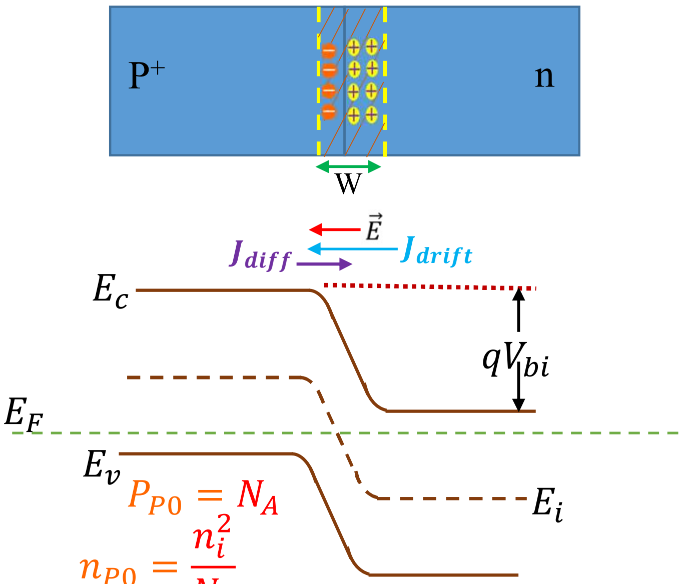


$$qV_{bi} = (E_i - E_F) + (E_F - E_i)$$

$$qV_{bi} = KT\left[ln\left(\frac{N_A}{n_i}\right) + ln\left(\frac{N_D}{n_i}\right)\right]$$

$$V_{bi} = \frac{KT}{q} ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Basics of semiconductor : Energy band & current



$P_{P0} = N_A$

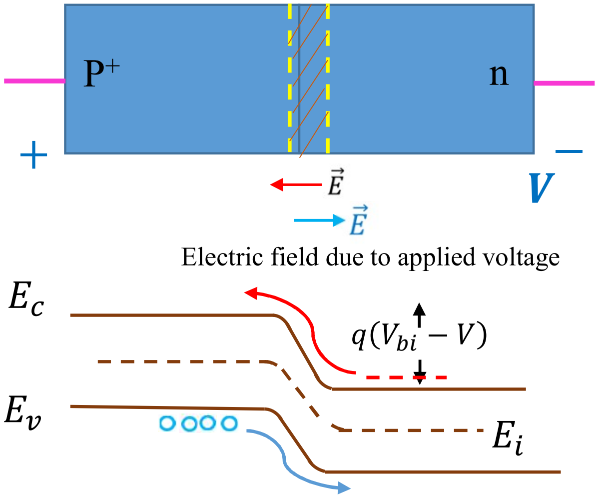
$n_{P0} = \frac{n_i^2}{N_A}$

$V_{bi} = V_T ln\left(\frac{N_A N_D}{n_i^2}\right)$

$= V_T ln\left(\frac{n_{n0}}{n_{po}}\right) = V_T ln\left(\frac{P_{P0}}{P_{no}}\right)$

$n_{n0} = n_{po}\, e^{V_{bi}/V_T} \quad P_{P0} = P_{no}\, e^{V_{bi}/V_T}$

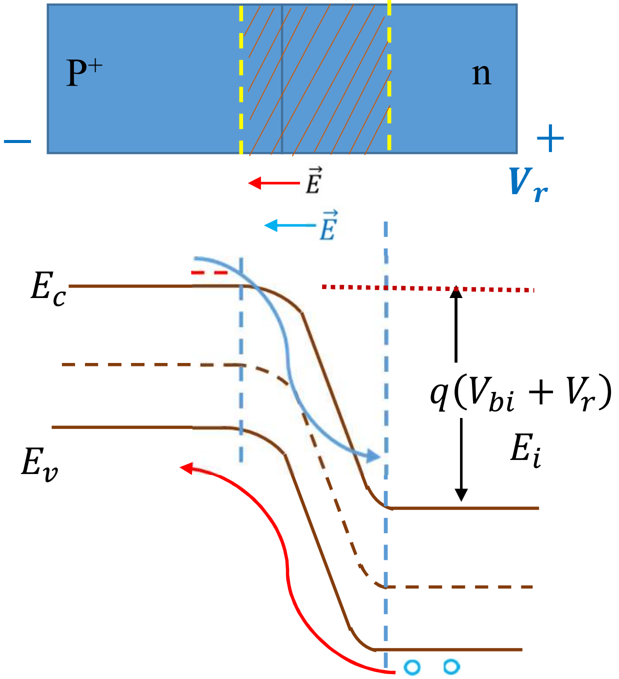
$$W = \left[\frac{2\varepsilon_0\varepsilon_r}{q} V_{bi}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\right]^{1/2}$$



Electric field due to applied voltage

$E\downarrow \quad I_{drift}\downarrow \quad I_{diff} \quad w\downarrow$

$$\underset{\downarrow}{W} = \left[\frac{2\varepsilon_0\varepsilon_r}{q}(V_{bi} - V)\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\right]^{1/2}$$

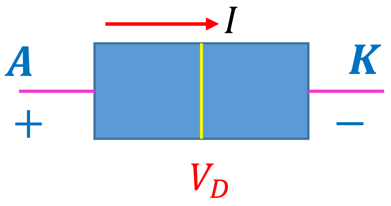


Only current exit here is drift current due to the electric field existence which is due to minority charge carrier

When the minority charge carrier reach near depletion region due to random movement due to thermal energy, there is the flow of minority charge carrier

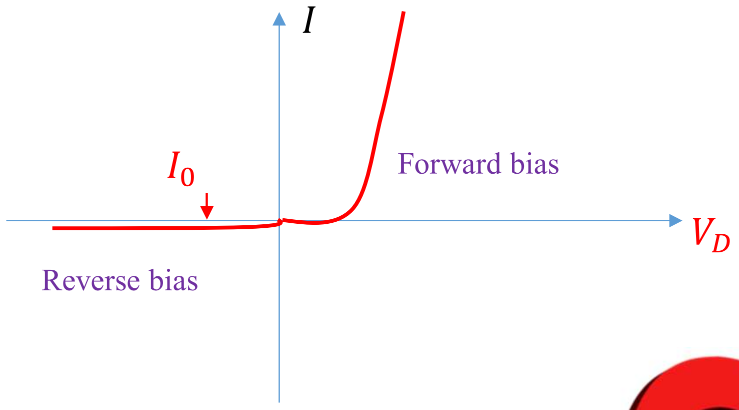
$$\uparrow W = \left[\frac{2\varepsilon_0\varepsilon_r}{q}(V_{bi} + V_r)\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\right]^{1/2}$$

Basics of semiconductor : diode current



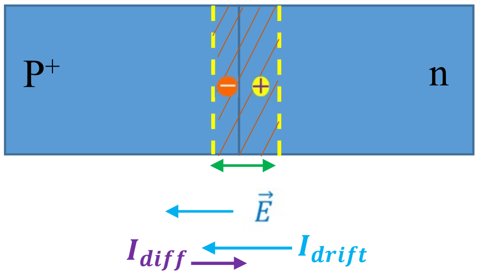
$$I = I_0\left(e^{V_D/\eta V_T} - 1\right)$$

$$V_T = \left(\frac{KT}{q}\right)$$



Reverse current is not dependent on the potential applied, why?

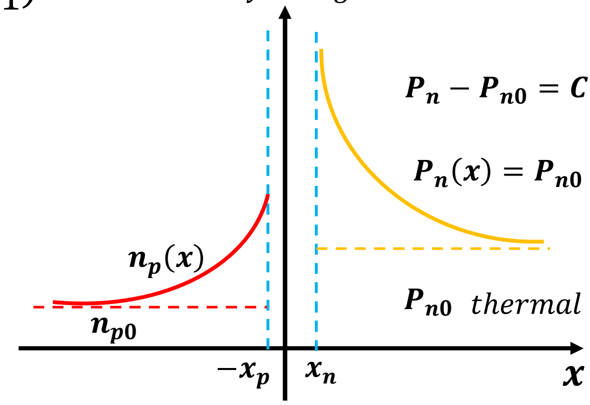
Basics of semiconductor : Diode current



$$I = I_0\left(e^{V_D/\eta V_T} - 1\right)$$

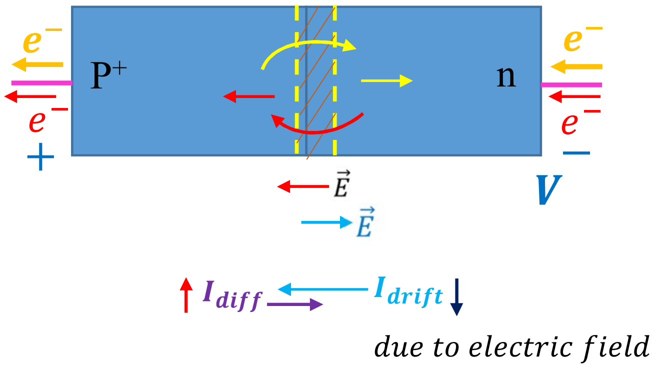
$$V_T = \left(\frac{KT}{q}\right)$$

minority charge carrier



$$P_n - P_{n0} = Ce^{-(x)/L_p}$$

$$P_n(x) = P_{n0} + P_{n0}\left(e^{V/V_T} - 1\right)e^{-(x-x_n)/L_p}$$



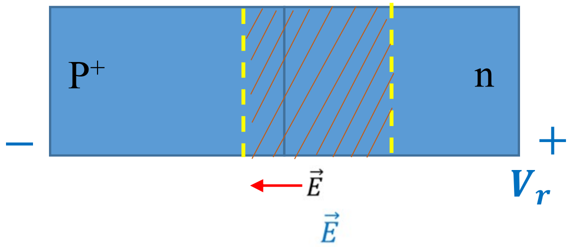
$$J_{Pdiff} = -qD_p\frac{\partial P_n}{\partial x} = -qD_pP_{n0}\left(e^{V/V_T} - 1\right)e^{-(x-x_n)/L_p}\left(-1/L_p\right)$$

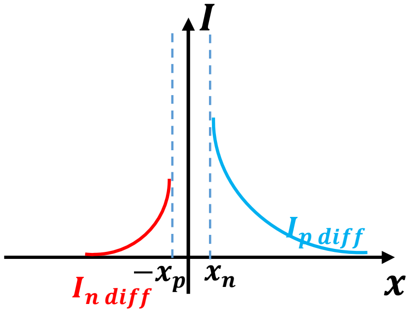
$$I_{Pdiff} = AJ_{Pdiff} = AqD_pP_{n0}\left(e^{V/V_T} - 1\right)e^{-(x-x_n)/L_p}\left(-1/L_p\right)$$

$$I_{ndiff} = AJ_{ndiff} = AqD_nn_{p0}\left(e^{V/V_T} - 1\right)e^{-(x+x_p)/L_n}\left(-1/L_n\right)$$

Basics of semiconductor : pn junction Energy band

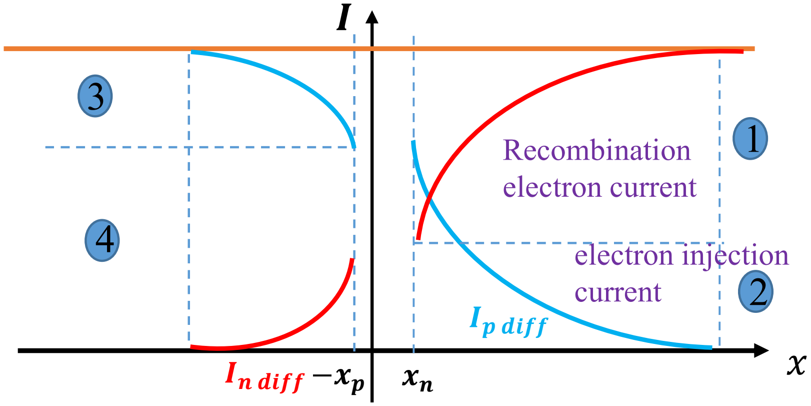
$$I_{Pdiff} = AJ_{Pdiff} = AqD_p\boldsymbol{P_{n0}}\left(\boldsymbol{e}^{V/V_T} - \boldsymbol{1}\right)\boldsymbol{e}^{-(x-x_n)/L_p\, i\omega t}\left(-\boldsymbol{1}/\boldsymbol{L_p}\right)$$





$$I = I_0\left(e^{V_D/\eta V_T} - 1\right)$$

$$I = I_{Pdiff}(x = x_n) + I_{ndiff}(x = -x_p)$$



$$V_T = \left(\frac{KT}{q}\right)$$