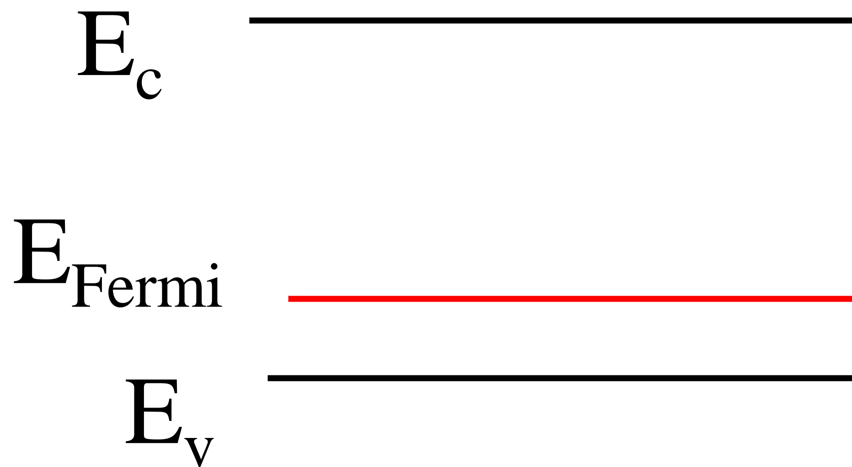
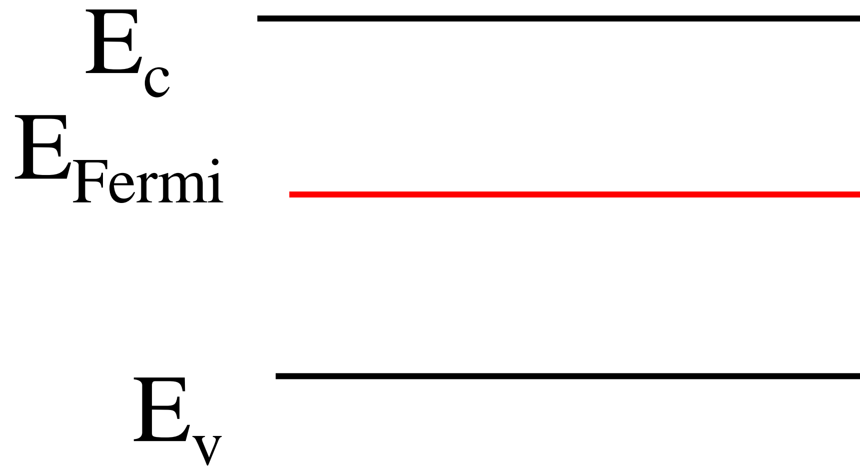
Lecture 3:
Two-terminal devices

Fermi levels

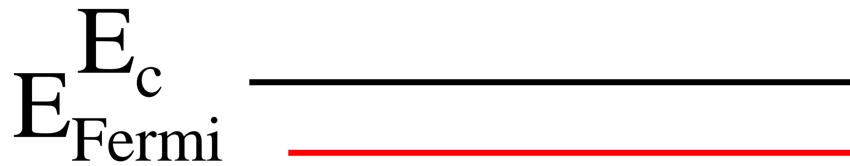


p-type

Fermi levels



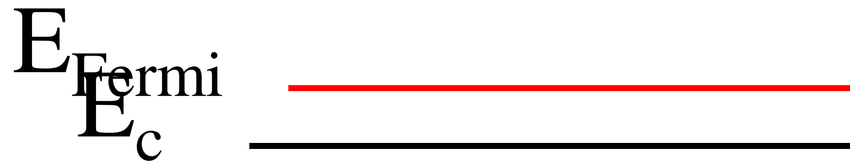
Fermi levels



E_v

n-type

Degenerate doping



n-type

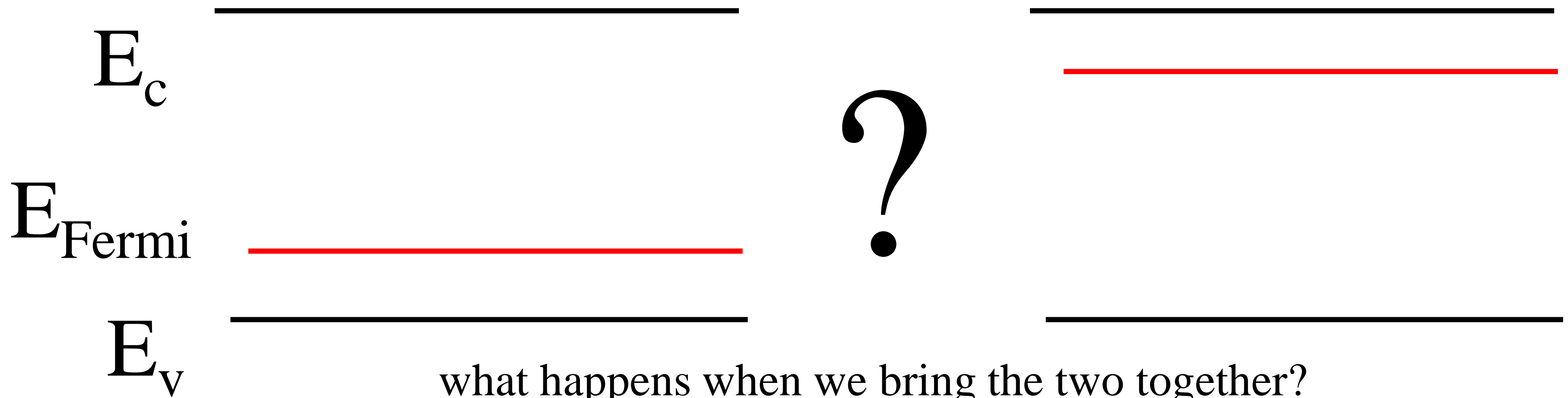
Invariance of Fermi level

- Fermi level must be constant if system is in equilibrium (no external voltage or force)
- Discuss on board

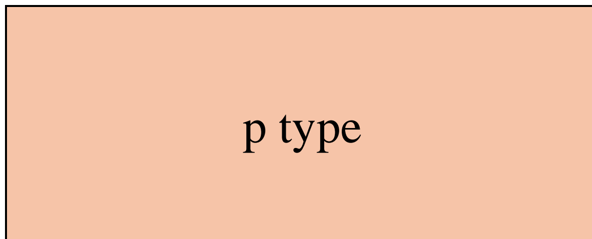
Junction types

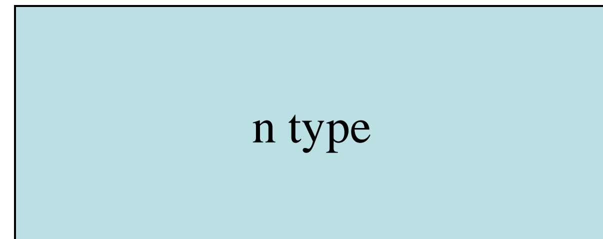
- Homojunction
- Heterojunction

p-n junction

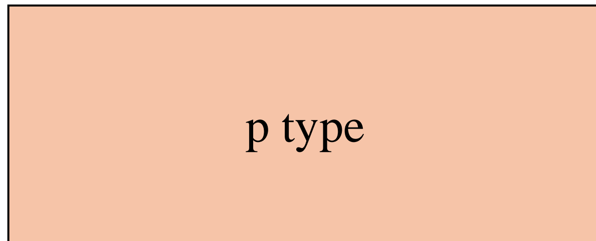


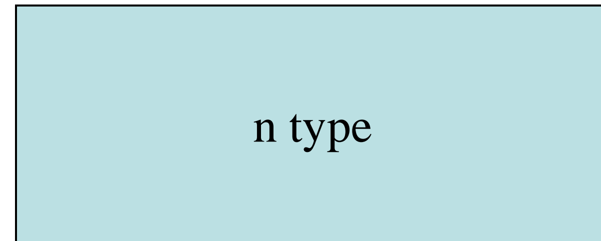
what happens when we bring the two together?
Electrons move from n to p
Holes move from p to n

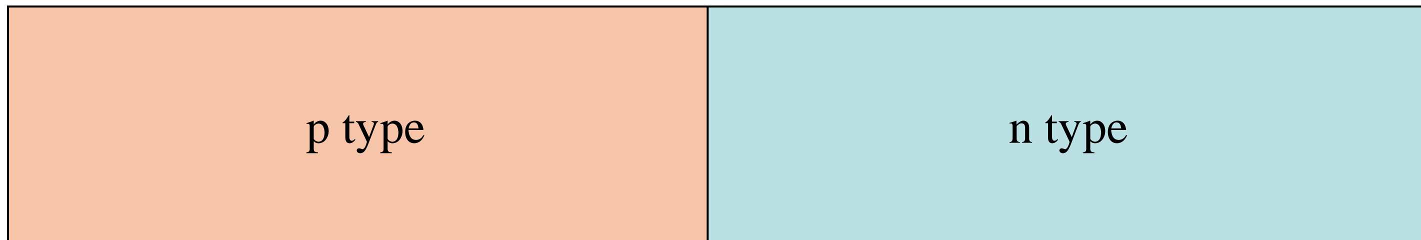


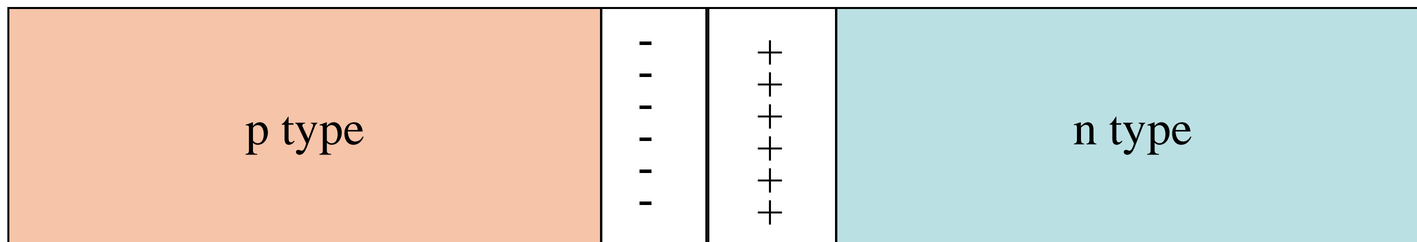


p-n junction

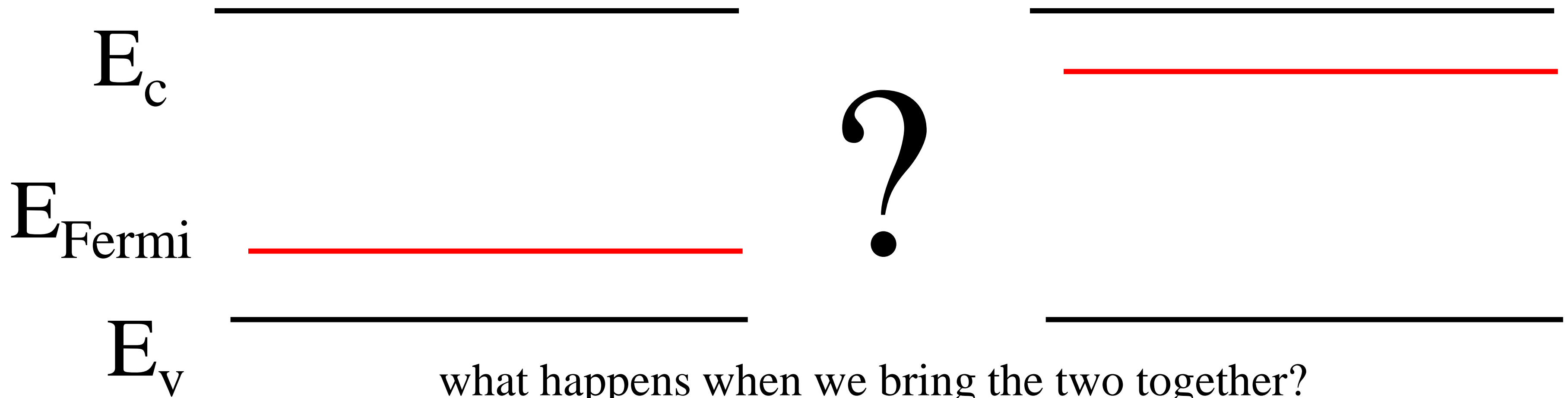








p-n junction



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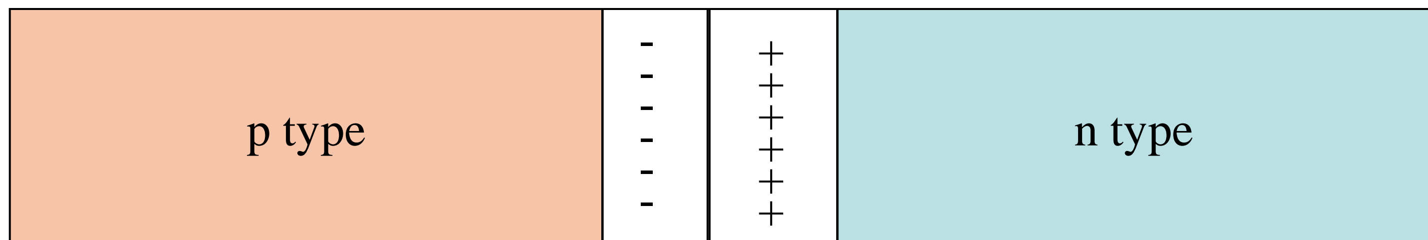
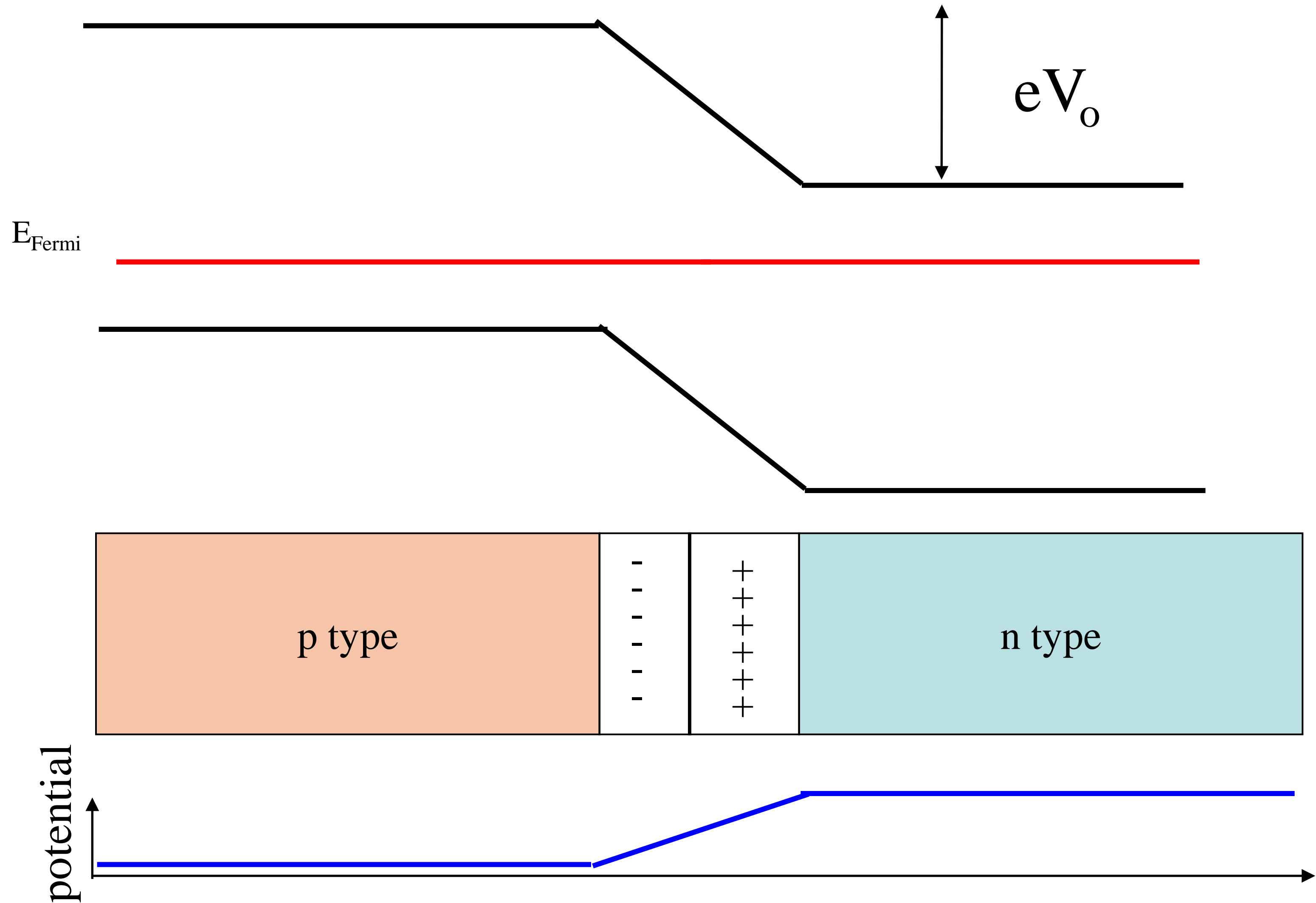


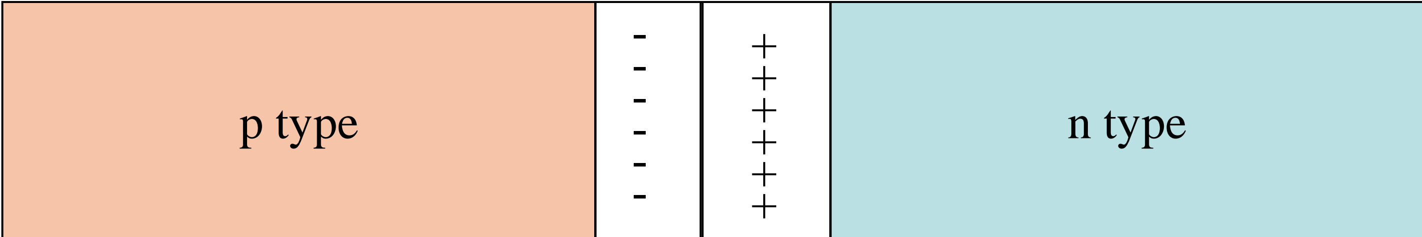
How to deal with?

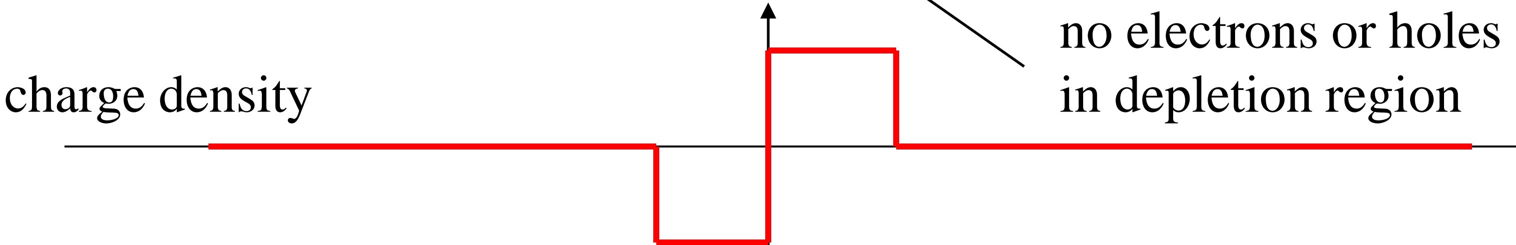
- Away from junction, same as bulk
- In “depletion region” or “space charge region” no carriers
- But, there is an electric field which causes potential energy difference
- “Band bending” method: shift all levels of p side relative to n side
- Rule: align Fermi levels

p n diode

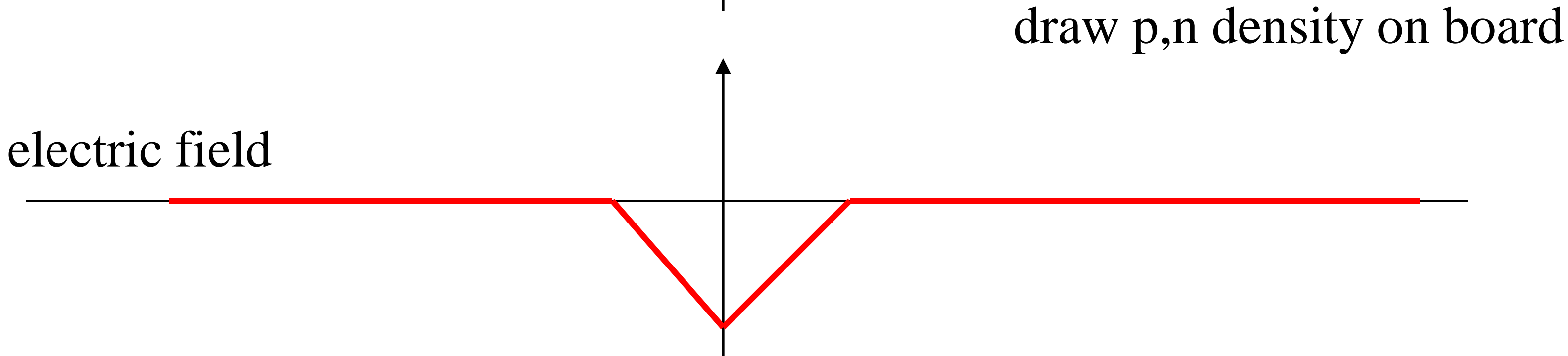


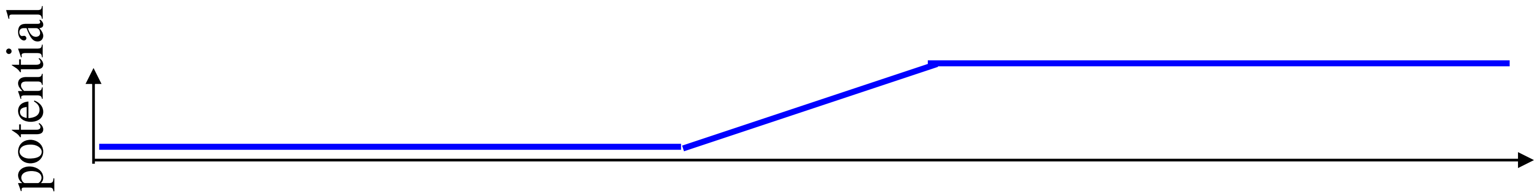
p n diode





draw p,n density on board





Poisson equation

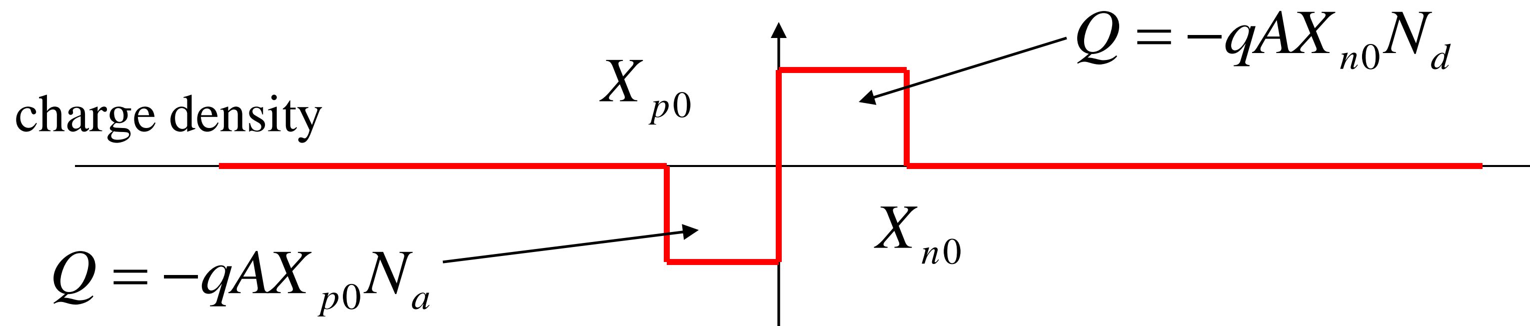
Actually first of Maxwell's four equations:

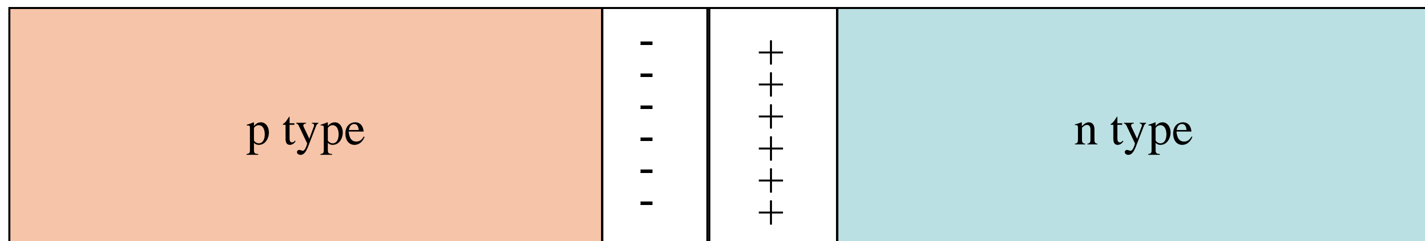
$$\vec{\nabla} \cdot \vec{E} = -\frac{\rho}{\varepsilon}$$

In the x-direction only:

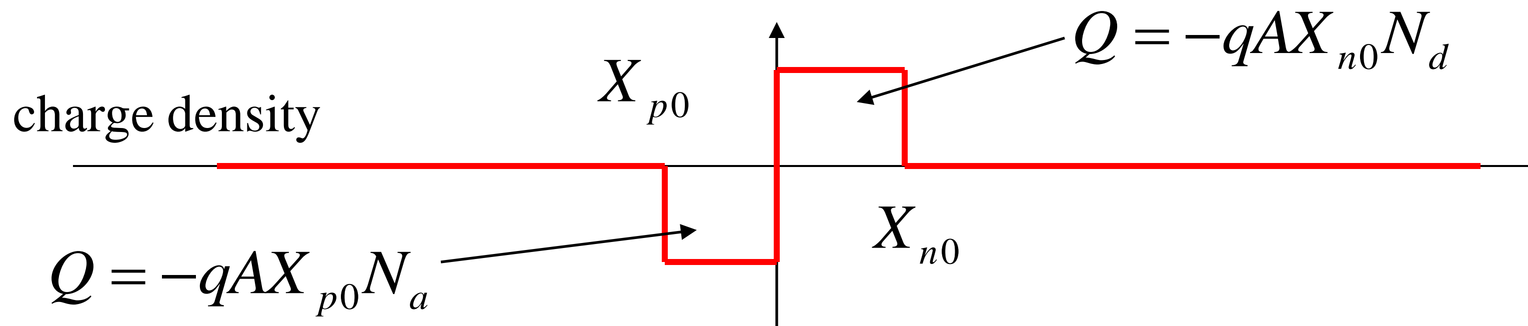
$$\frac{dE}{dx} = \frac{q}{\varepsilon_p}\left(p - n + N_d^+ - N_a^-\right)$$

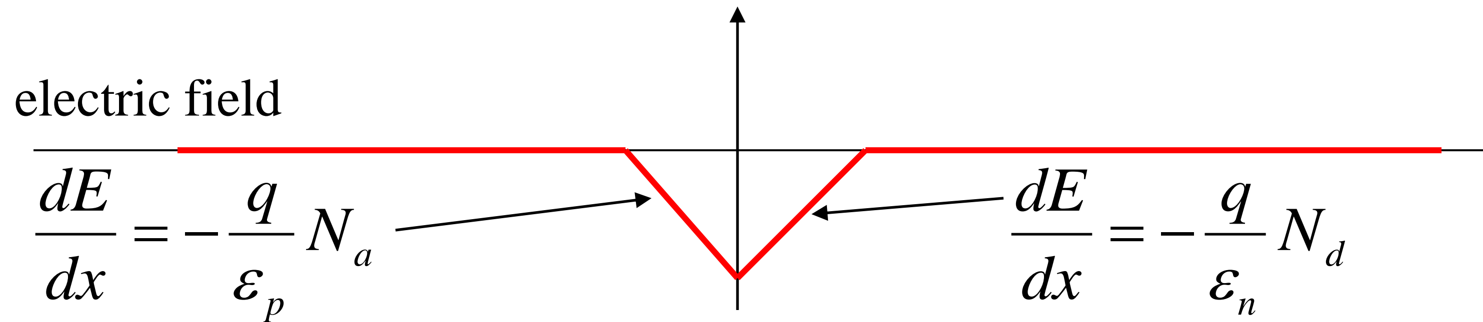
Charge density





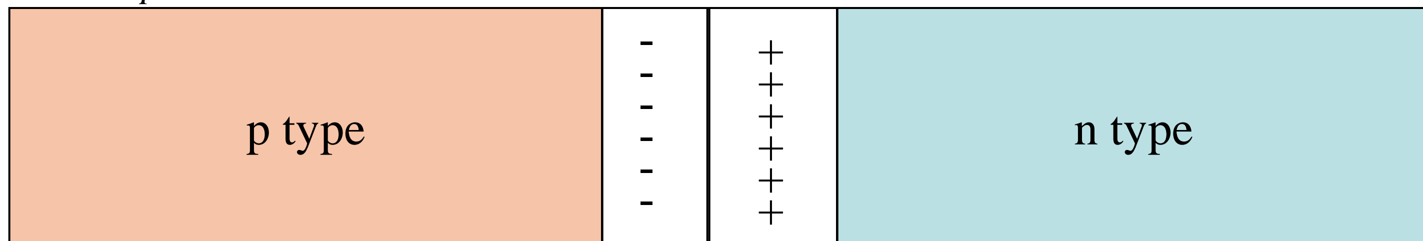
Electric field





$$E(x) = -\frac{q}{\varepsilon_p} N_a (x + X_{p0})$$

$$E(x) = -\frac{q}{\varepsilon_p} N_d (X_{n0} - x)$$



Electric potential

electric field

$$\frac{dE}{dx} = -\frac{q}{\varepsilon_p} N_a \qquad \frac{dE}{dx} = -\frac{q}{\varepsilon_n} N_d$$

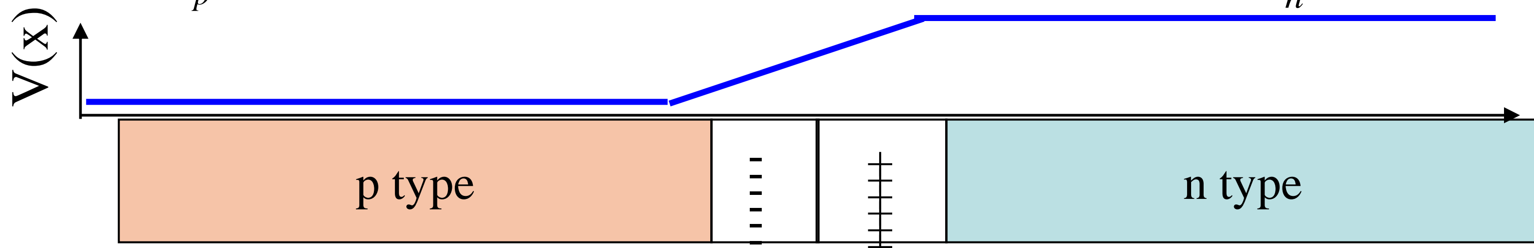
$$E(x) = -\frac{q}{\varepsilon_p} N_a (x + X_{p0}) \qquad E(x) = -\frac{q}{\varepsilon_p} N_d (X_{n0} - x)$$

$$V(x) = -\int E(x)dx = \frac{q}{\varepsilon_p} N_a \left(\frac{x^2}{2} + X_{p0}x\right) + C$$

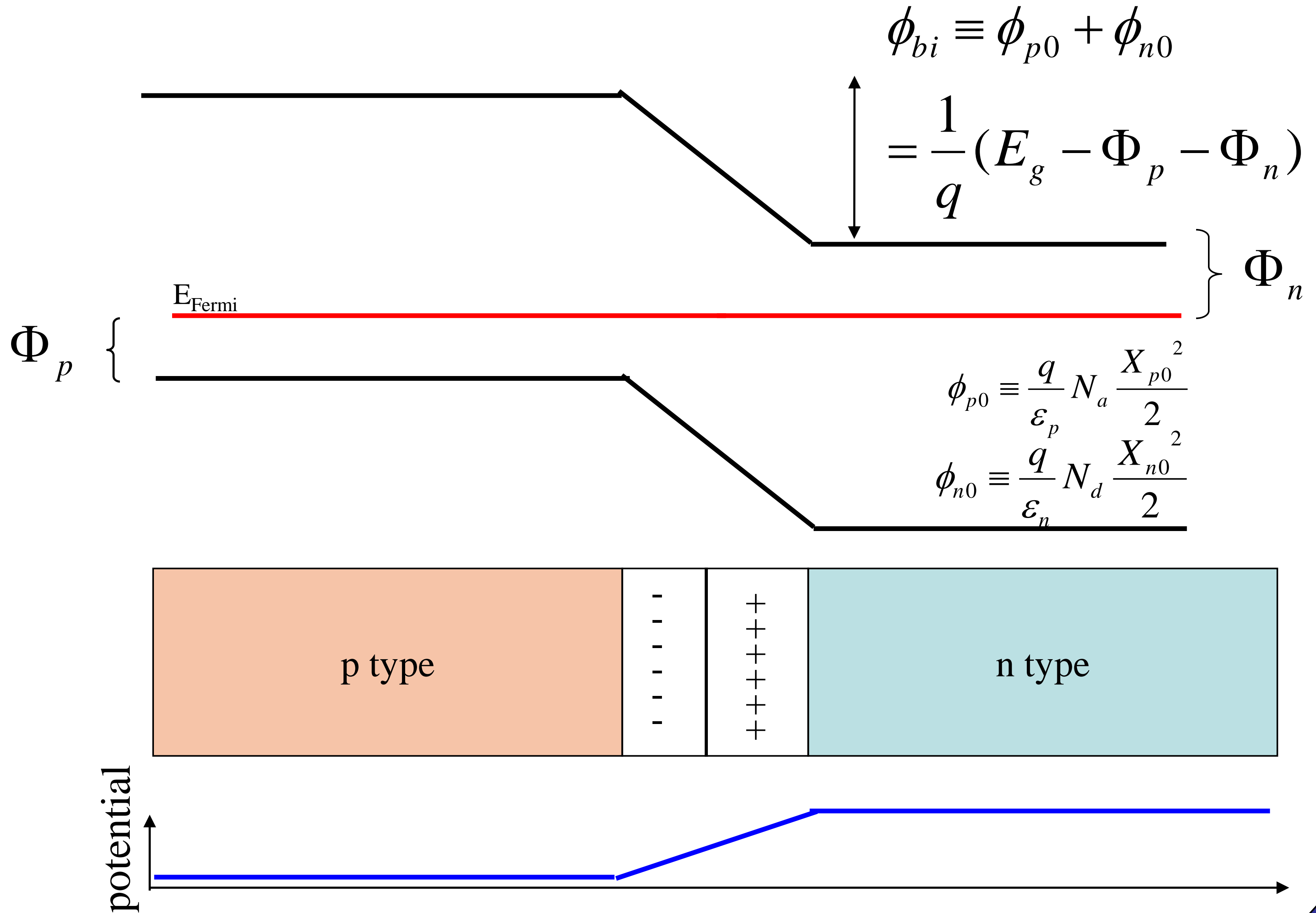
Define zero of V(x) at p side

$$V(x) = \frac{q}{\varepsilon_p} N_a \left(\frac{x^2}{2} + X_{p0}x + \frac{X_{p0}^{\ 2}}{2} \right) \qquad V(x) = \frac{q}{\varepsilon_n} N_d \left(X_{n0}x - \frac{x^2}{2} \right) + \phi_{p0}$$

$$V(0) = \frac{q}{\varepsilon_p} N_a \frac{X_{p0}^{\ 2}}{2} \equiv \phi_{p0} \qquad \phi_{n0} \equiv V(x) = \frac{q}{2\varepsilon_n} N_d X_{n0}^{\ 2}$$



built in potential



Depletion region width

$$\phi_{bi} \equiv \phi_{p0} + \phi_{n0} = \frac{1}{q}(E_g - \Phi_p - \Phi_n)$$

$$\phi_{p0} \equiv \frac{q}{\varepsilon_p} N_a \frac{X_{p0}^2}{2} \qquad \phi_{n0} \equiv \frac{q}{\varepsilon_n} N_d \frac{X_{n0}^2}{2}$$

$$Q_p = -qAX_{p0}N_a \qquad Q_n = -qAX_{n0}N_d$$

$$Q_p = Q_n \Rightarrow qAX_{p0}N_a = -qAX_{n0}N_d$$

$$\Rightarrow$$

$$W = \sqrt{\frac{2\varepsilon\phi_{bi}}{q}\left(\frac{1}{N_d} + \frac{1}{N_a}\right)}$$

Numerical example

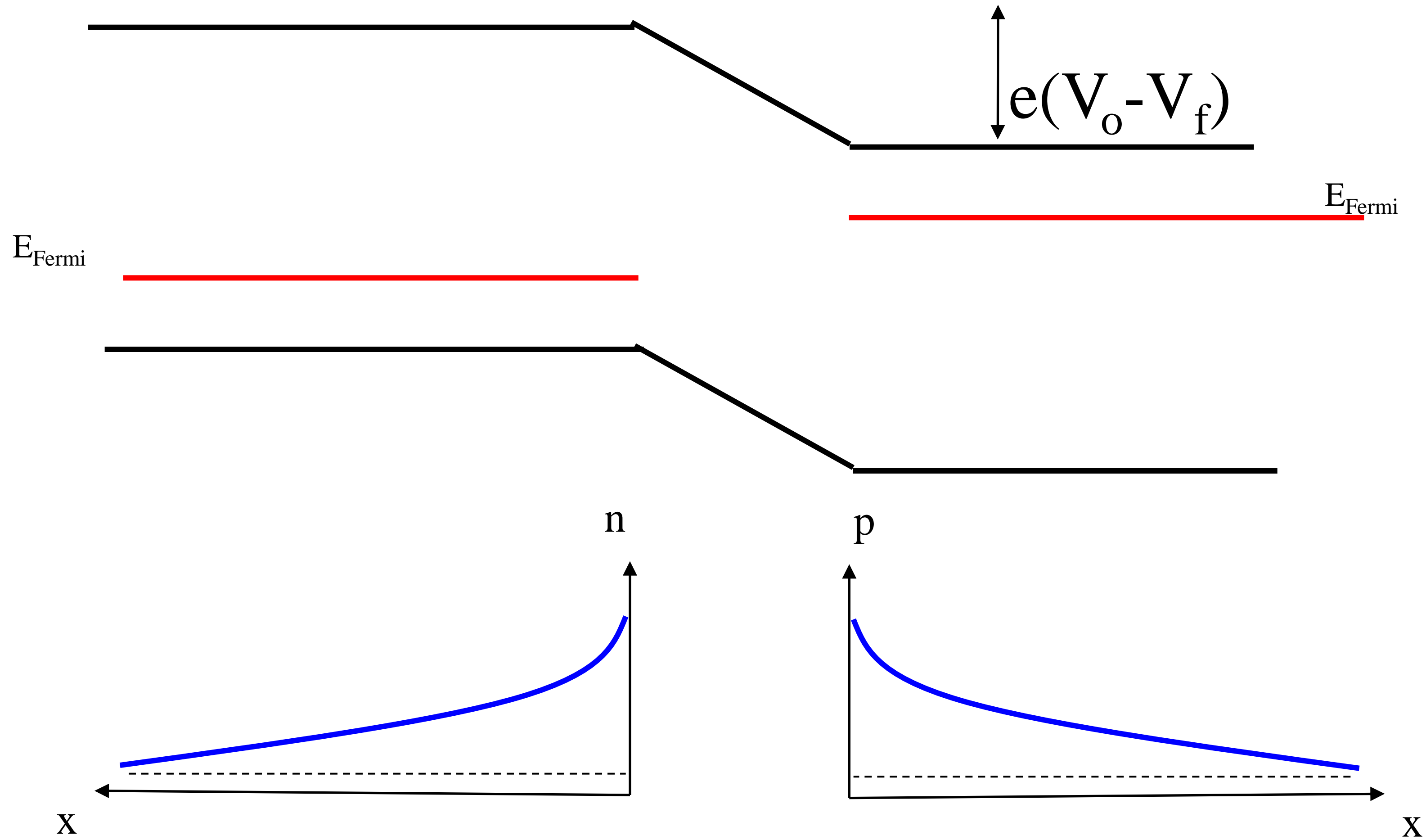
$$N_d = 10^{16} cm^{-3}$$

$$N_a = 10^{18} cm^{-3}$$

$$\Rightarrow W = X_{p0} + X_{n0} = 0.33 \mu m$$

$$\Rightarrow X_{p0} = 8.3 A$$

Forward bias

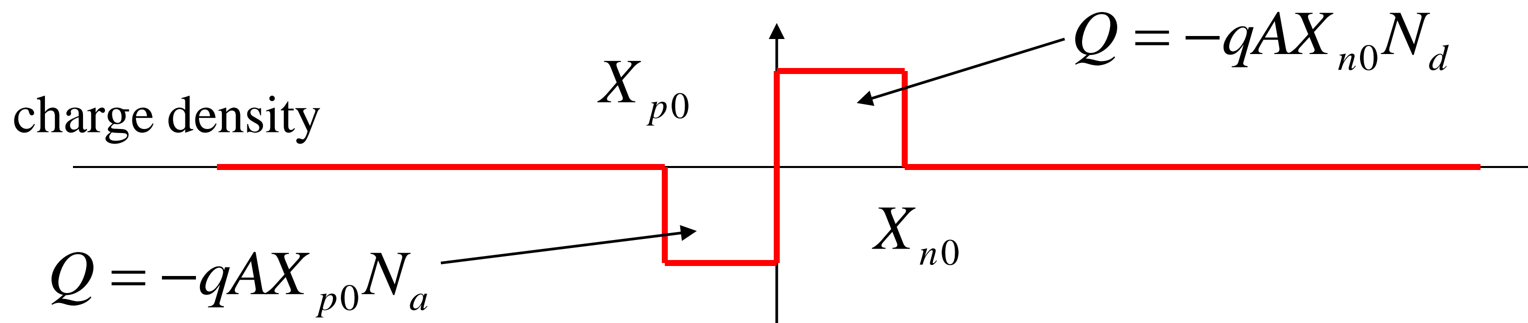


Discuss current vs. x

$$j_n = dn/dx$$

$$j = j_n + j_p$$

Capacitance



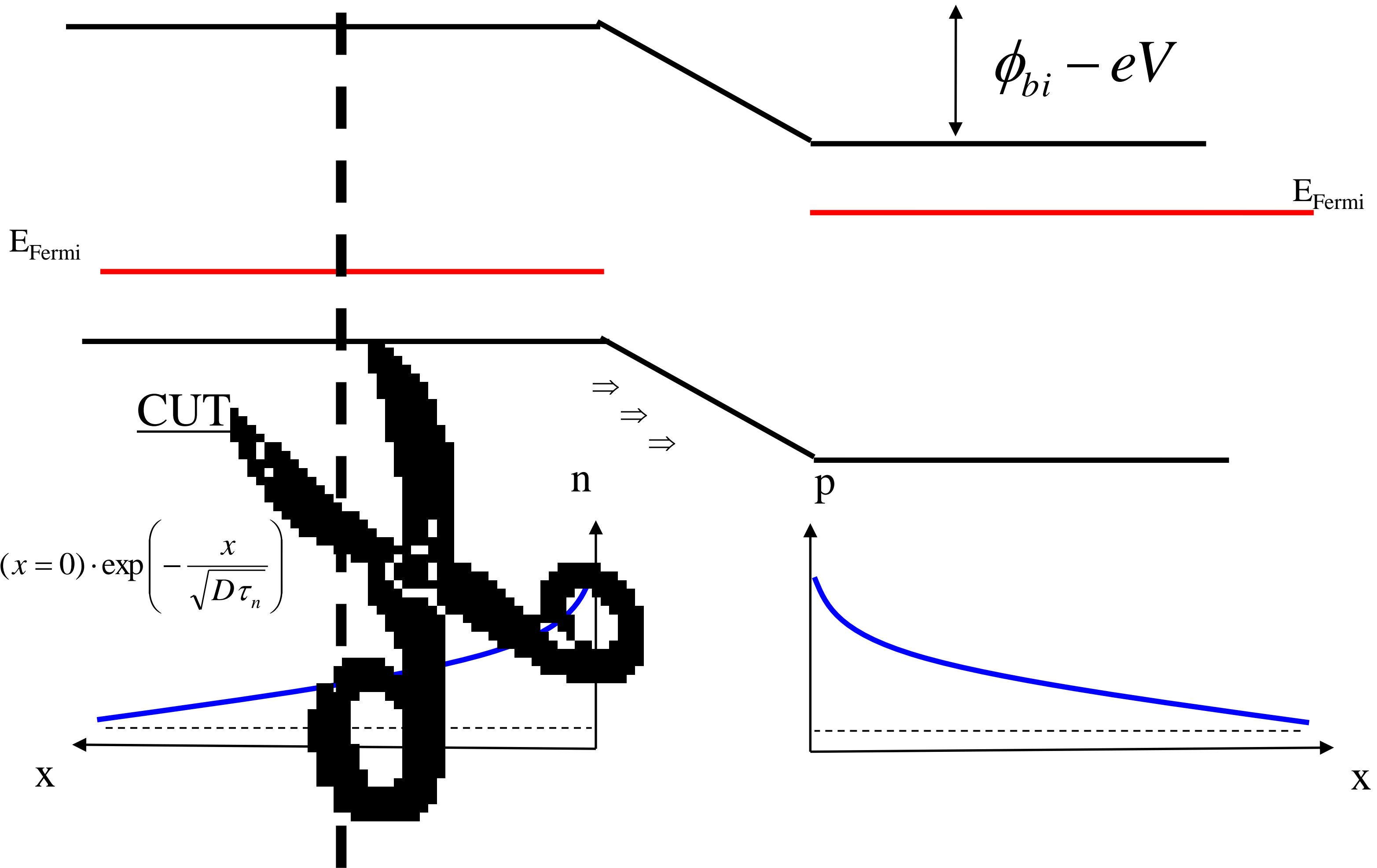
$$X_{p0}=\sqrt{\frac{2\varepsilon\phi_{bi}}{q}\frac{1}{N_a(1+N_a/N_d)}}\rightarrow\sqrt{\frac{2\varepsilon(\phi_{bi}-V)}{q}\frac{1}{N_a(1+N_a/N_d)}}$$

$$Q=-qAX_{p0}N_a=-qAN_a\sqrt{\frac{2\varepsilon(\phi_{bi}-V)}{q}\frac{1}{N_a(1+N_a/N_d)}}$$

$$C=\frac{dQ}{dV}=\frac{A}{2}\sqrt{\frac{2q\varepsilon}{(\phi_{bi}-V)}\frac{N_dN_a}{(N_d+N_a)}}$$

This will be important in high-speed bipolar transistors.

"Short" diodes



Exactly what we will do with bipolar transistors!

“Short” diodes

$$D\frac{\partial^2 \delta n}{\partial x^2} = \frac{\delta n}{\tau} \qquad \Rightarrow \delta n(x) = \delta n(x=0)\cdot \exp\left(-\frac{x}{\sqrt{D\tau_n}}\right)$$

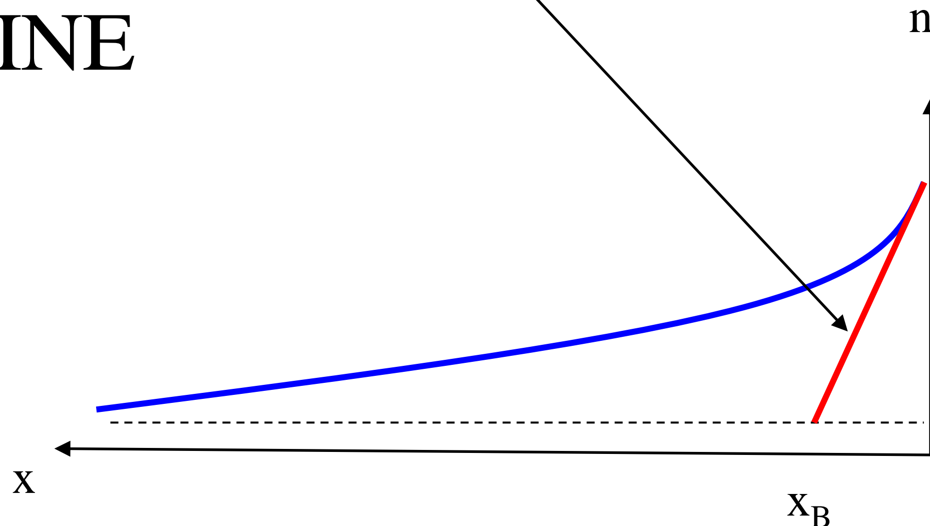
New boundary condition: $\delta n(x = x_B) = 0$

$$\delta n(x) = A\exp\left(-\frac{x}{\sqrt{D\tau_n}}\right) + B\exp\left(+\frac{x}{\sqrt{D\tau_n}}\right)$$

$$\rightarrow (prefactor)\left(\exp^{\left(-x/\sqrt{D\tau_n}\right)} - \exp^{\left(+x/\sqrt{D\tau_n}\right)}\right)$$

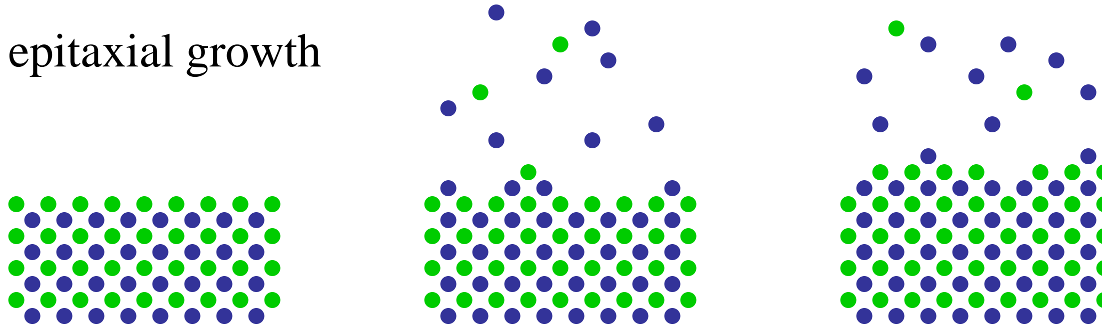
$\approx$ A STRAIGHT LINE

$$If\ \mathrm{x_N} < \sqrt{D\tau_n}$$



MBE

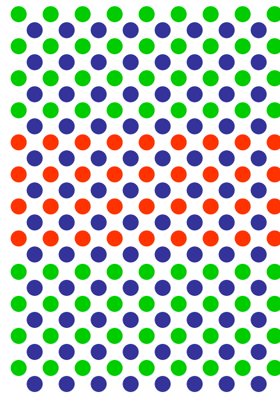
epitaxial growth

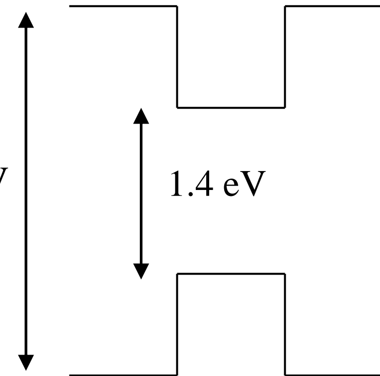


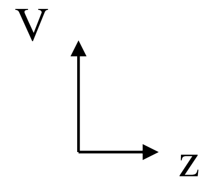
AlAs

GaAs

AlAs



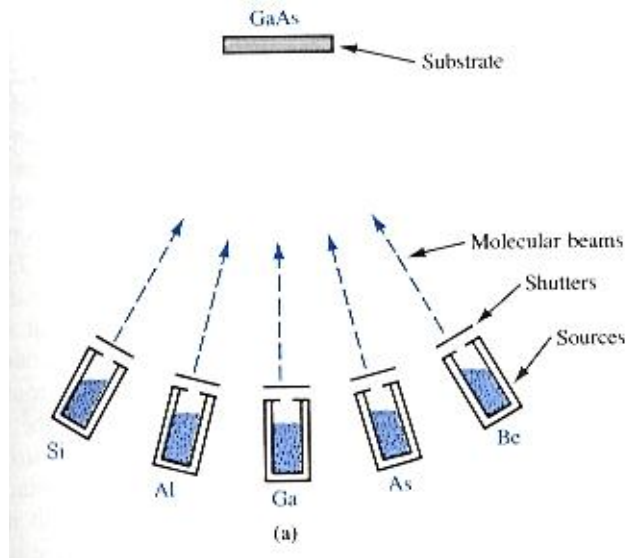


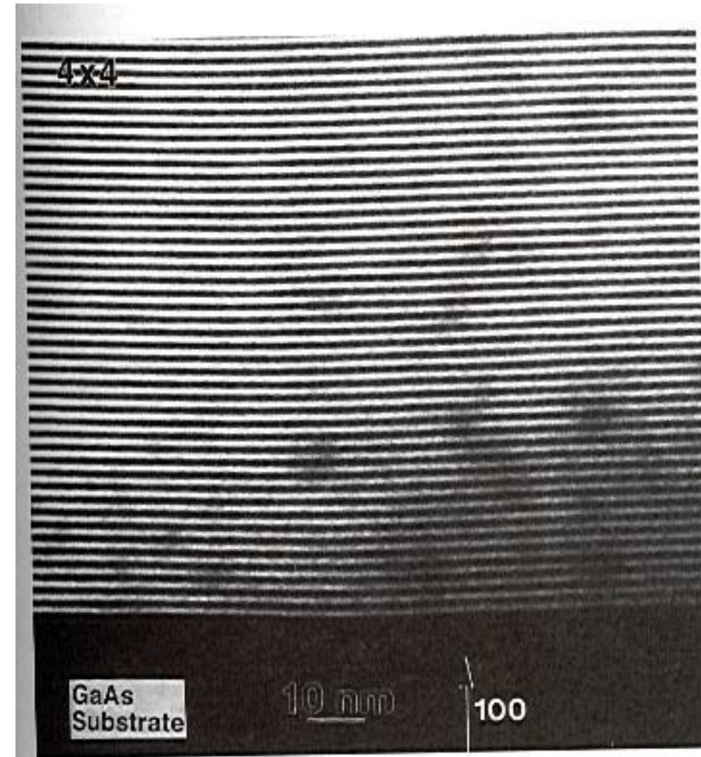


Also InP, InGaAs, InAlAs, InGaAsP …

Picture adapted from M. Lilly.

MBE

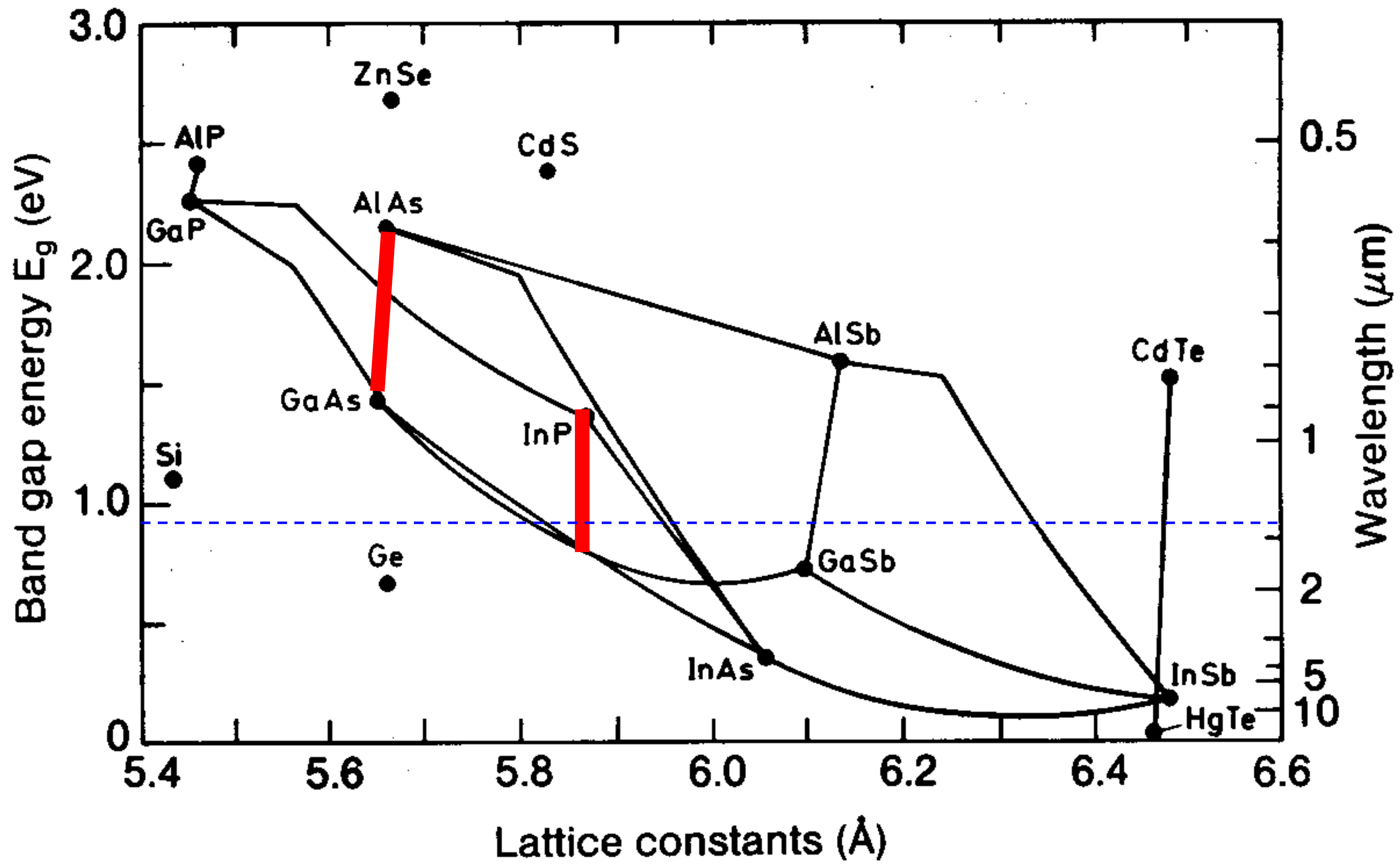




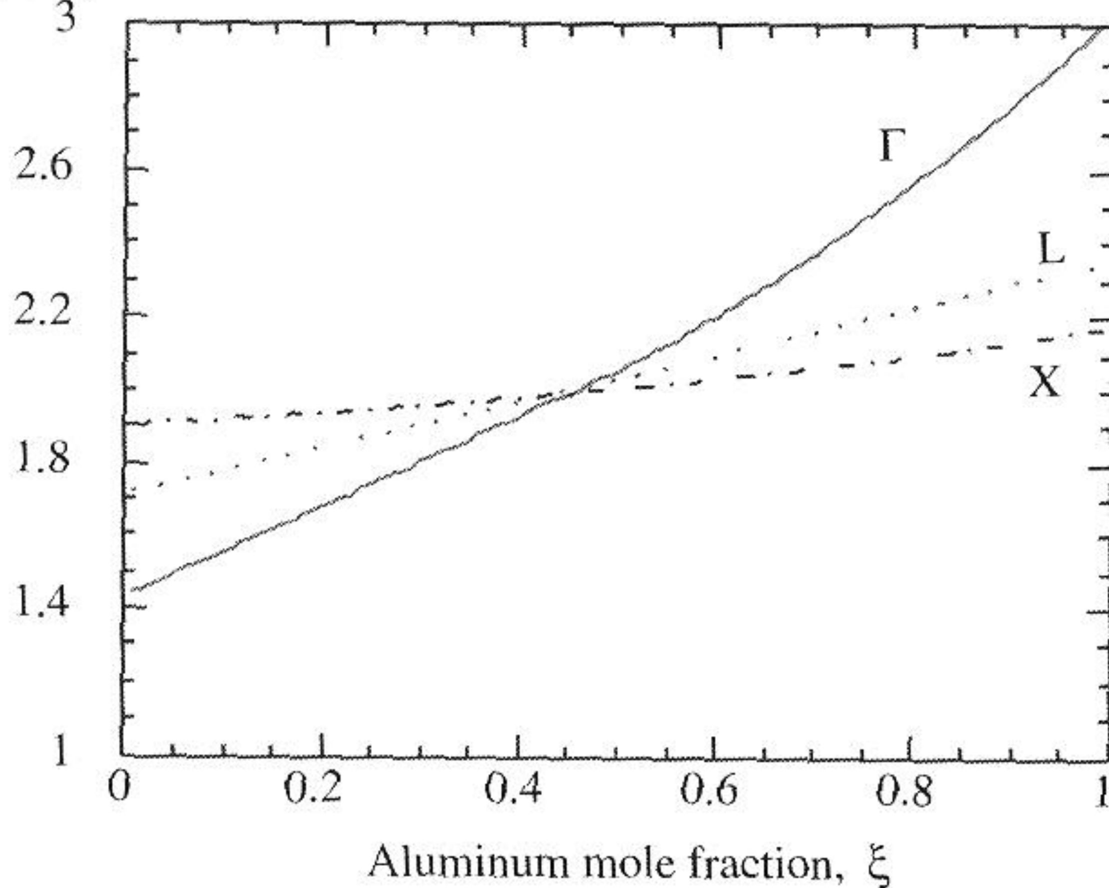
4 atom per layer!

(From Streetman, Solid State Electronic Devices)

Band gaps

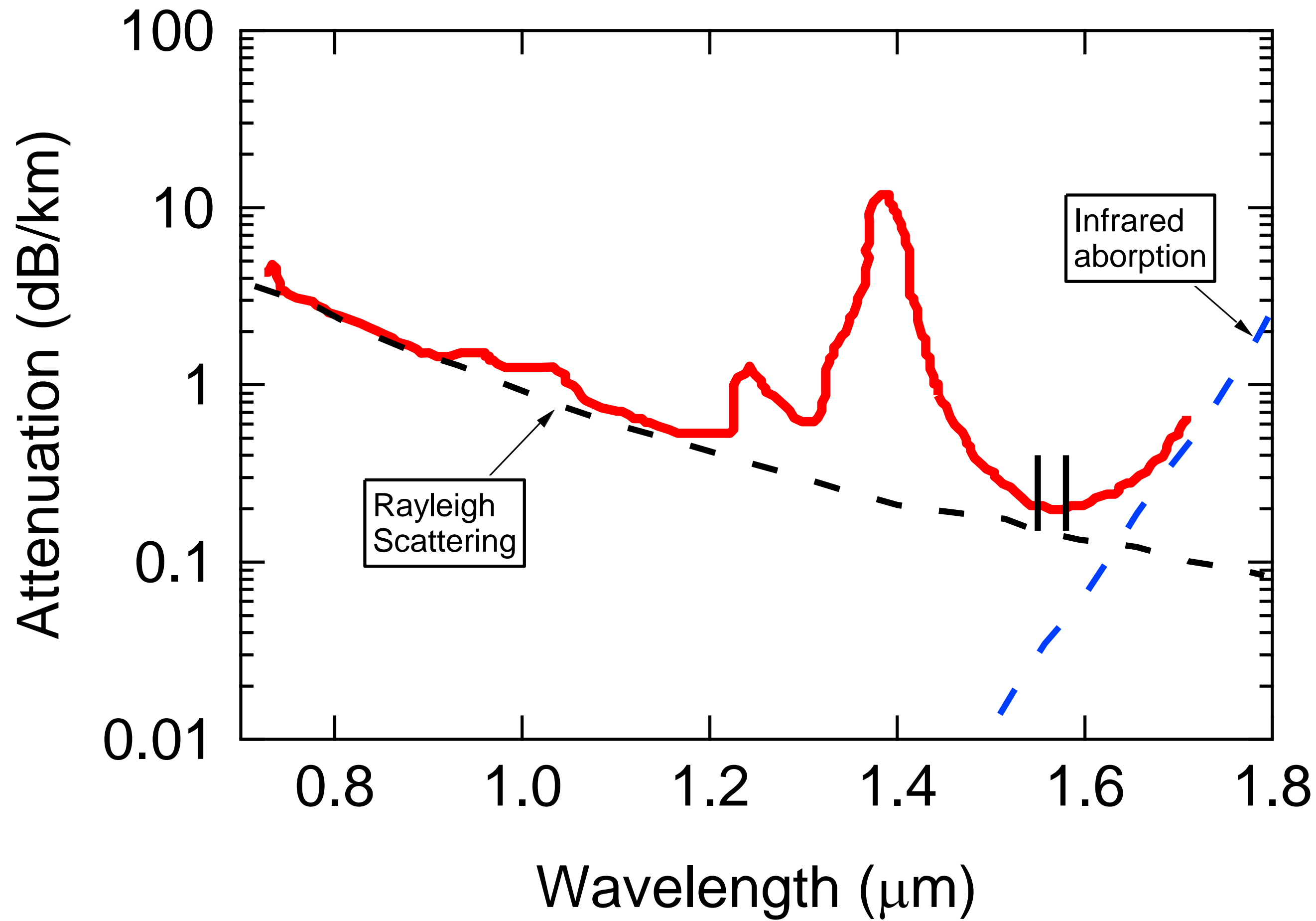


Band gap engineering



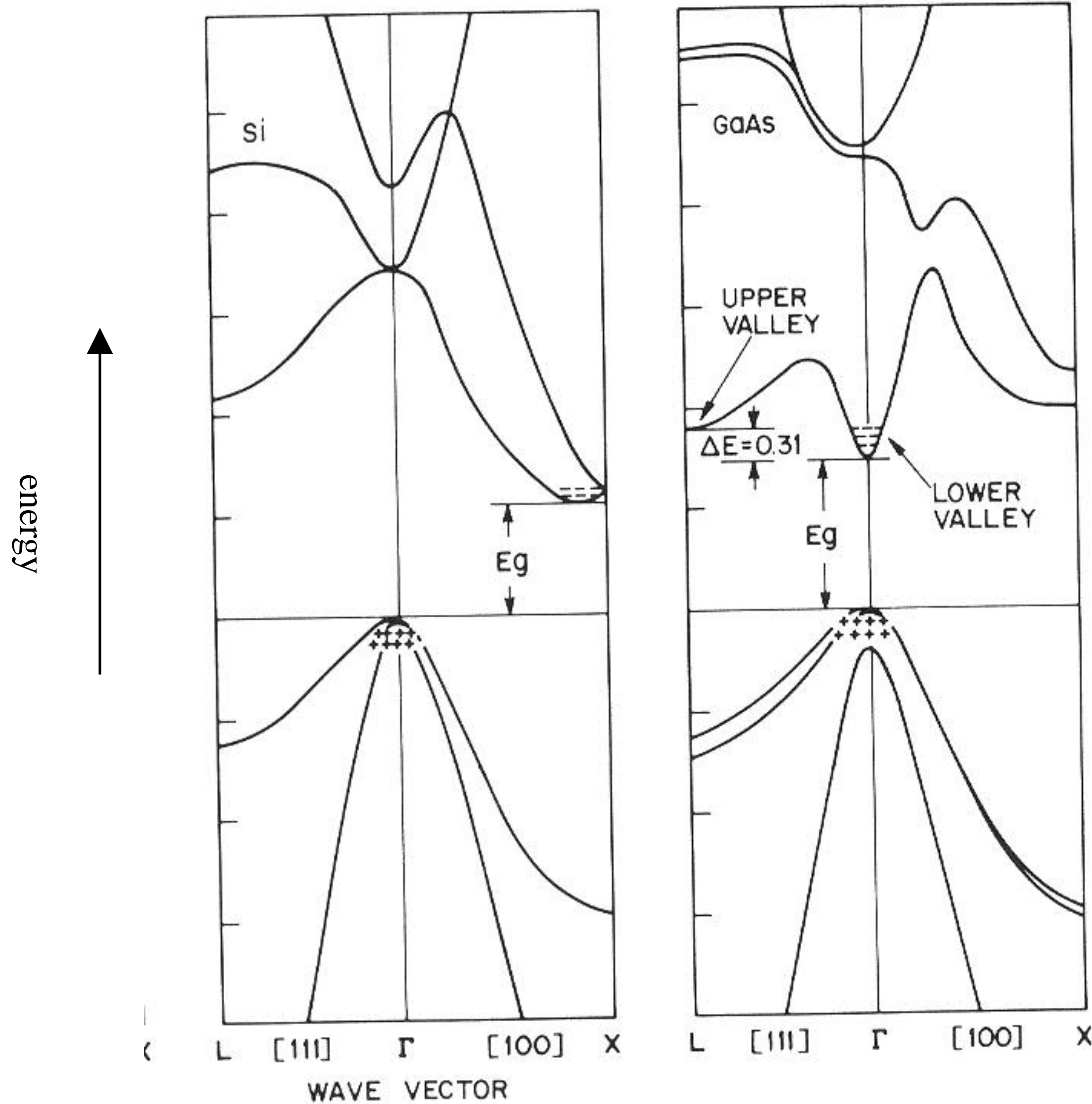
From Liu

Optics



(Adapted from Streetman, Solid State Electronic Devices)

Realistic dispersion curves

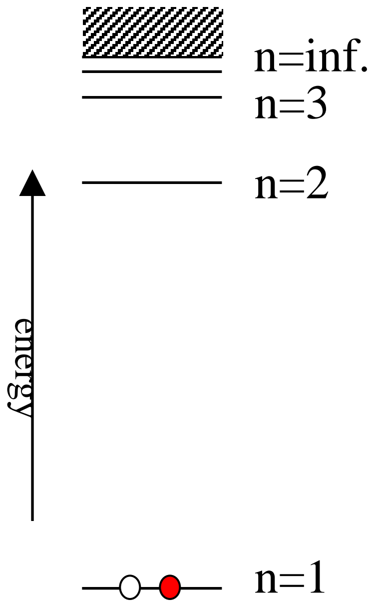


From Sze, Physics of Semiconductor Devices

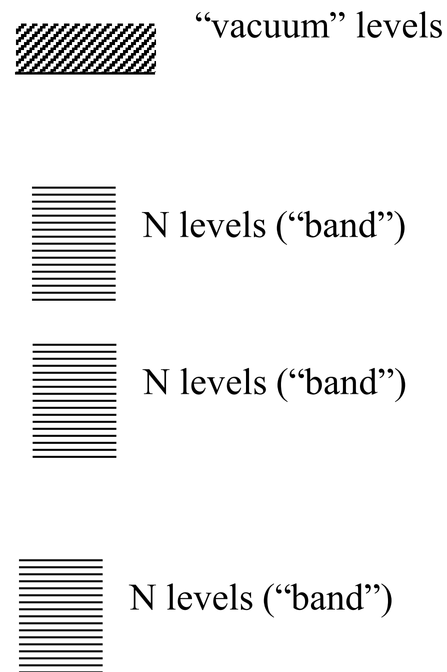
Heterojunctions

"Vacuum level"

1 Hydrogen atom:



Solid:



Vacuum level

E_0

"electron affinity"

$e\chi = 4.07$ eV

in GaAs

E_c

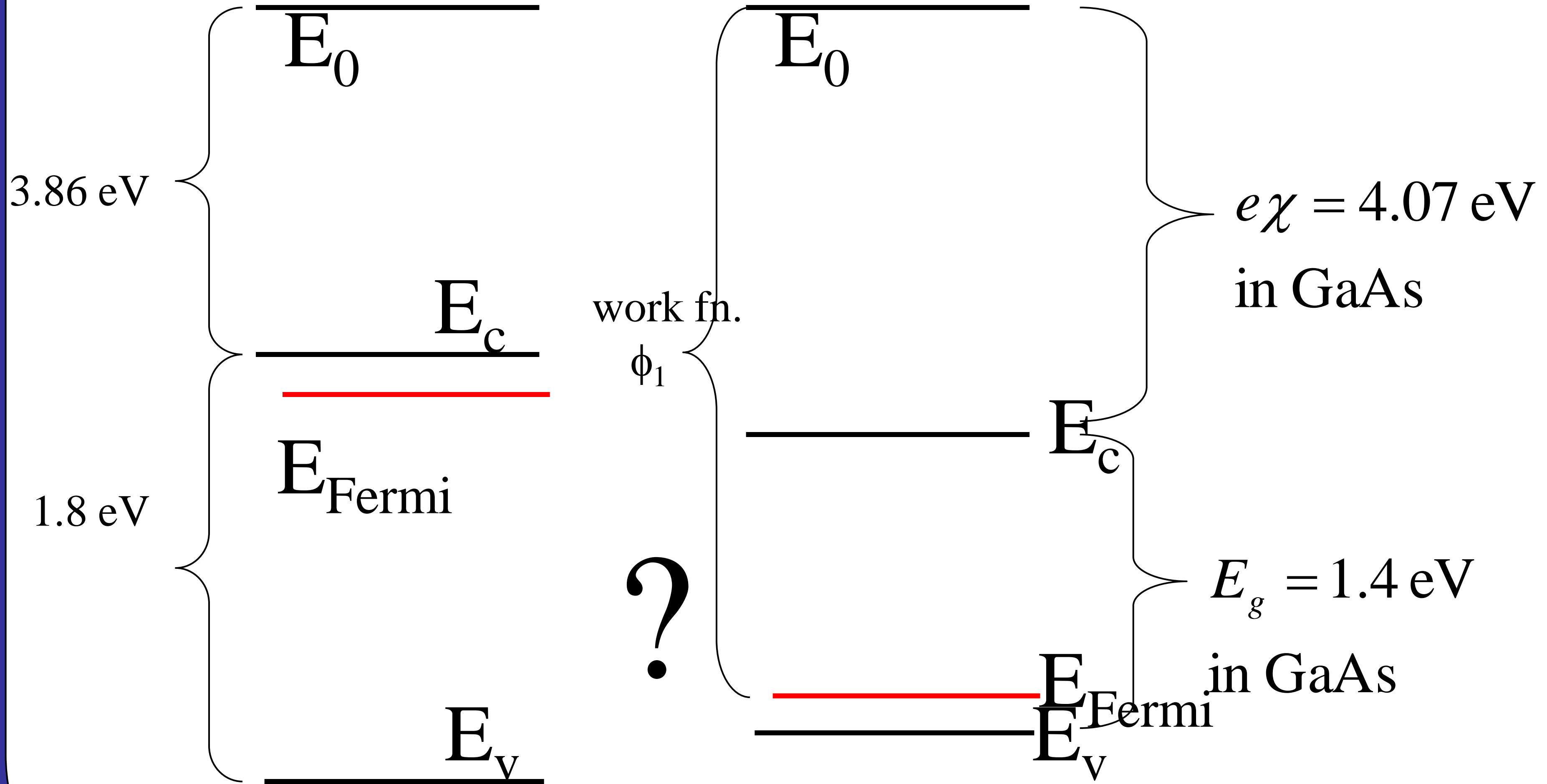
E_{Fermi}

$E_g = 1.4$ eV

in GaAs

E_v

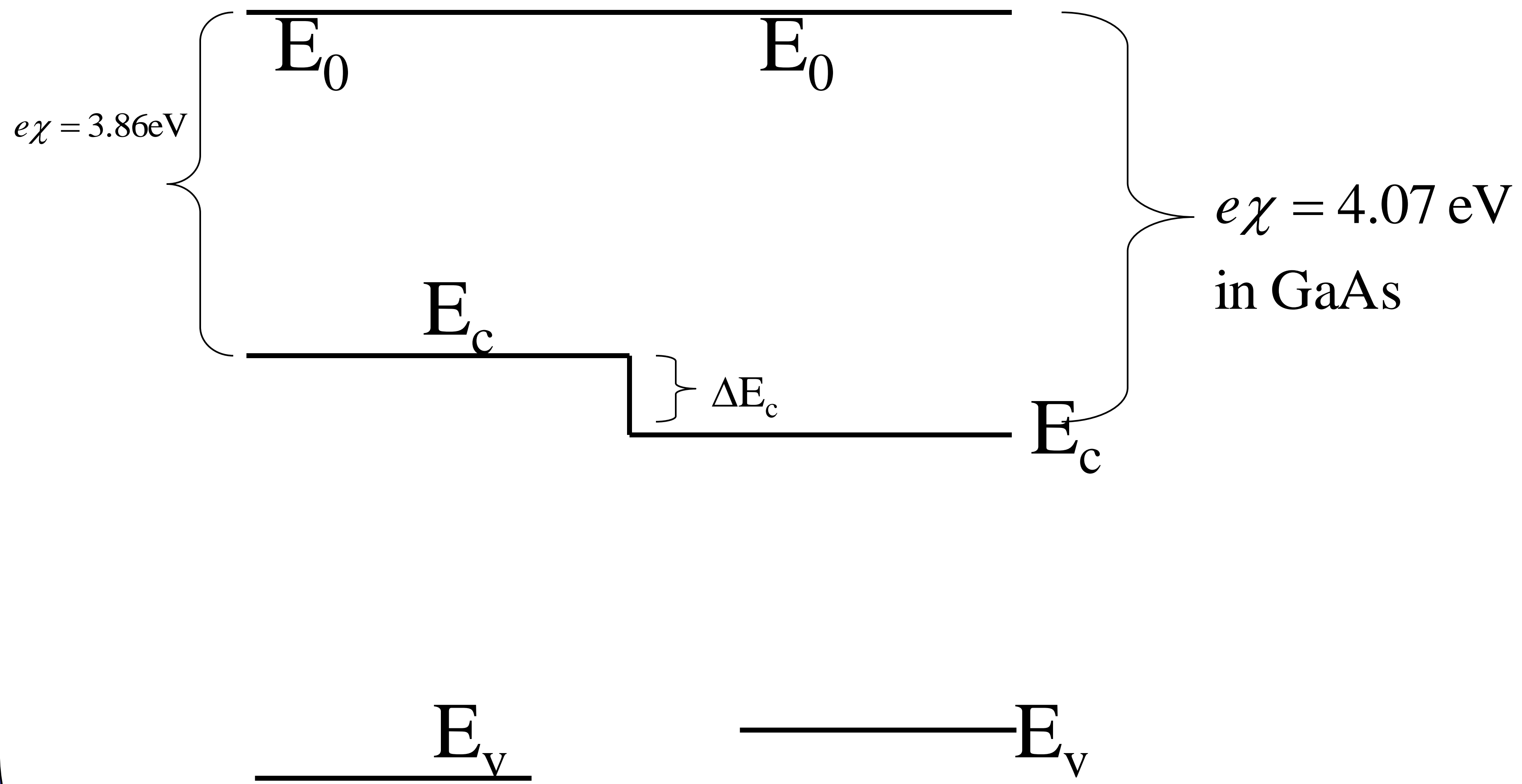
Intrinsic heterojunction



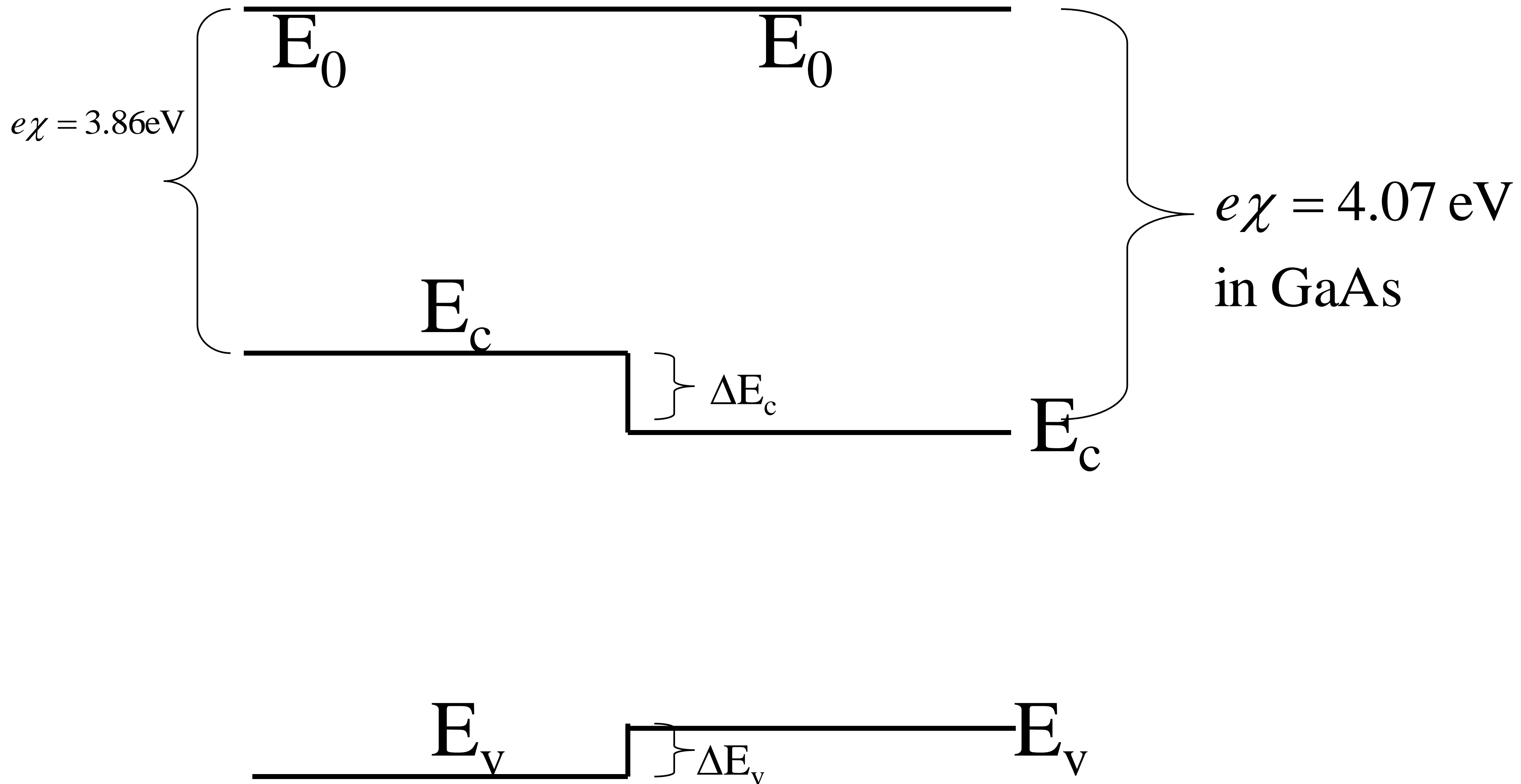
Heterojunction band diagrams

- Determine $\Delta E_c = \chi_1 - \chi_2$ (Vacuum levels line up)
- Determine $\Delta E_v = \Delta E_g - \Delta E_c$
- There will be some charge transfer and built-in electric field/voltage as in p-n homojunction
- Built in voltage $\phi = \phi_1 - \phi_2$
- Draw the diagram (You will in HW#2)
- p-N: capital letter is larger gap side

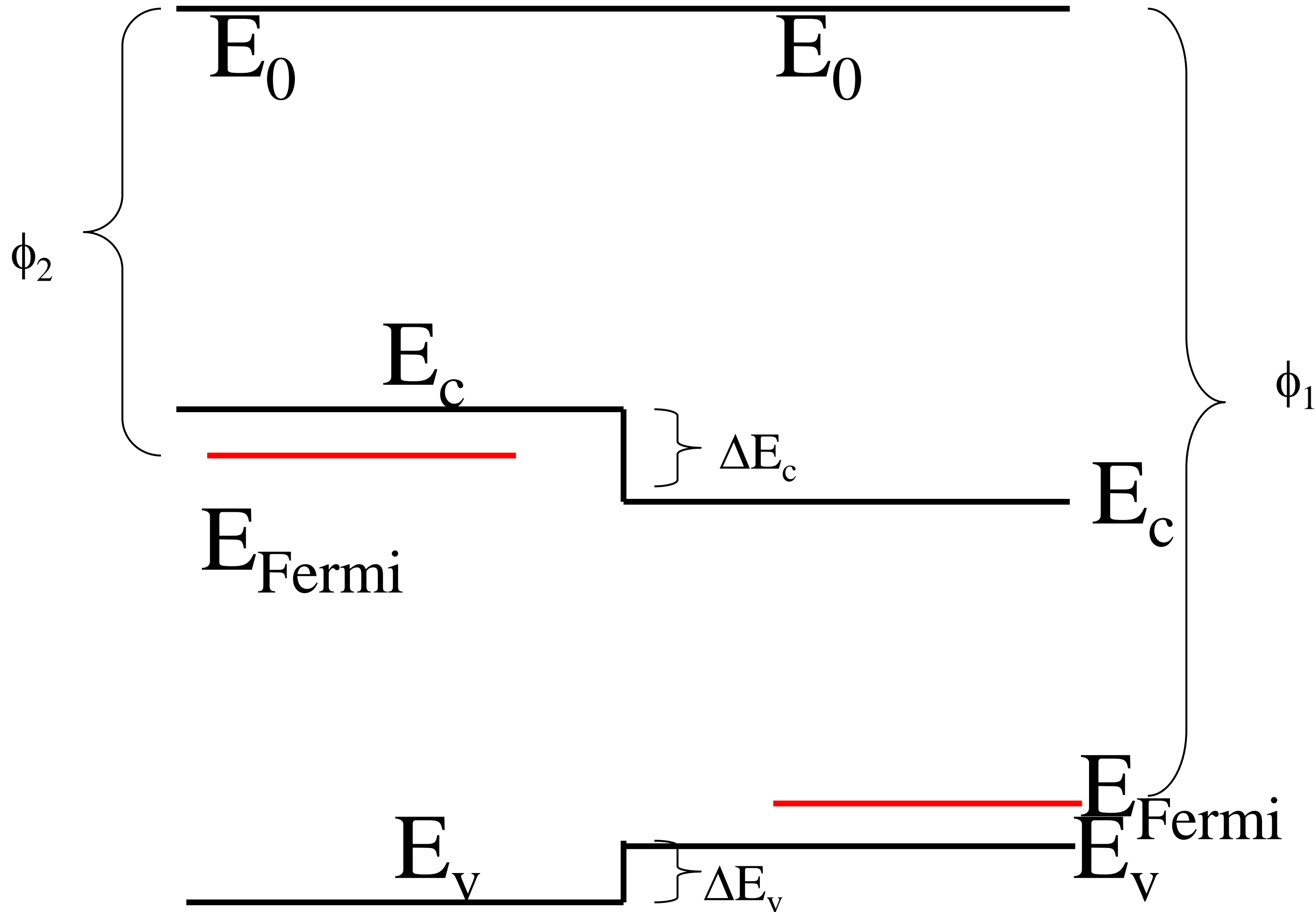
Determine $\Delta E_c = \chi_1 - \chi_2$



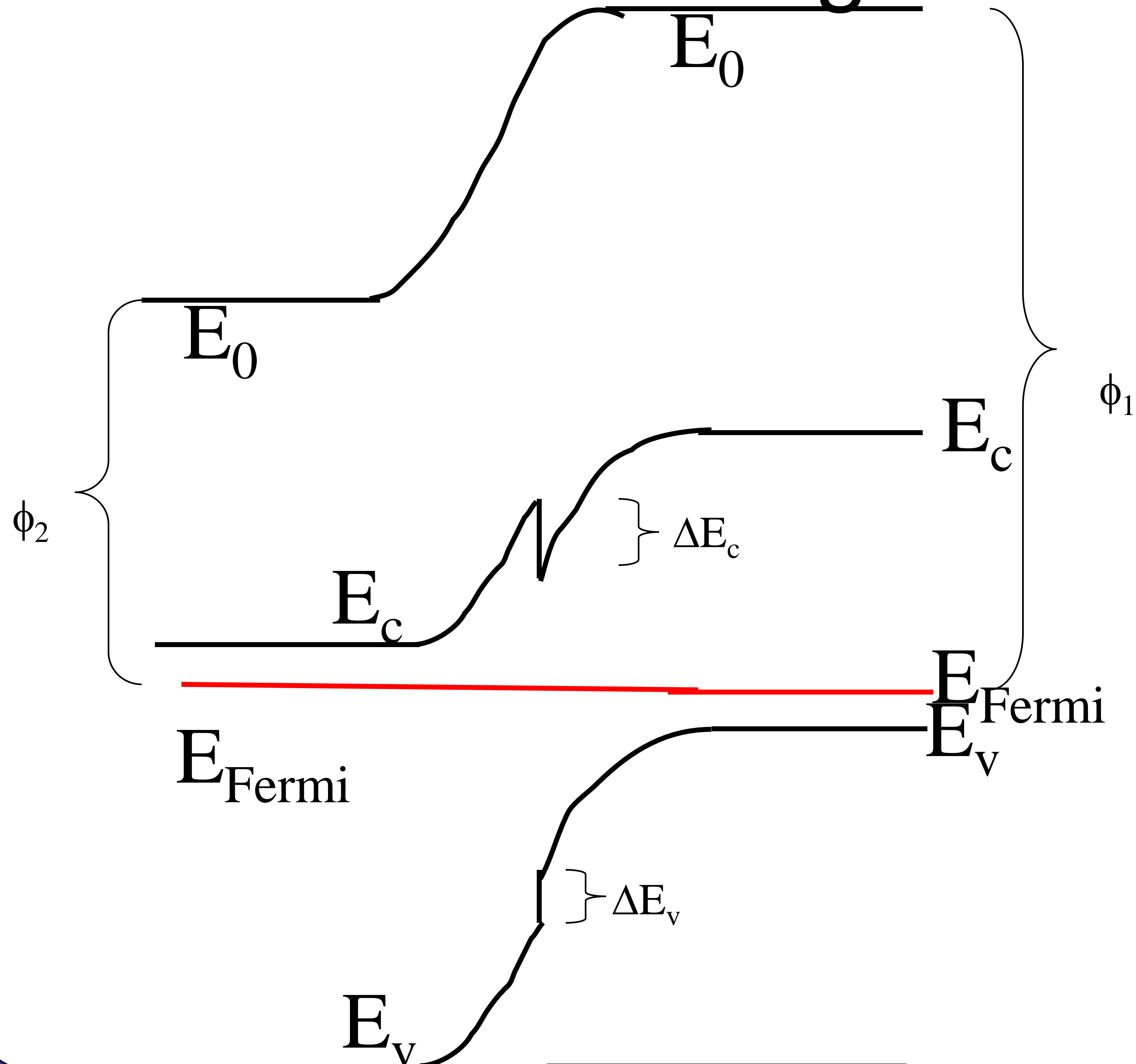
Determine $\Delta E_v = \Delta E_g - \Delta E_c$



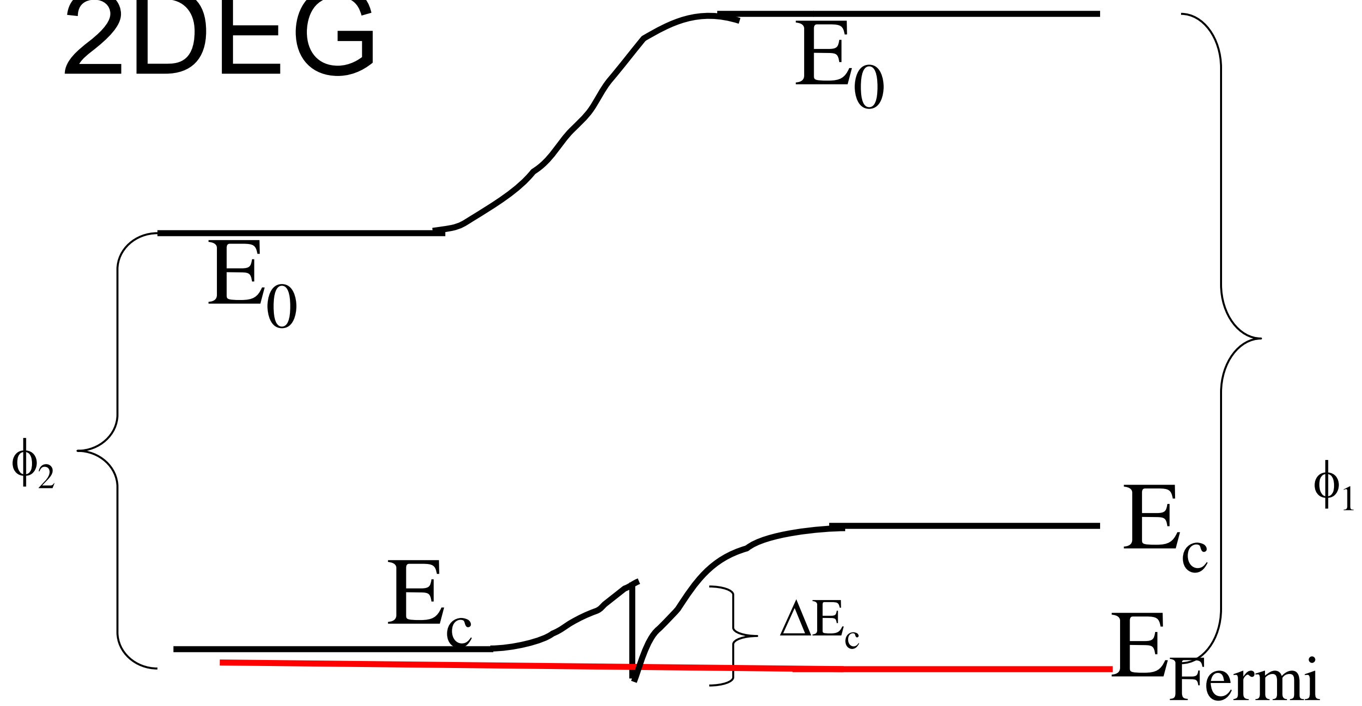
Built in voltage $\phi = \phi_1 - \phi_2$

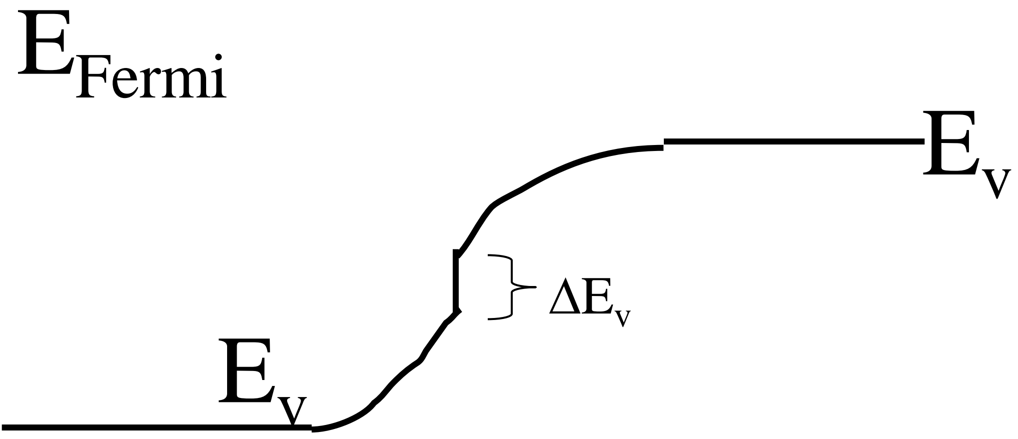


Draw the diagram

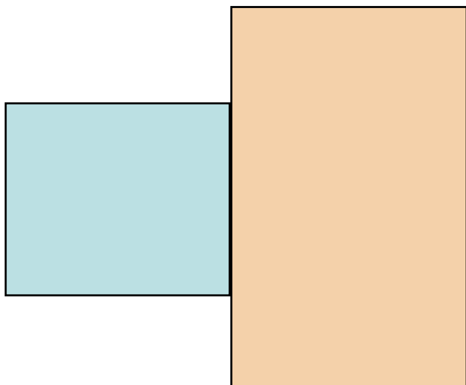
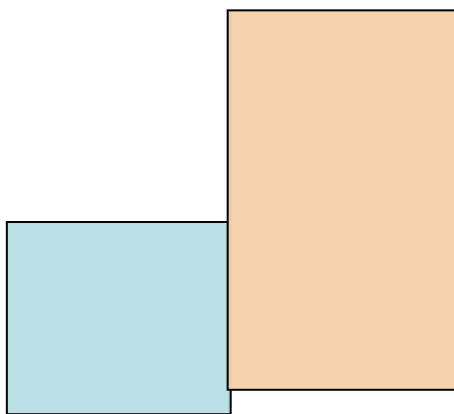
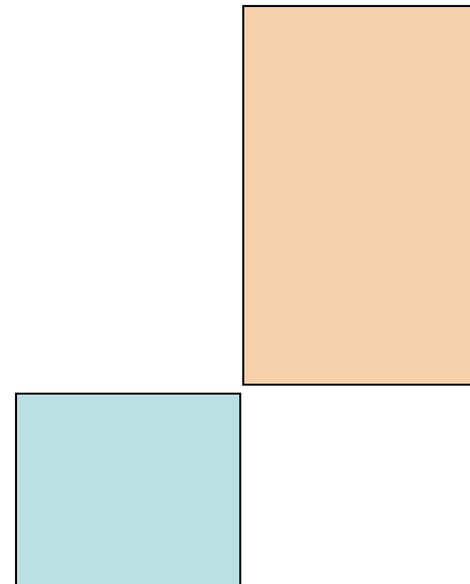


2DEG





Types

I	II	III
		
most common	less common	Only GaSb-InAs

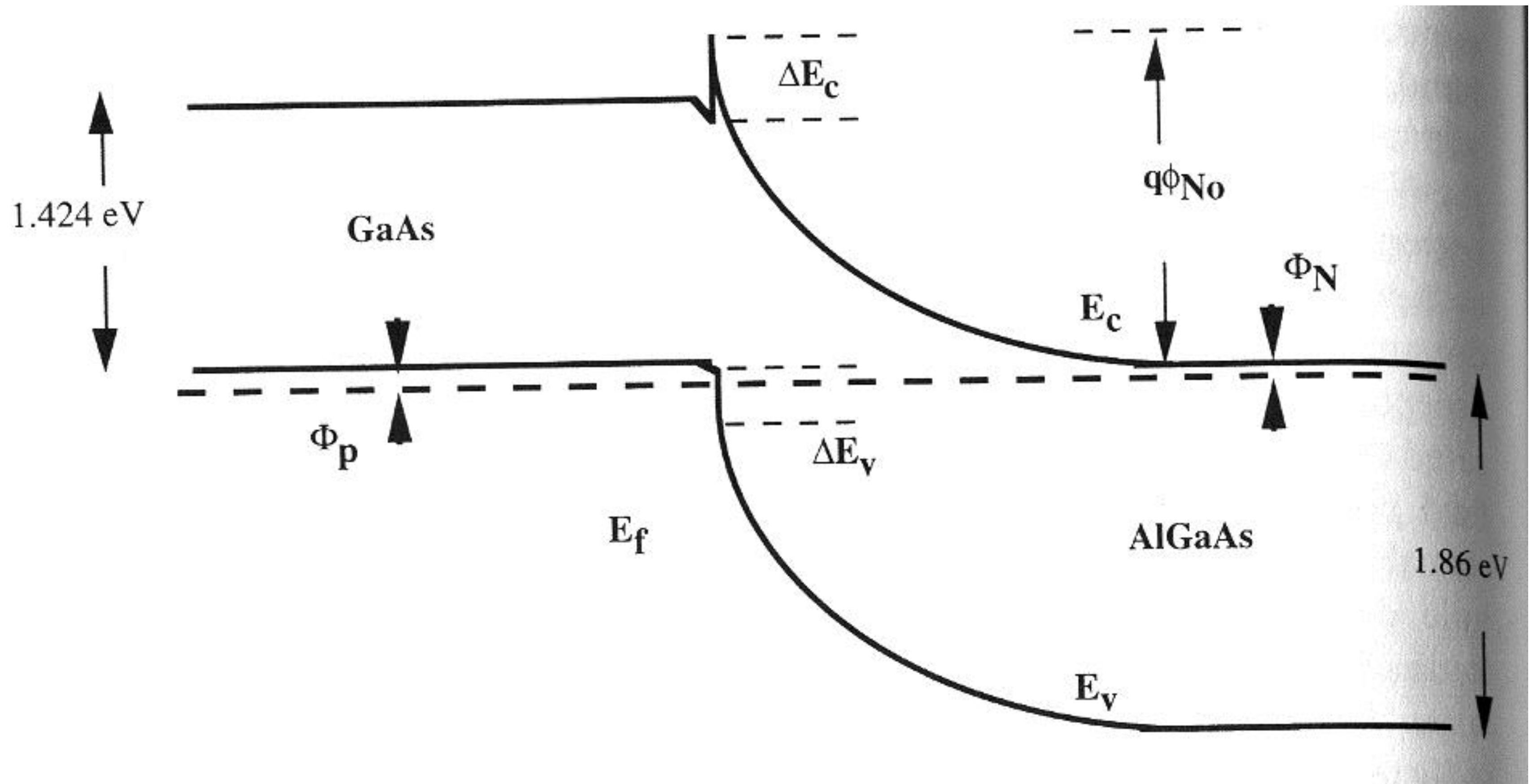
Under bias

- Same as p-n homojunction, except for discontinuity in gaps (important for HBT)
- Still have "space charge" or "depletion" region (different dielectric constants in Poisson equation)
- p^+ N most common (because HBT)
- OR: p N^+
- OR: P^+ n
- OR: P n^+

p^+ N

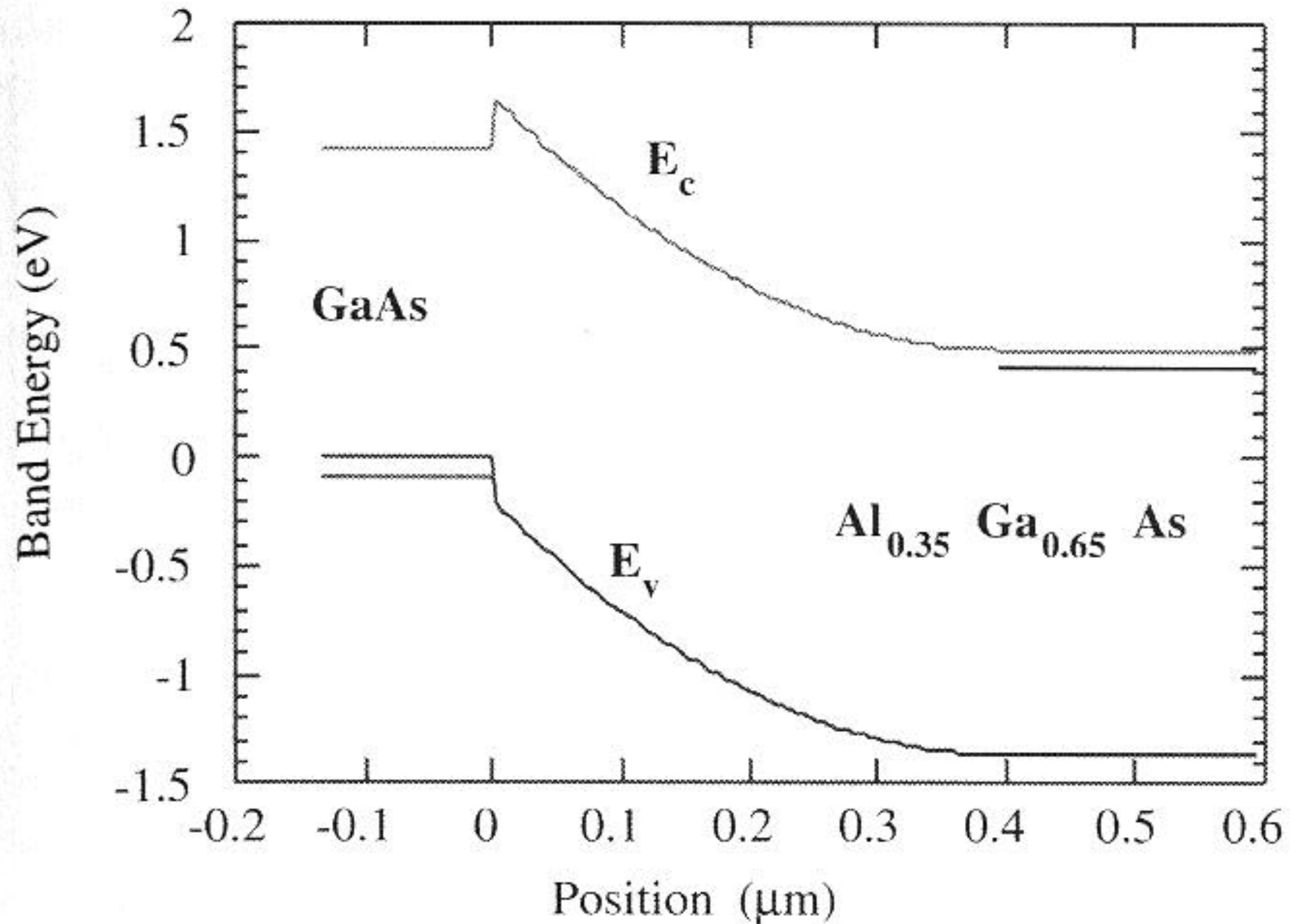
- Band diagram at V=0 from Liu 2.2
- Band diagram at V>0 from Liu 2.11
- Band diagram at V<0 from Liu 2.12
- Be sure to discuss asymmetry

p^+ N at V=0



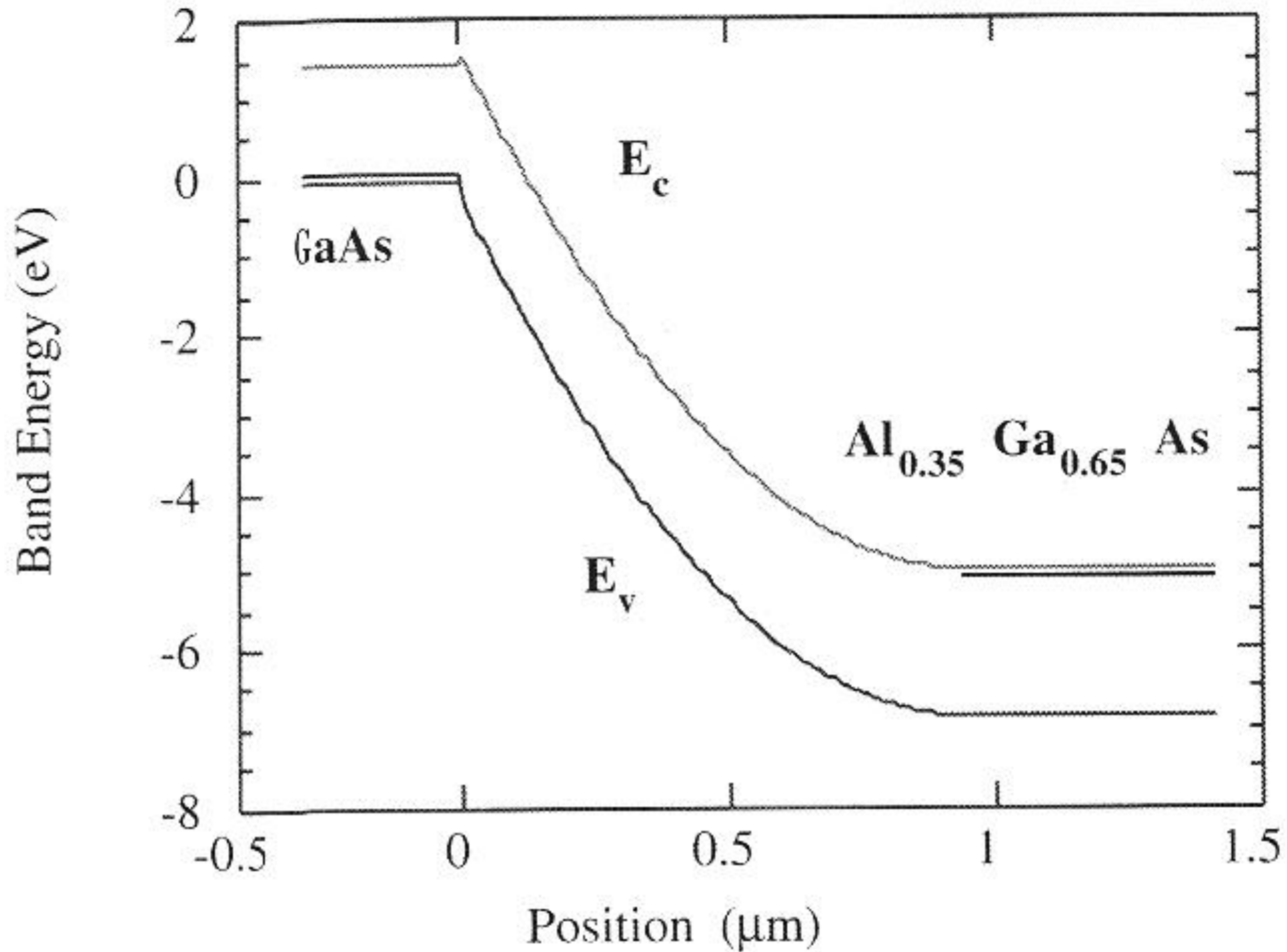
From Liu

p^+ N at V>0



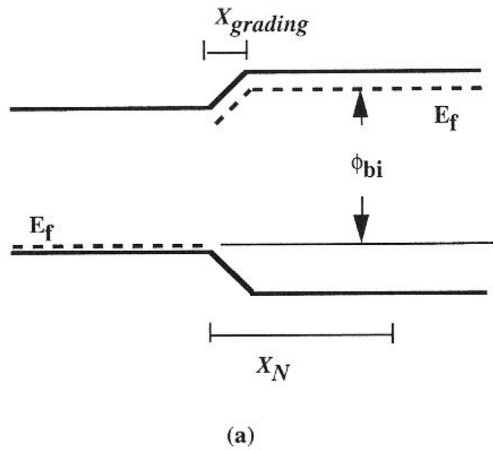
From Liu

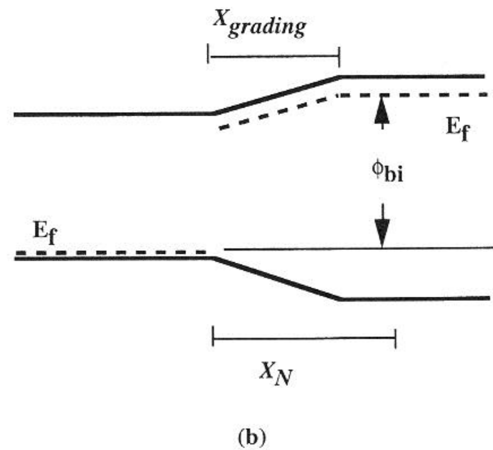
p^+ N at V<0

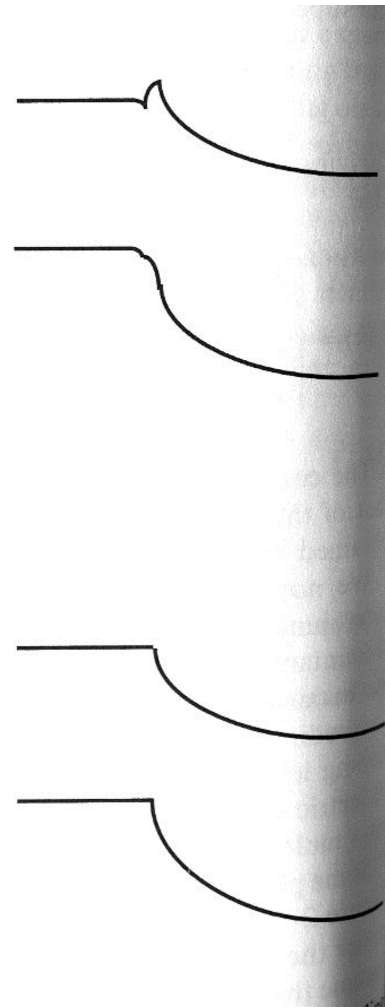


From Liu

Graded heterojunctions

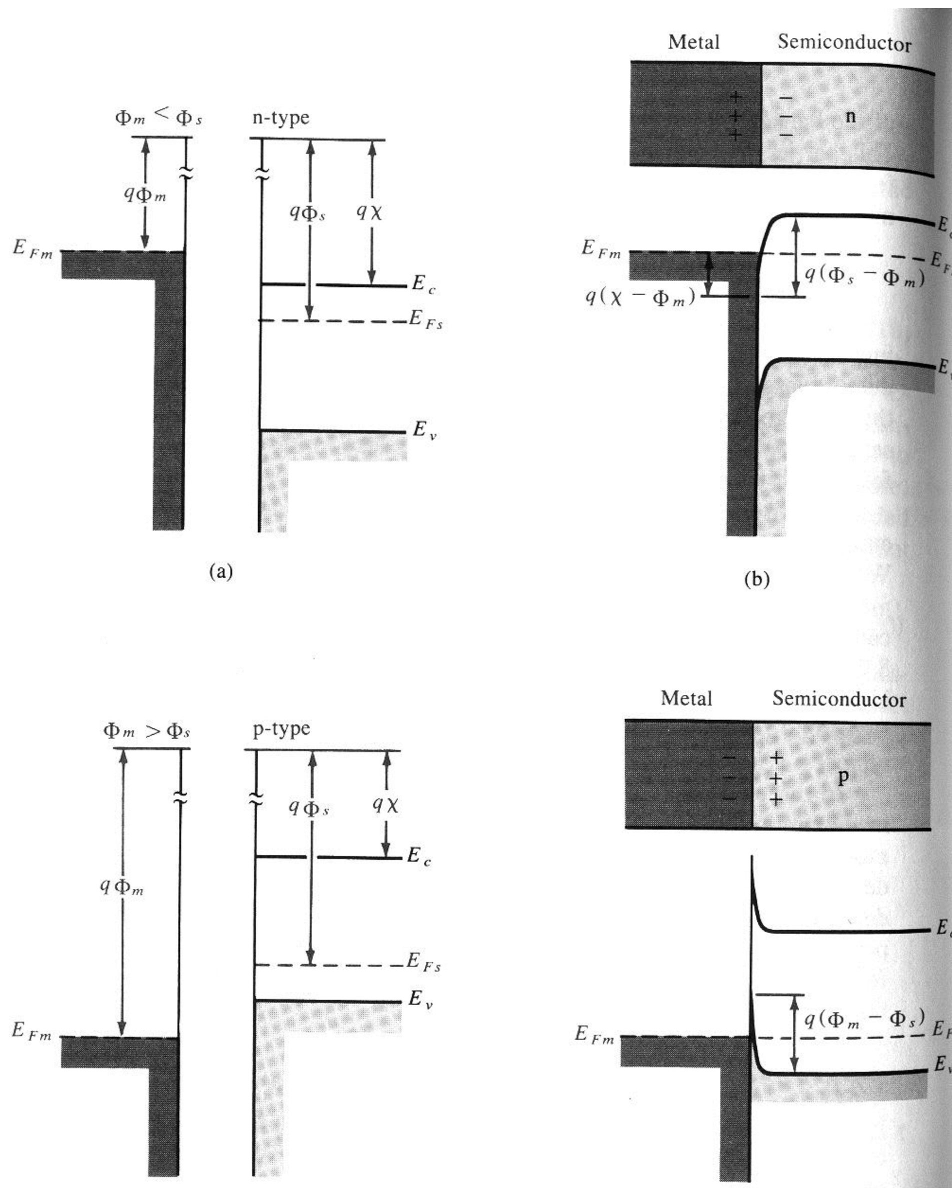






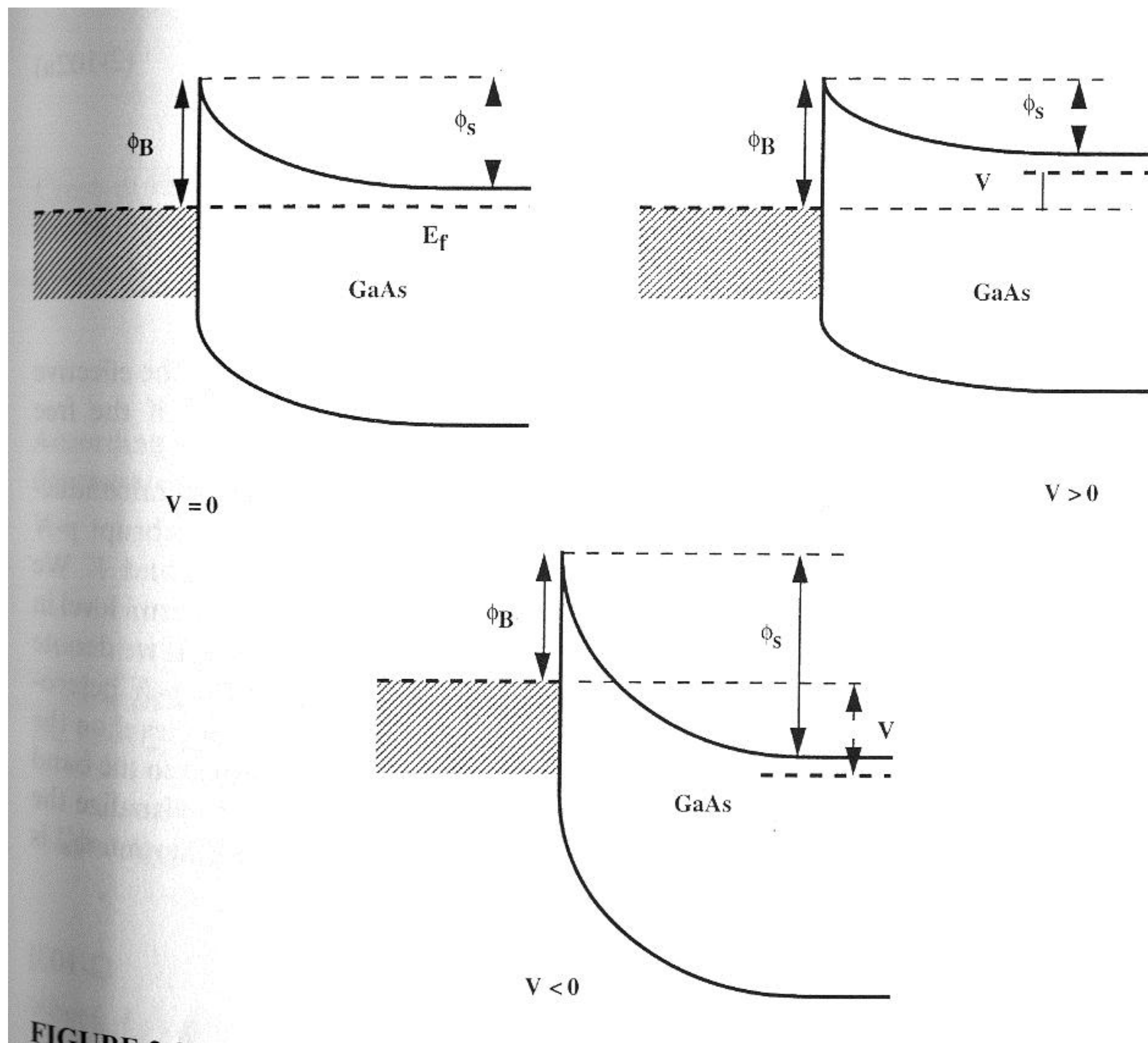
From Liu

Schottky barriers



From Streetman

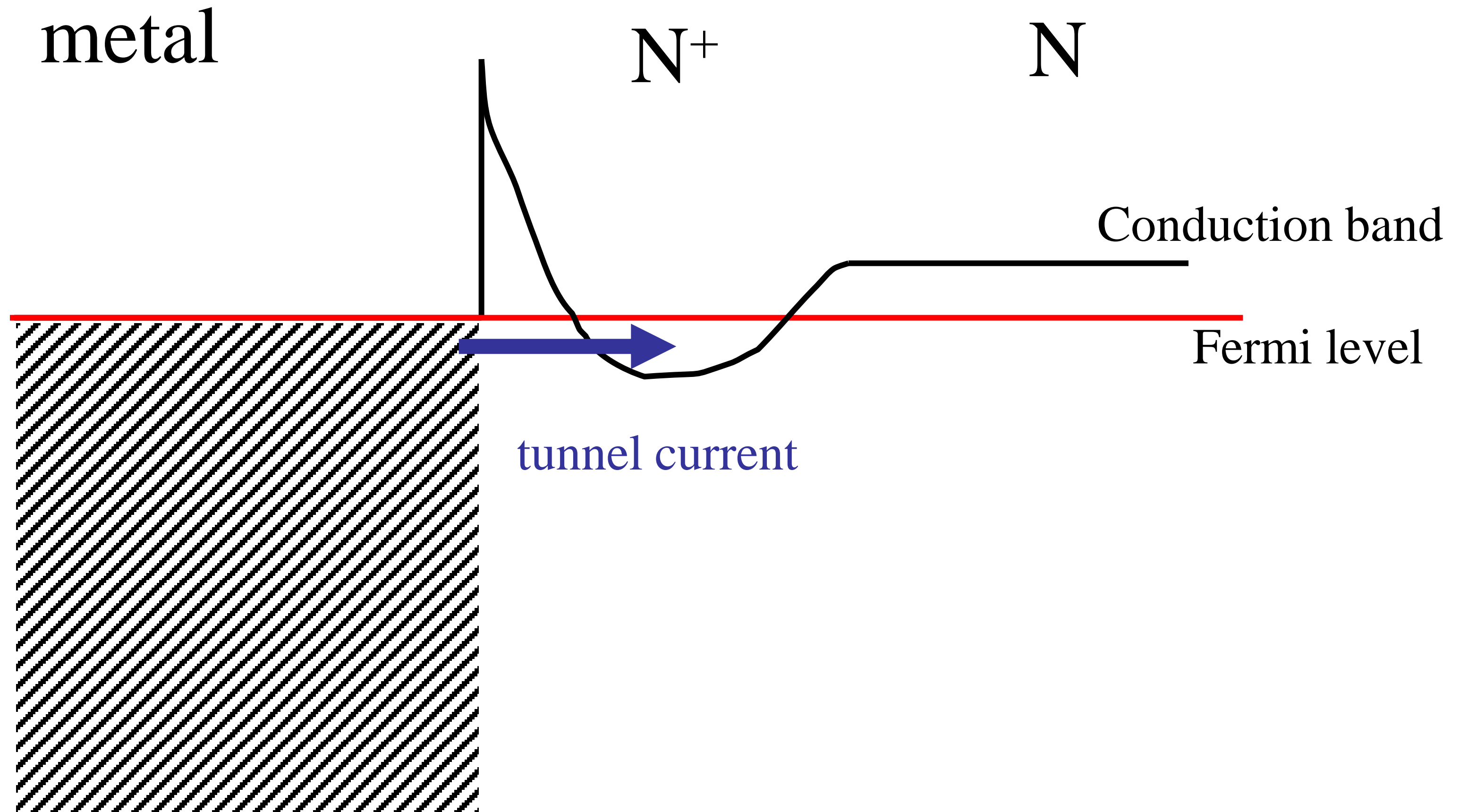
Schottky barriers



From Liu

Ohmic contact

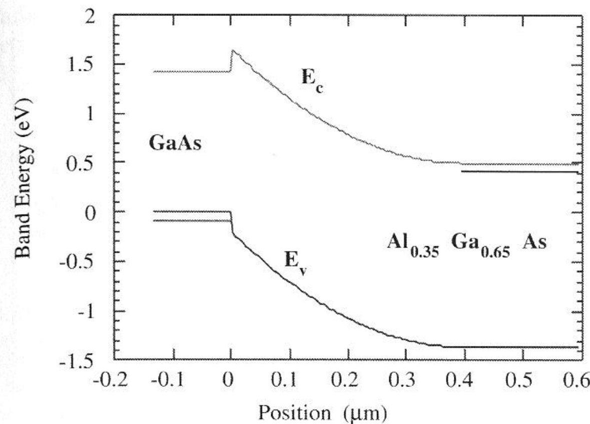
Not on HW but obviously very important in real life.



Ohmic contact

- Not always contacting bulk (e.g. 2DEG)
- A technique to improve: anneal
  Metal diffuses into semiconductor
- Experimental science
- Typically 400-450 C for 30 sec. to 10 min.
- Rapid anneal better
- Au/Ni/Ge best for GaAs
- Typically 10^{-6} ohm-cm^2
  (discuss units on board)

p+ N I-V curve



From Liu

As in p-n homojunction:
Diffusion current: Electrons with energy > eV_0
Exponentially increased. (Explain).
Drift current :not really effected.

$$I = I_{diffusion} - |I_{drift}|$$

exponentially larger (points to $I_{diffusion}$)

about the same (points to I_{drift})

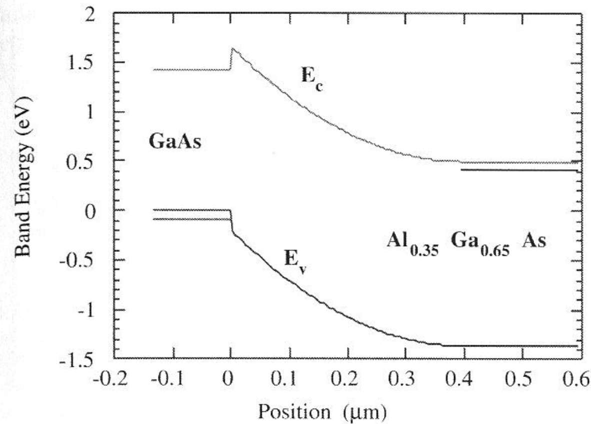
$$I = I_0\left(e^{qV/kT} - 1\right) \rightarrow I_0\left(e^{qV_n/kT} - 1\right)$$

But only voltage drop across N region matters

$$I = I_0\left(\exp\left[\frac{qV}{kT}\frac{1}{1+K}\right] - 1\right)$$

$$K = \frac{\varepsilon_N N_d}{\varepsilon_p N_a}$$

Grated p^+ N I-V curve



From Liu

As in p-n homojunction
but MORE CURRENT

$$I = I_{diffusion} - |I_{drift}|$$

exponentially larger

about the same

$$I = I_0\left(e^{qV/kT} - 1\right)$$

I_0 larger in grated p^+N than in abrupt p^+N.