

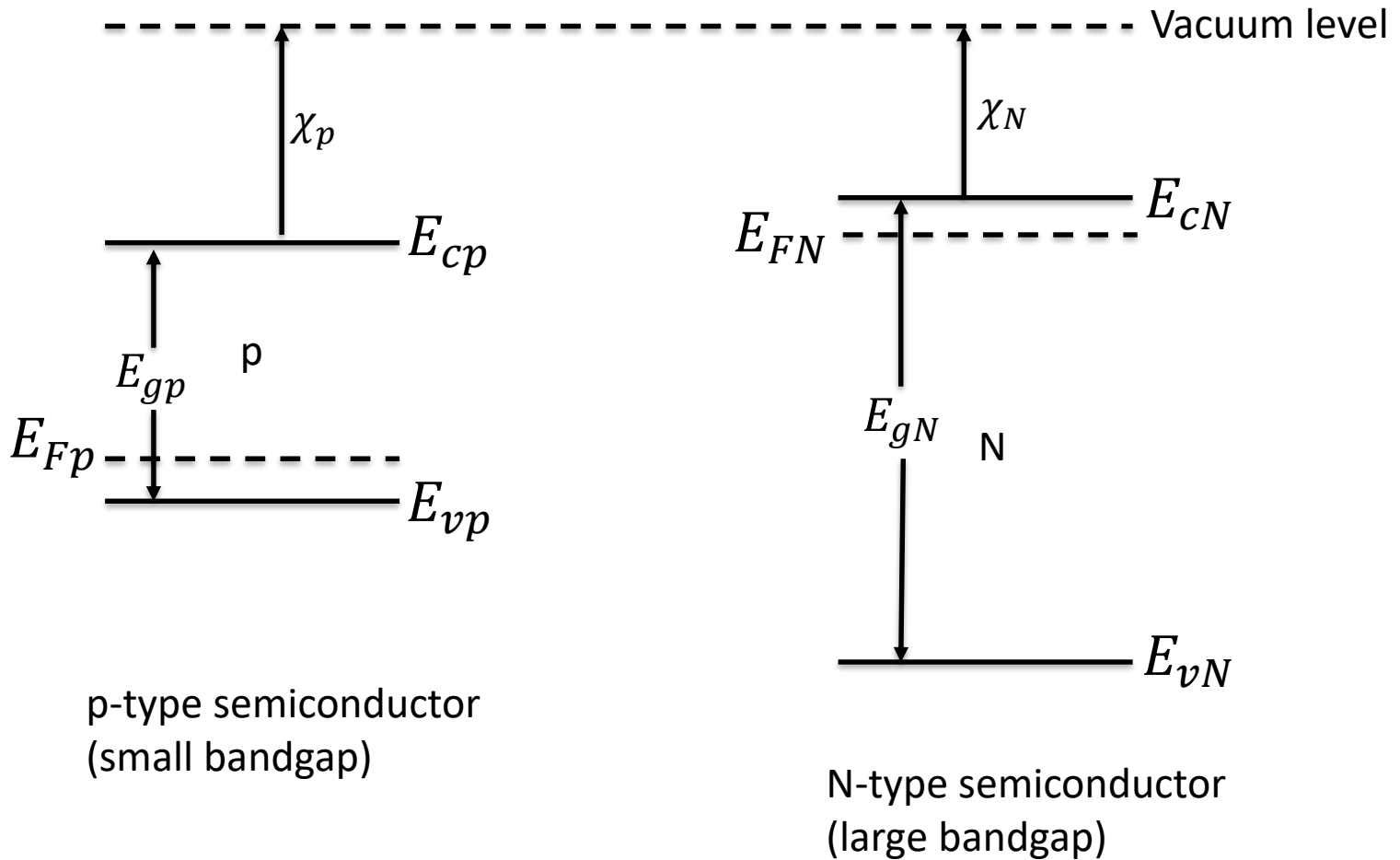
EE 232: Lightwave Devices

Lecture #4 – Heterojunction Devices

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p-N heterojunction



Type I Band Alignment

p-N heterojunction

$$\Delta E_g = E_{gN} - E_{gp}$$

(Anderson Model) $\Delta E_c = \chi_p - \chi_N$

$$\Delta E_v = \Delta E_g - (\chi_p - \chi_N)$$

(Empirical)

AlGaAs/GaAs system

$$\Delta E_c \cong 0.67\Delta E_g$$

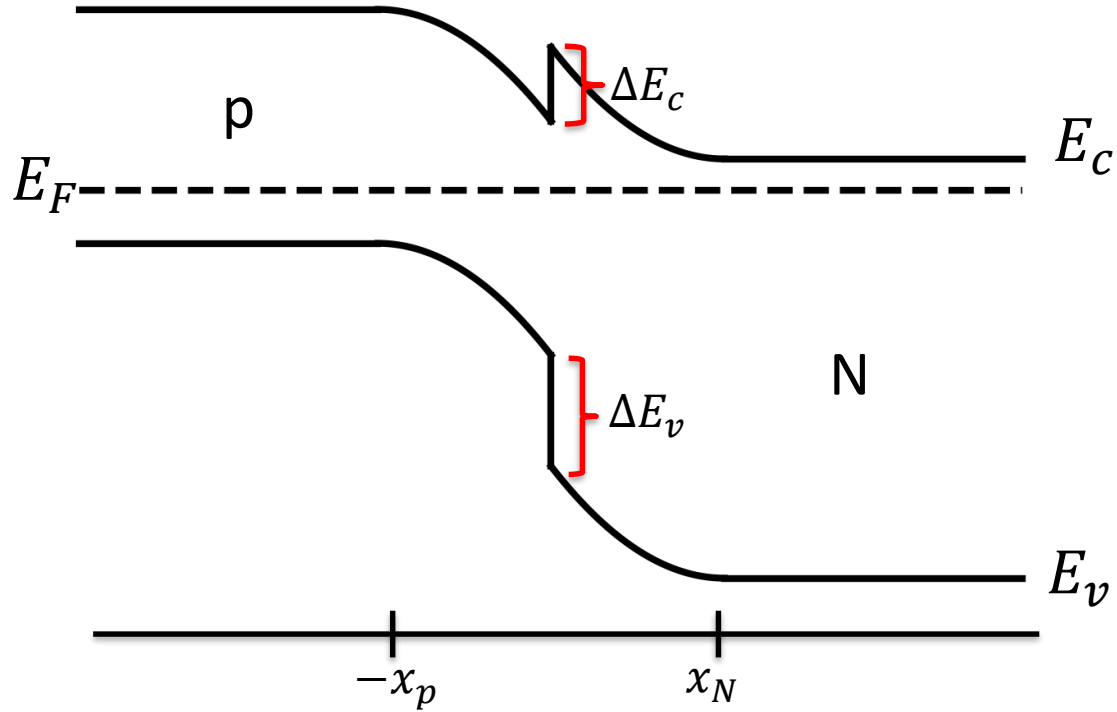
$$\Delta E_v \cong 0.33\Delta E_g$$

InP/InGaAs system

$$\Delta E_c \cong 0.4\Delta E_g$$

$$\Delta E_v \cong 0.6\Delta E_g$$

p-N heterojunction



p-N heterojunction (electric-field)

$$\nabla \cdot (\epsilon \mathbf{E}) = \rho(x) \quad (\text{Gauss's Law})$$

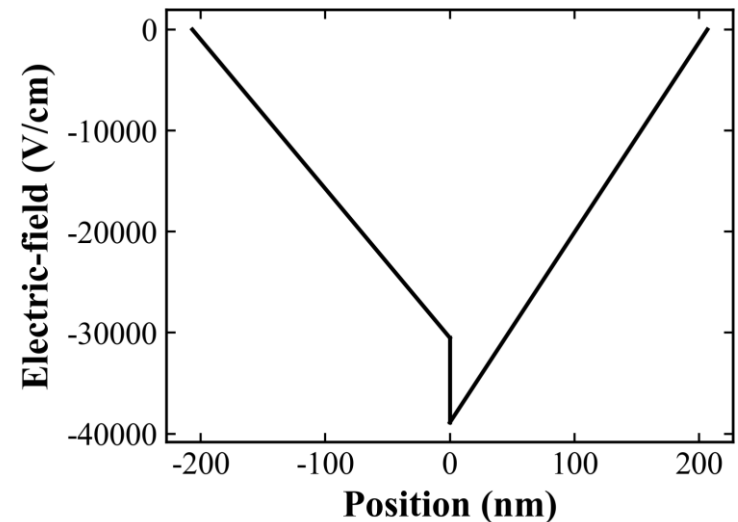
$$\rho(x) = \begin{cases} -qN_A & -x_p < x < 0 \\ qN_D & 0 < x < x_N \end{cases}$$

(Depletion approximation)

$$\frac{d}{dx} E(x) = \begin{cases} \frac{-qN_A}{\epsilon_p} & -x_p < x < 0 \\ \frac{qN_D}{\epsilon_N} & 0 < x < x_N \end{cases}$$

$$E(x) = \begin{cases} \frac{-qN_A}{\epsilon_p} (x + x_p) & -x_p < x < 0 \\ \frac{qN_D}{\epsilon_N} (x - x_N) & 0 < x < x_N \end{cases}$$

Using B.C. $E(x = -x_p) = E(x = x_N) = 0$

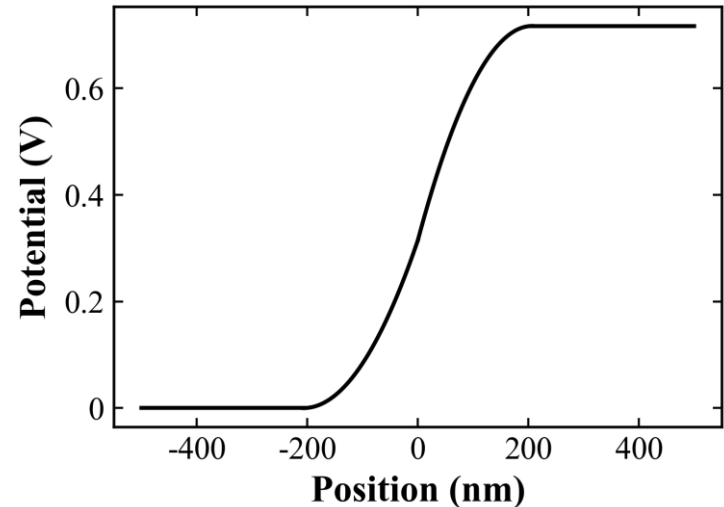


p-N heterojunction (potential)

$$-\nabla\phi(x) = E(x) \quad (\text{Poisson eqn.})$$

$$\text{Let } \phi(-x_p) = 0$$

$$\phi(x) = \begin{cases} 0 & x < -x_p \\ \frac{qN_A}{2\epsilon_p}(x+x_p)^2 & -x_p < x < 0 \\ \frac{qN_A x_p^2}{2\epsilon_p} + \frac{qN_D}{2\epsilon_N}(2xx_N - x^2) & 0 < x < x_N \\ V_0 & x > x_N \end{cases}$$



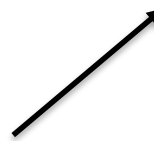
$$V_0 = V_{op} + V_{oN} = \frac{qN_A x_p^2}{2\epsilon_p} + \frac{qN_D x_N^2}{2\epsilon_N}$$

$$\text{Since } N_A x_p = N_D x_N$$

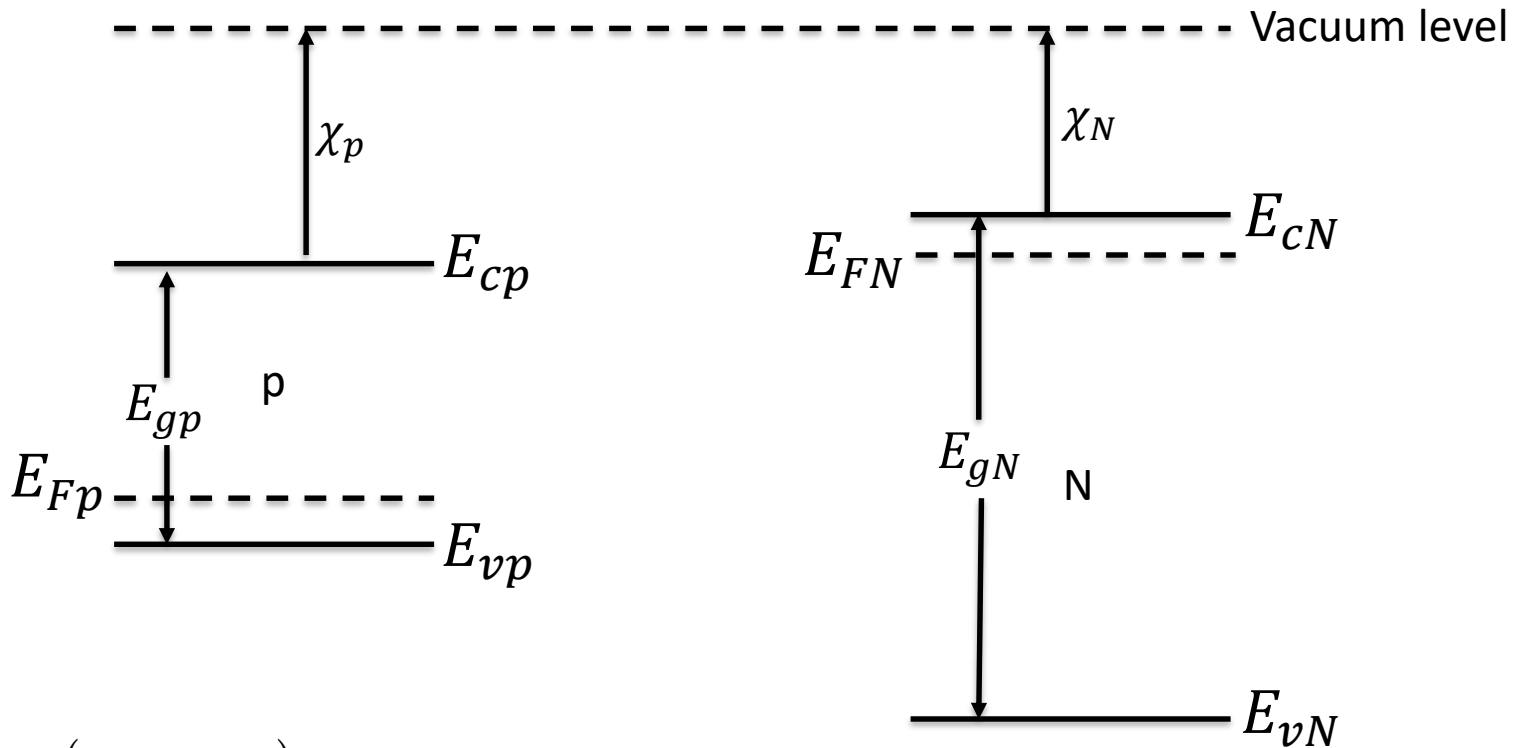
$$V_0 = \frac{qN_A}{2\epsilon_p} \frac{N_D^2}{(N_A + N_D)^2} x_W^2 + \frac{qN_D}{2\epsilon_N} \frac{N_A^2}{(N_A + N_D)^2} x_W^2$$

$$\text{where } x_W = x_p + x_N$$

$$x_W = \left[\frac{2\epsilon_p V_0}{qN_A N_D \left(N_D + \frac{\epsilon_p}{\epsilon_N} N_A \right)} \right]^{1/2} (N_A + N_D)$$



p-N heterojunction (potential)



$$V_0 = (E_{FN} - E_{Fp}) / q$$

$$= (E_{vp} + E_{gp} + \Delta E_c - (E_{cN} - E_{FN}) - (E_{Fp} - E_{vp})) / q$$

p-N heterojunction (band diagram)

$$n = N_c \exp\left(\frac{E_F - E_c}{kT}\right)$$

$$p = N_v \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$-kT \ln\left(\frac{n}{N_{cN}}\right) = E_{cN} - E_{FN}$$

$$-kT \ln\left(\frac{p}{N_{vp}}\right) = E_{Fp} - E_{vp}$$

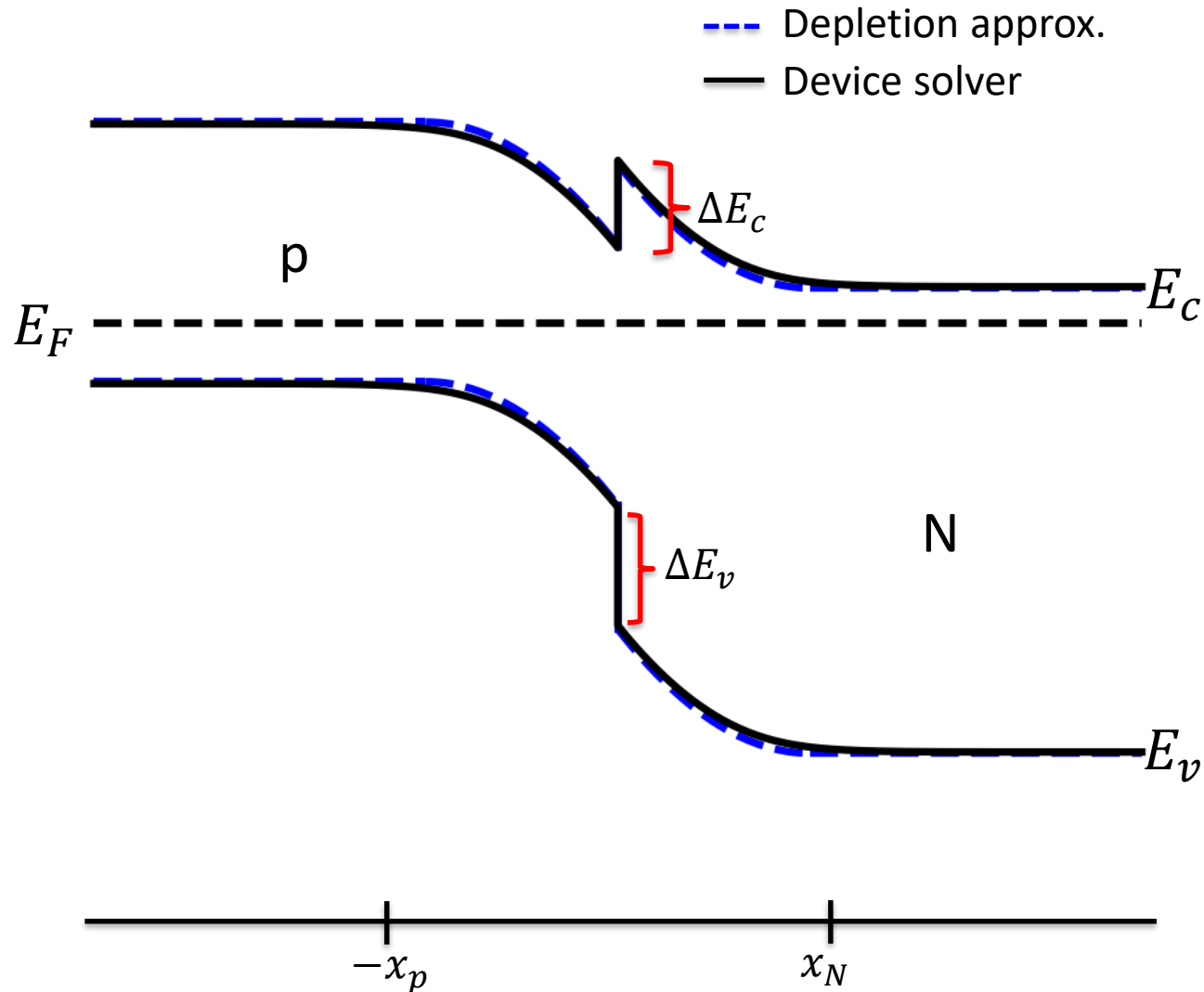
$$\begin{aligned} V_0 &= (E_{vp} + E_{gp} + \Delta E_c - (E_{cN} - E_{FN}) - (E_{Fp} - E_{vp})) / q \\ &= \left[E_{gp} + \Delta E_c + kT \ln\left(\frac{N_D}{N_{cN}}\right) + kT \ln\left(\frac{N_A}{N_{vp}}\right) \right] / q \end{aligned}$$

$$E_v(x) = \begin{cases} -q\phi(x) & \text{p-side} \\ -\Delta E_v - q\phi(x) & \text{N-side} \end{cases}$$

$$E_c(x) = \begin{cases} E_{gp} + E_v(x) & \text{p-side} \\ E_{gN} + E_v(x) & \text{N-side} \end{cases}$$

We are done, we have everything we need to understand the band diagram

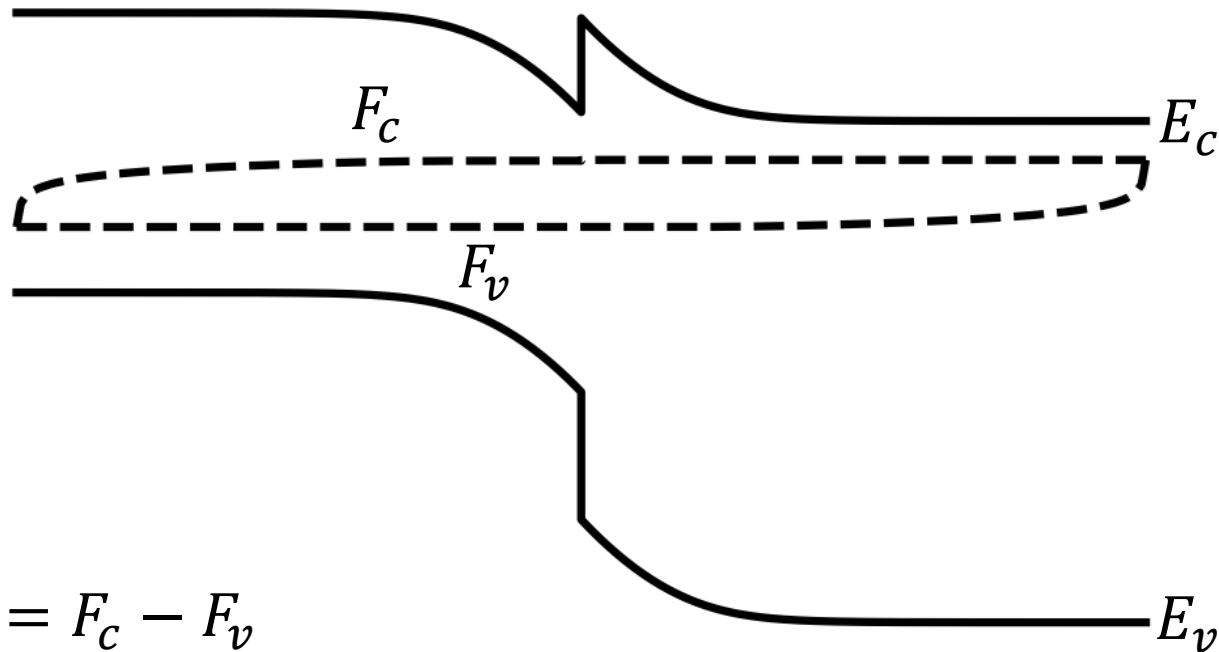
p-N heterojunction (band diagram)



p-N heterojunction (low bias)

$$J = q \left(\frac{D_n}{W_n} n_{p0} + \frac{D_p}{W_p} p_{N0} \right) (e^{qV_A/kT} - 1)$$

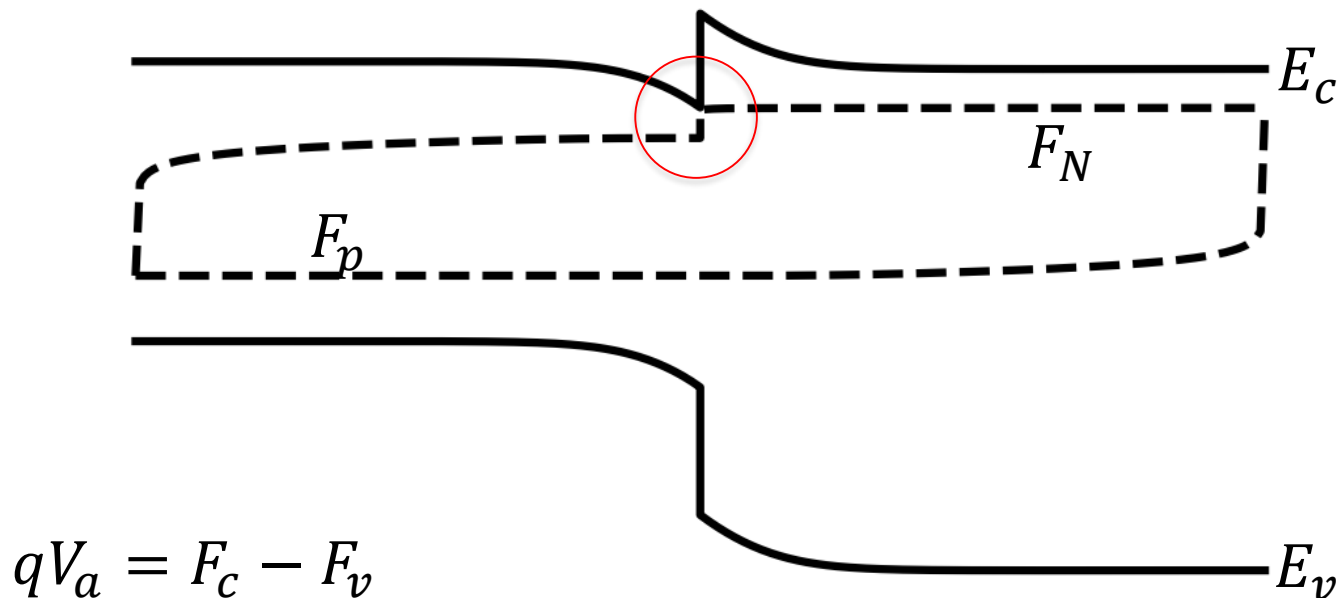
Assuming “Law of Junction” applies
(i.e. flat quasi-Fermi level in junction)
see Chuang pg 66



$$qV_a = F_c - F_v$$

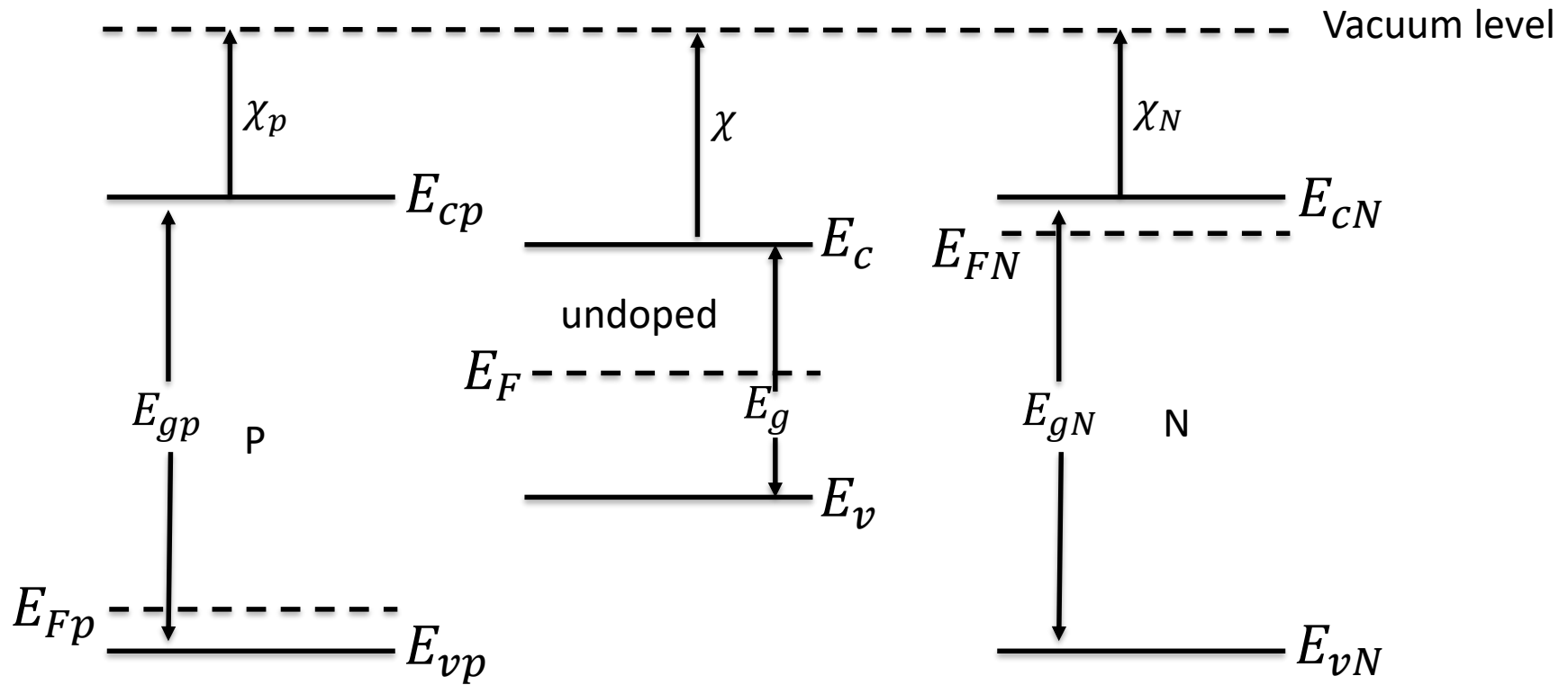
p-N heterojunction (high bias)

“Law of Junction” may break down at high bias
Thermionic emission over barrier spike becomes rate
limiting step for electron transport across junction

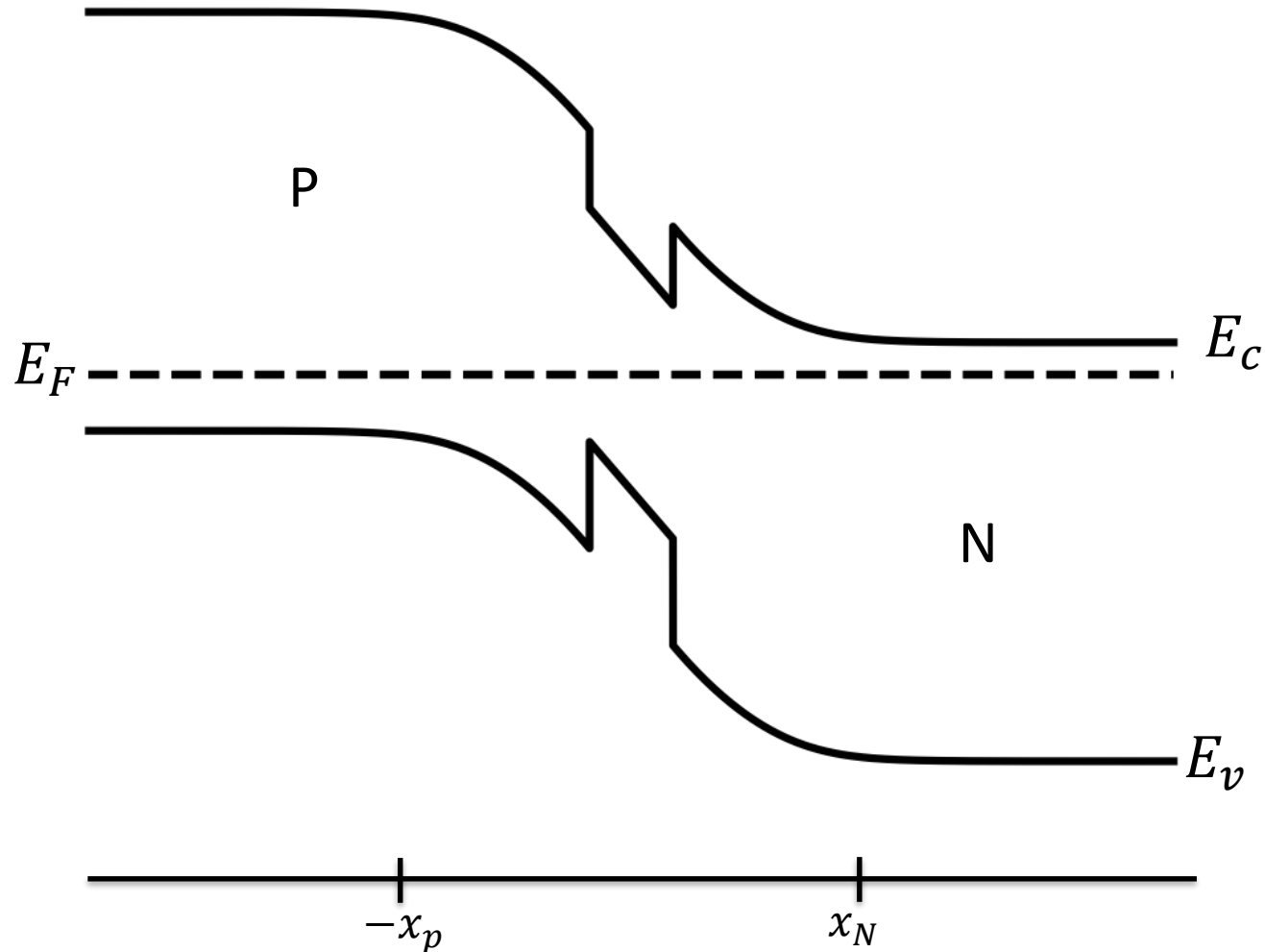


See useful derivation “Law of the Junction Revisited” by Prof. M. Lundstrom
(<https://nanohub.org/groups/ece606lundstrom>)

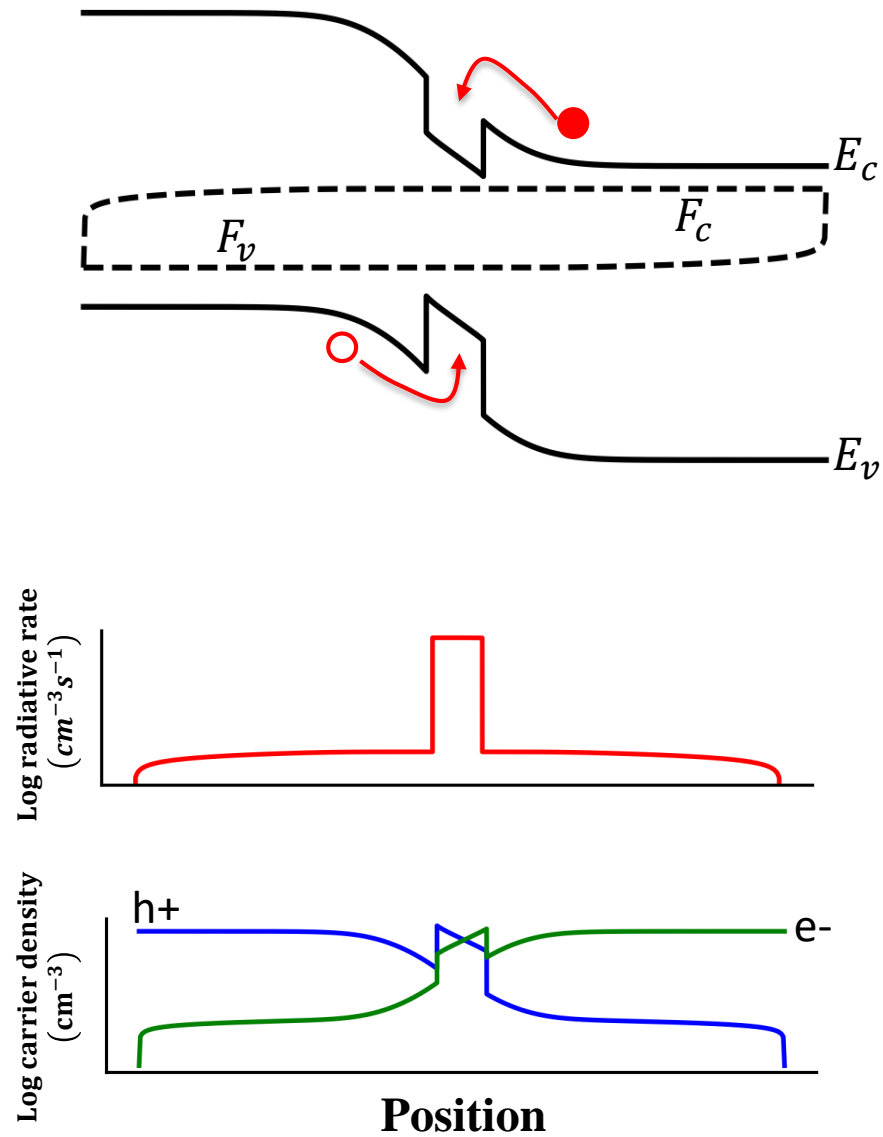
Double heterojunction



Double heterojunction (no bias)

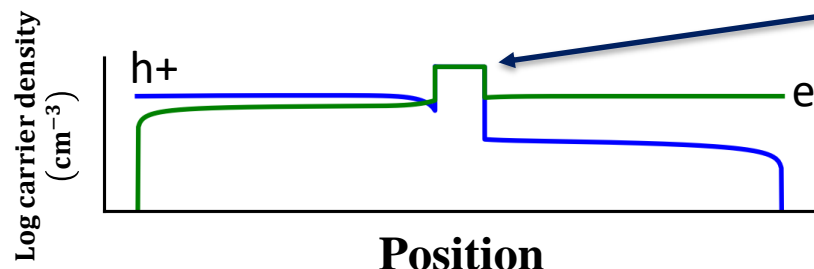
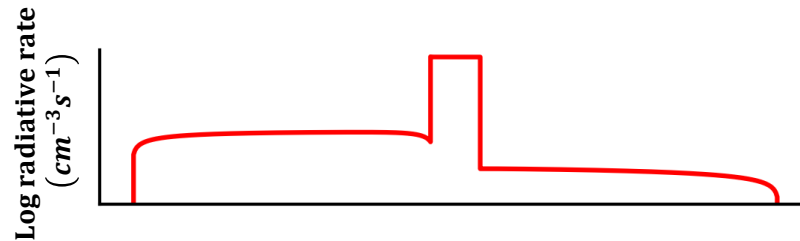
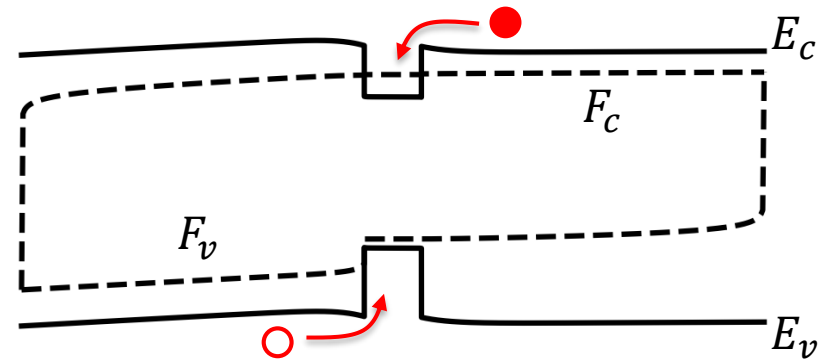


Double heterojunction (low bias)



Double heterojunction (high bias)

Quasi-fermi level on p-side not flat from series resistance and low thermionic emission over valence band barrier spike



Bands flatten
Carrier density uniform

Double heterojunction (high bias)

- Assumptions: All carriers are captured into active region, quasi-neutrality condition applies, carrier density is uniform

δn : Injected electron density in active region

$$\begin{aligned} \frac{d\delta n}{dt} &= -R + \frac{1}{q} \nabla J_n \\ &= -\frac{\delta n}{\tau} + \frac{1}{q} \frac{d}{dx} J_n \\ &= -\frac{\delta n}{\tau} + \frac{1}{q} \frac{J_n}{d} \end{aligned}$$

d = active region thickness

At equilibrium:

$$\frac{\delta n}{\tau} = \frac{J_n}{qd} = \frac{J}{qd}$$

$$\frac{\delta p}{\tau} = \frac{\delta n}{\tau} = \frac{J}{qd}$$

