Lecture contents

- Heterojunctions
  - Types of heterostructures
  - Electrostatics
  - Current
  - Isotype heterojunctions

Heterojunction: Band lineup

- Determine band discontinuities ΔE_c and ΔE_v from difference in electron affinities:

$$\Delta E_c = E_{c2} - E_{c1} = \chi_1 - \chi_2$$

$$\Delta E_v = E_{v1} - E_{v2} = E_{g2} - E_{g1} - \Delta E_c = \Delta E_g - \Delta E_c$$

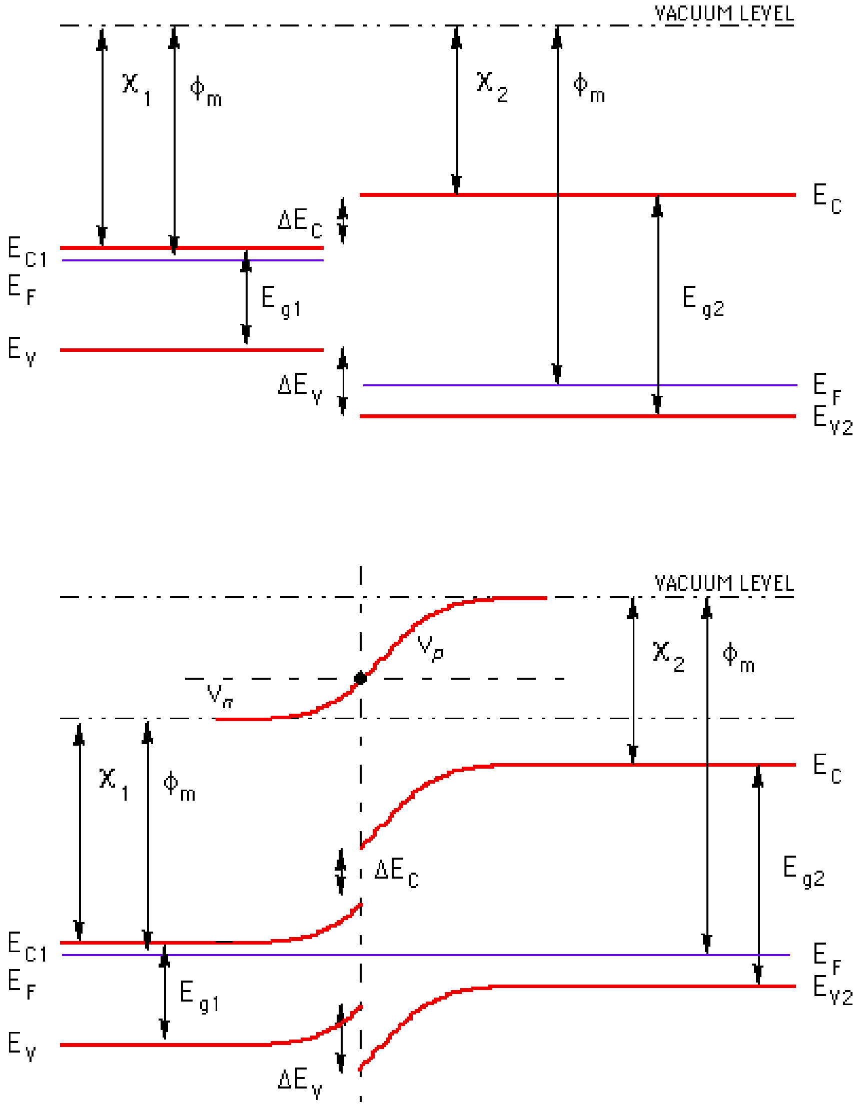
- Determine the built-in voltage from the difference in work functions.

$$q\phi_i = E_{Fn} - E_{Fp} = q\phi_{m1} - q\phi_{m2}$$

- Draw the bands at $\pm\infty$ for the appropriate doping

- Determine V_n and V_p and x_n and x_p from the solution of Poisson's Equation using Full Depletion Approximation with ϕ_i as a boundary condition.

Formation of P-n heterojunction



Types of heterojunctions

Type I (Straddling Alignment)

- AlGaAs/GaAs
- GaSb/AlSb
- GaAs/GaP

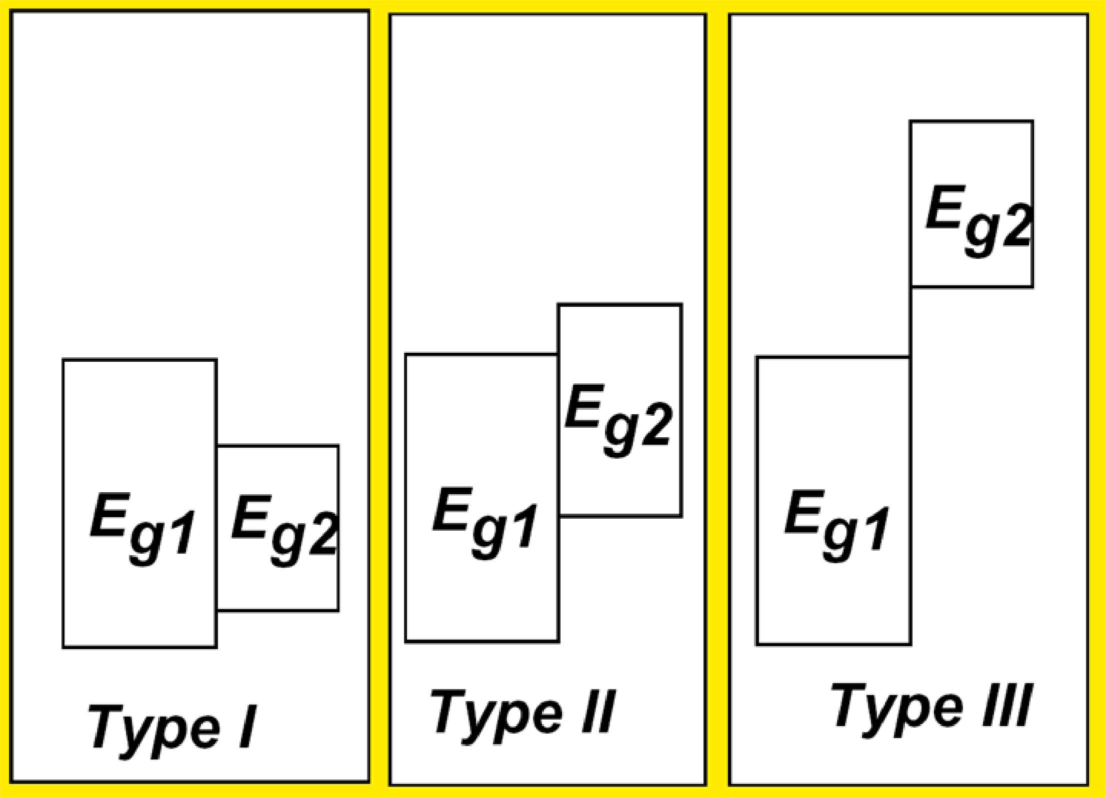
Type II (Staggered)

Either ΔE_c or ΔE_v is $> \Delta E_g$

- $InP/Al_{0.48}In_{0.52}P$
- $InxGa_{1-x}As/Ga_xSb_xAs$
- $Al_xIn_{1-x}As/InP$

Type III (broken gap)

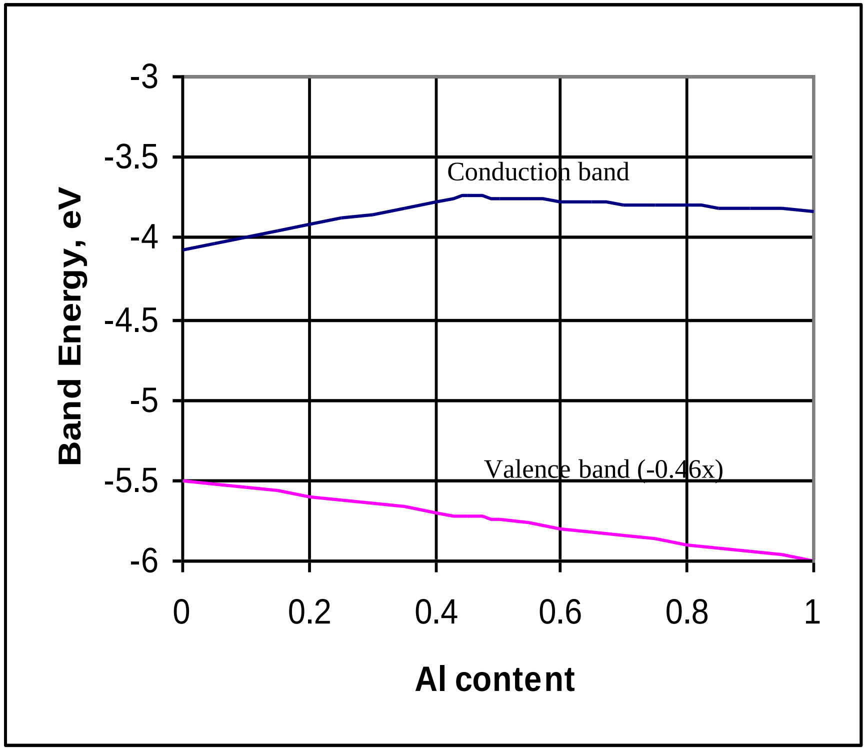
- InAs/GaSb



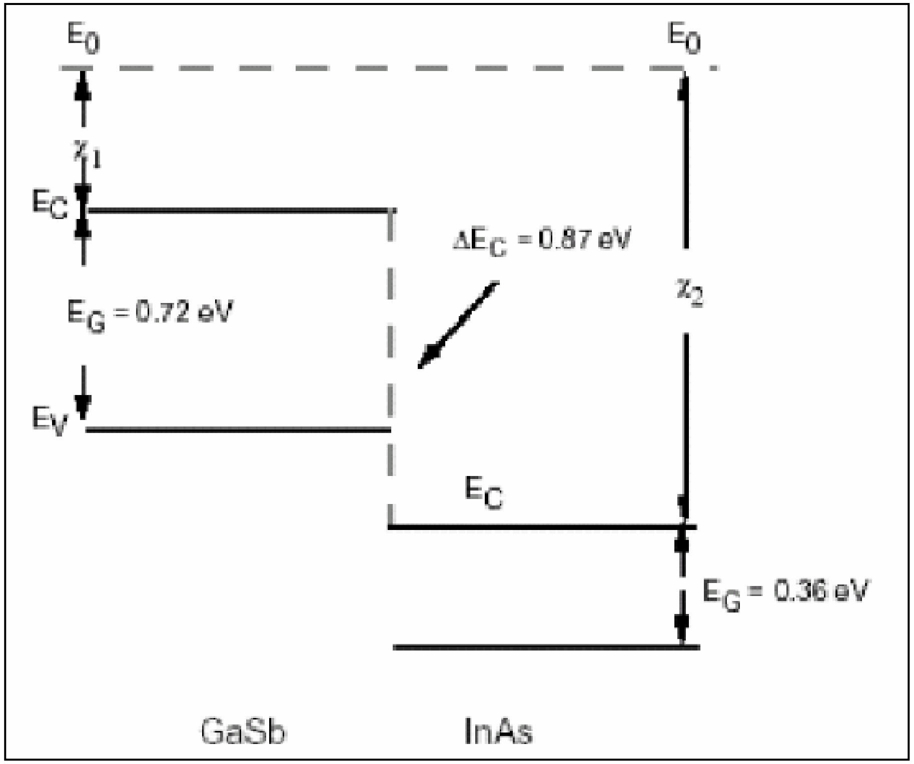
From Shur, 2003

Types of heterojunctions

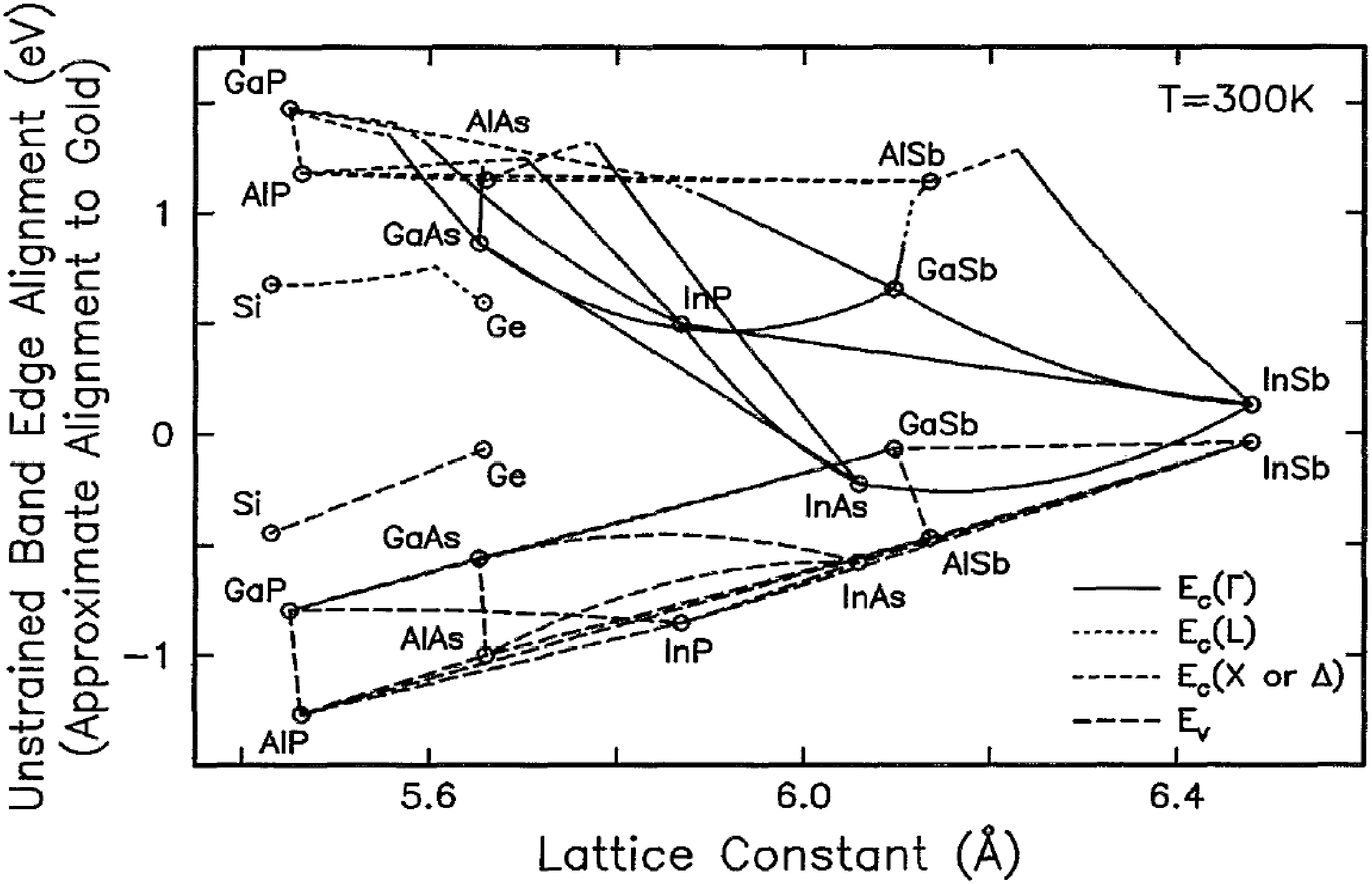
Type I: AlGaAs/GaAs



Type III : InAs/GaSb



Band edges alignment



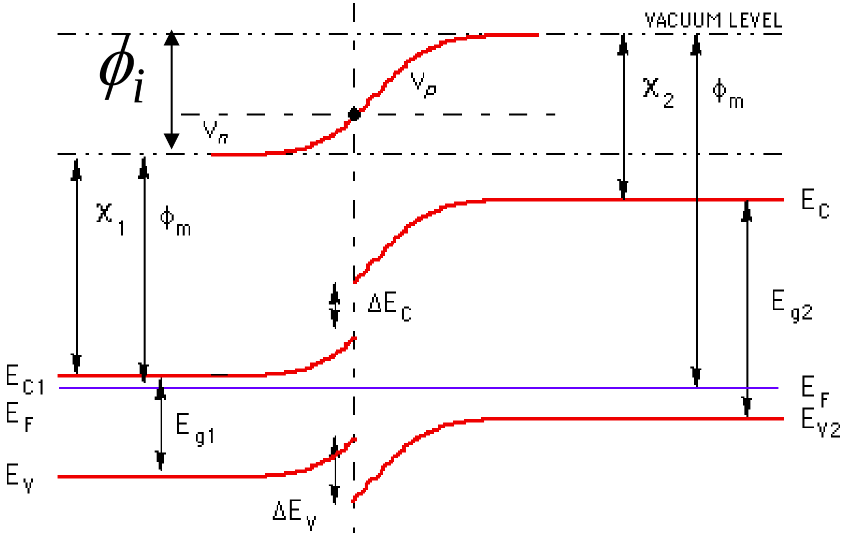
(From Tiwari and Frank, APL 1992)

p-N heterojunction: electrostatics

Junction barrier:

$$q\phi_i = E_{Fn} - E_{Fp} = \Delta E_c + kT\ln\frac{n_{n0}N_{cp}}{n_{p0}N_{cn}}$$

Flat-band diagram of a p-n heterojunctions



The same using valence band parameters

$$q\phi_i = -\Delta E_v + kT\ln\frac{p_{p0}N_{vn}}{p_{n0}N_{vp}}$$

- Or combining the two, independent of the free carrier concentrations:

$$q\phi_i = \frac{\Delta E_c - \Delta E_v}{2} + kT\ln\frac{N_d N_a}{n_{in}n_{ip}} + \frac{kT}{2}\ln\frac{N_{vn}N_{cp}}{N_{cn}N_{vp}}$$

p-N heterojunction: electrostatics

Depletion widths and band bending are calculated similar to a p-n homojunction by solving the Poisson equation:

$$x_n = \sqrt{\frac{2\varepsilon_n}{q}\frac{(1-\xi)}{N_d}(\phi_i - V_a)}$$

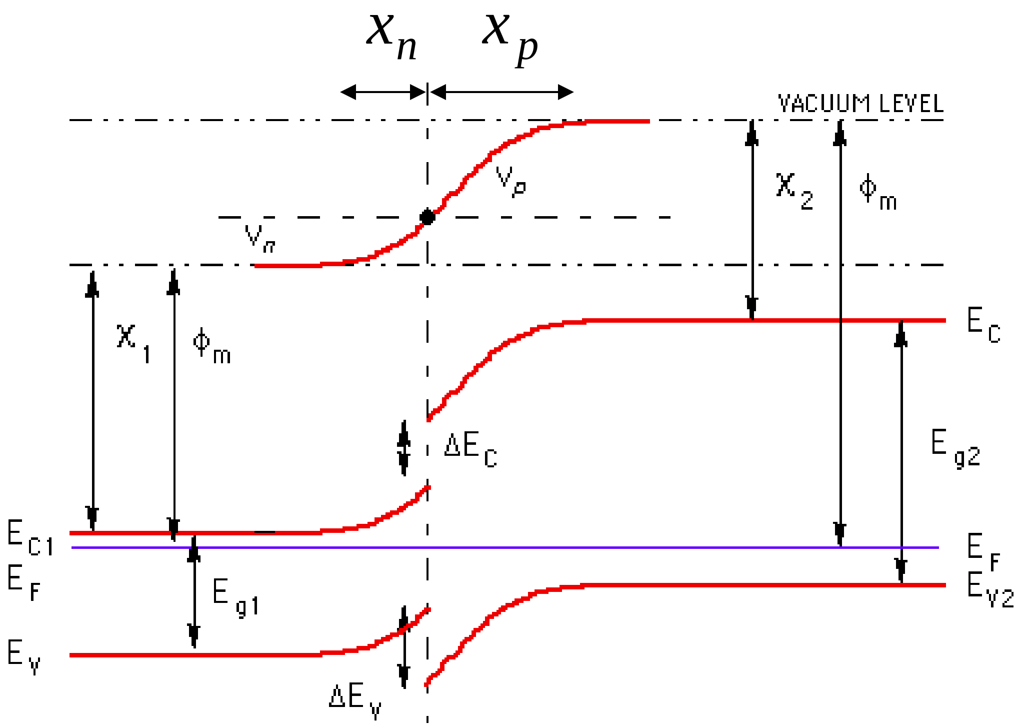
$$x_p = \sqrt{\frac{2\varepsilon_p}{q}\frac{\xi}{N_a}(\phi_i - V_a)}$$

$$V_n = (1-\xi)(\phi_i - V_a) - (1-2\xi)V_t$$

$$V_p = \xi(\phi_i - V_a) + (1-2\xi)V_t$$

with $$\xi = \frac{\varepsilon_n N_d}{\varepsilon_n N_d + \varepsilon_p N_a}$$

Band diagram of a n-P heterojunctions



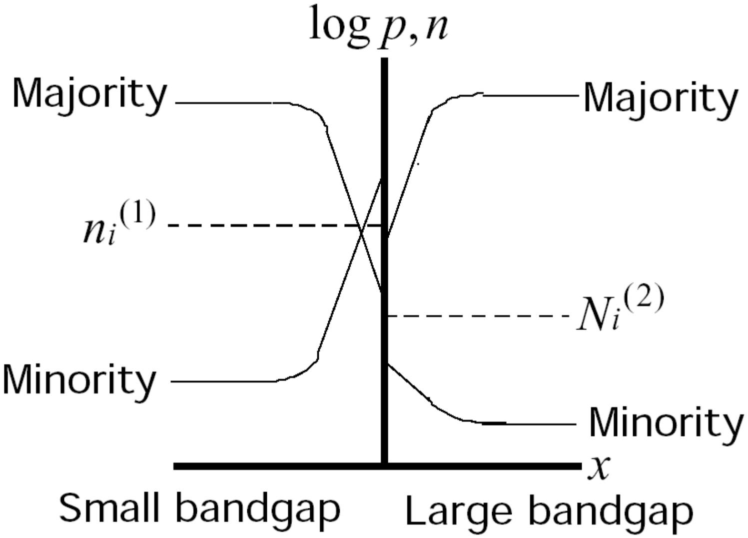
P-n heterojunction: free carrier profiles

- Band discontinuities result in the abrupt changes in carrier densities at the heterojunction
- In homojunction, the carrier densities are continuous
- Carrier jump scales as (e.g. for holes):

$$Exp\left(-\frac{\Delta E_v}{k_B T}\right)$$

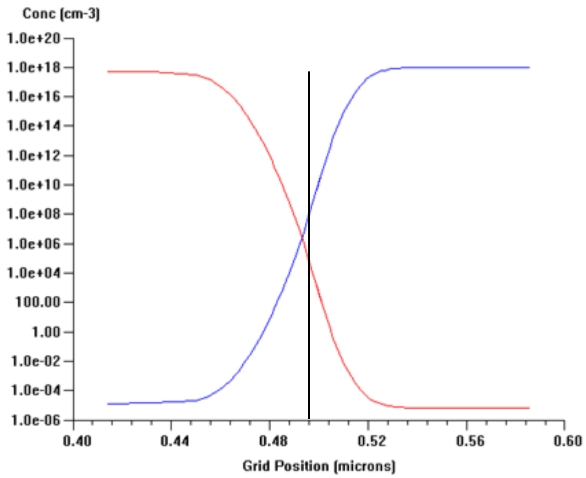
- If $V_p=V_n$ when $\varepsilon_n N_d = \varepsilon_p N_a$ then majority carrier densities will be equal at the interface, but this is rather special case.

Free carrier densities in p-N heterojunction



From Harris, 2002

Free carrier densities in p-n homojunction



Currents in heterojunctions

Direct bias: injection

Carrier injection is controlled by the energy barriers. Majority carrier injection from the wide bandgap material is favored (electrons in the Figs.) because of the reduction of barrier for electrons by ΔE_c and increase of barrier for holes by ΔE_v .

Currents: major mechanisms

Graded

Forward

- Diffusion of majority carriers
- Traps & recombination in depletion region

Reverse

- Drift of Minority Carriers
- Traps & recombination in depletion region

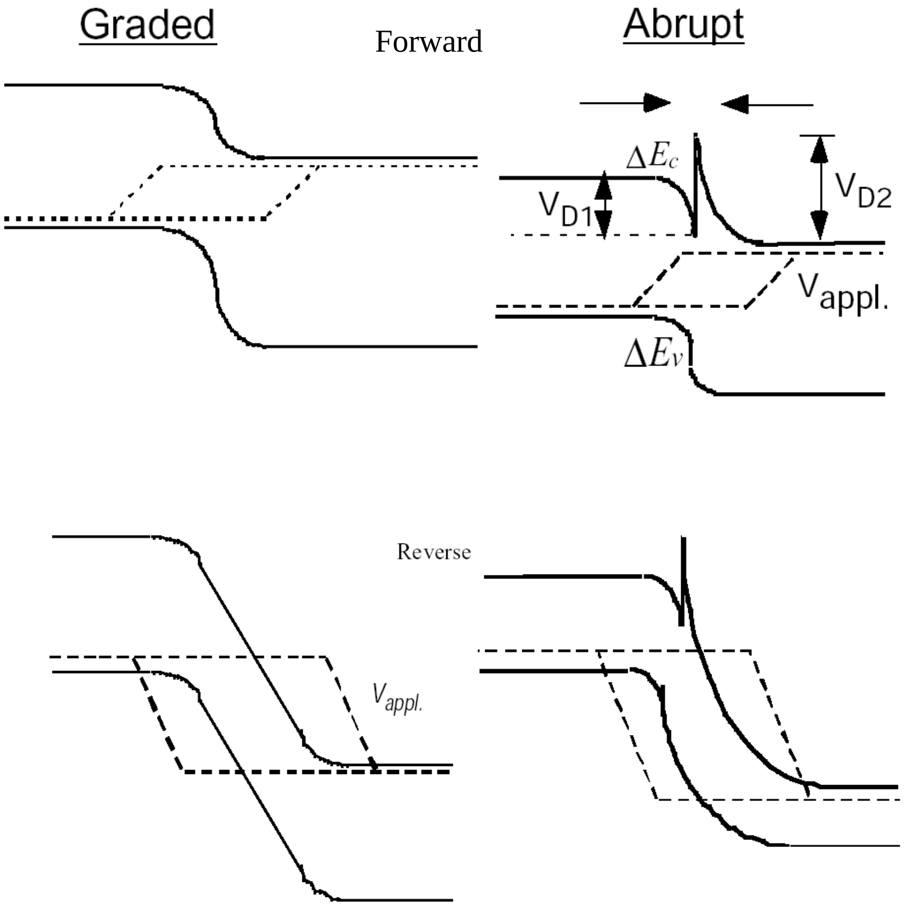
Abrupt

Forward

- Thermionic emission over abrupt barrier

Reverse

- Thermionic emission over abrupt barrier
- Drift of Minority Carriers



From Harris, 2002

Mechanisms can change with bias and doping asymmetry

Current in heterojunctions

Under forward bias at the edge of depletion region:

$$n_p p_p = n_i^2 e^{V_a/V_t}$$

Low level injection,

- majority carrier density is constant:

$$p_p = N_a$$

- minority carrier density

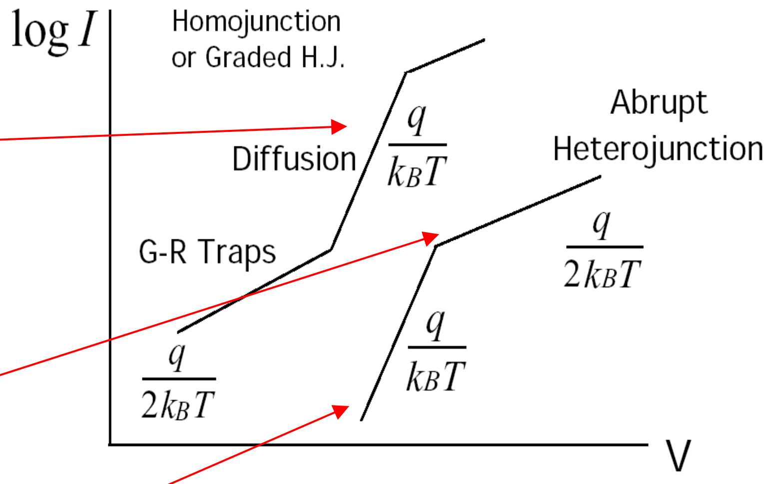
$$n_p = \frac{n_i^2}{N_a} e^{V_a/V_t}$$

High level injection,

- Minority & majority carrier density ~ equal

$$n_p = p_p = n_i e^{V_a/2V_t}$$

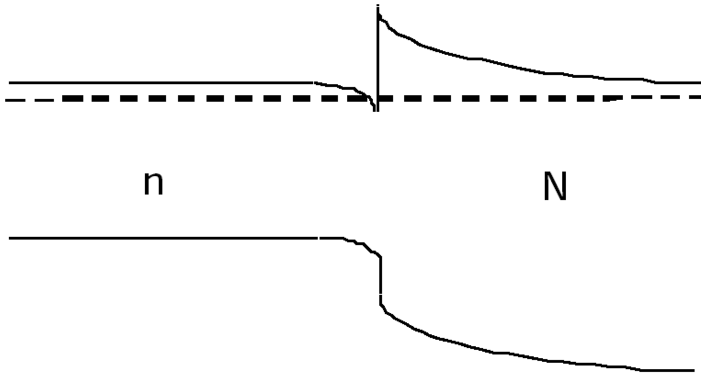
By having most of the depletion region in the widegap material, G-R in the depletion region is ~N_i ,and therefore, significantly reduced



Isotype heterojunction

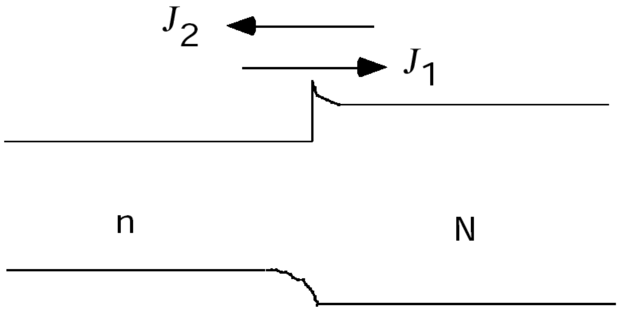
- Isotype N-n$^+$ heterojunction in thermal Equilibrium

  The properties of such junctions are very important in VCSELs because there can be as many as 60-70 of them in series!



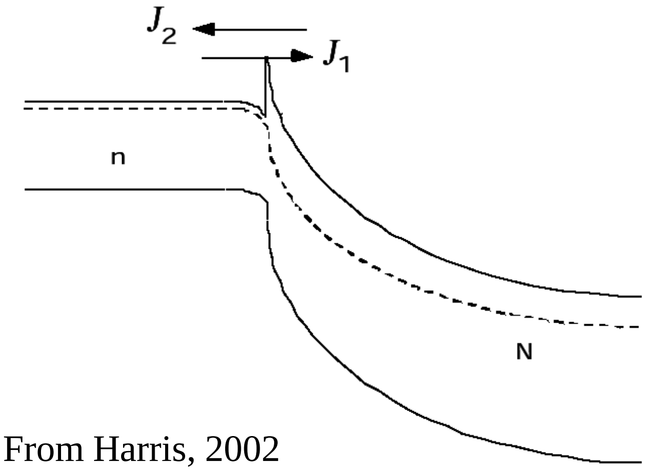
- Isotype N-n heterojunction under "Forward" bias (negative bias to N-side)

  Barrier V_N decreases with applied bias, greatly increasing J_2 while J_1 remains relatively constant (compare with injection from wide-bandgap material).



- Isotype N-n heterojunction under "Reverse" bias (Positive bias to N-side)

  Barrier V_N increases with applied bias, reducing J_2 to zero while J_1 remains relatively constant, hence the reverse current "saturates"

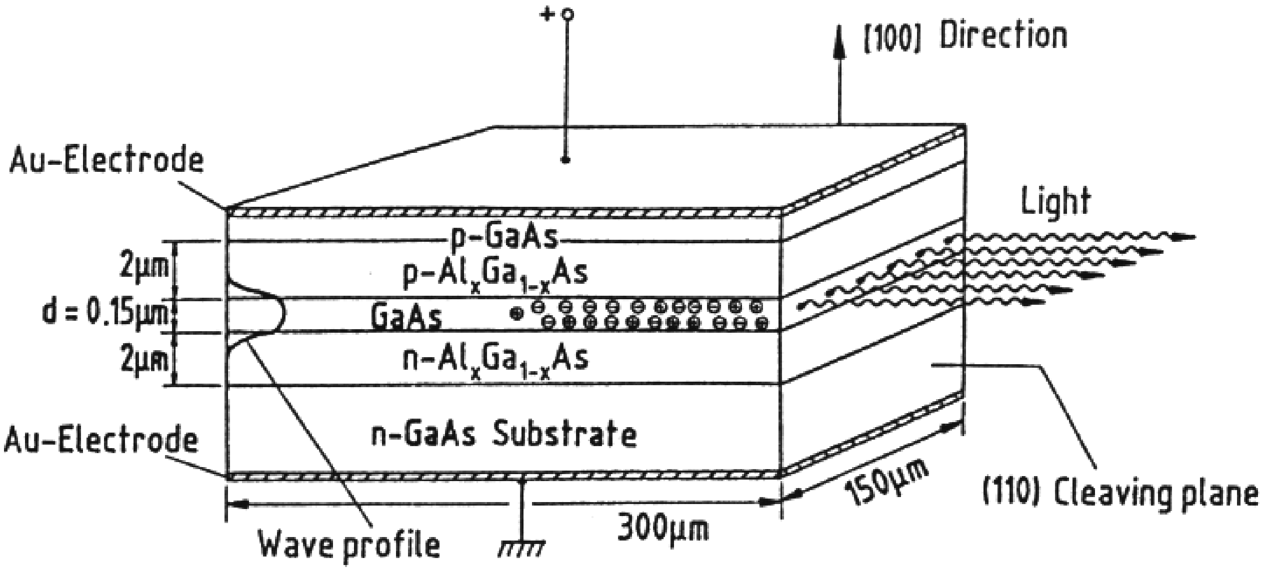


- Current is mainly thermionic as in M-S.

From Harris, 2002

Simple edge-emitting semiconductor laser diode

- In principle, a simple *p-n* junction may operate as a laser. However, a double-heterostructure (DHS) laser diode is much more effective.



Broad area DHS semiconductor laser

From Ebeling, 1992

- **Advantage**: acts as a light guide in the lateral direction
  - Would be disadvantage for an LED: re-absorption
  - However, the **absorption becomes the gain - is favorable for lasing** !
- **Favorable** for lasing also are:
  - Confinement of electrons and holes - efficient recombination
  - Confinement of light can be further control in separate confinement structures

Simple edge-emitting semiconductor laser diode

- In p-n homojunction concentration of carriers is determined by diffusion length and injection current.

- Problem of carrier diffusion can be overcome by heterojunction barrier.

- for $Al_xGa_{0.7}As$ barrier with x = 0.3 ΔE_n & ΔE_p >12kT,

$$\frac{n_{Active}}{n_{confining}} = 1.63\times10^5$$

- Carrier leakage is reduced

- Injection rate $$\left.\frac{dn}{dt}\right|_{inj} = \frac{J}{qd}$$