ECE 656: Electronic Transport in Semiconductors Fall 2017

Heterostructure Fundamentals

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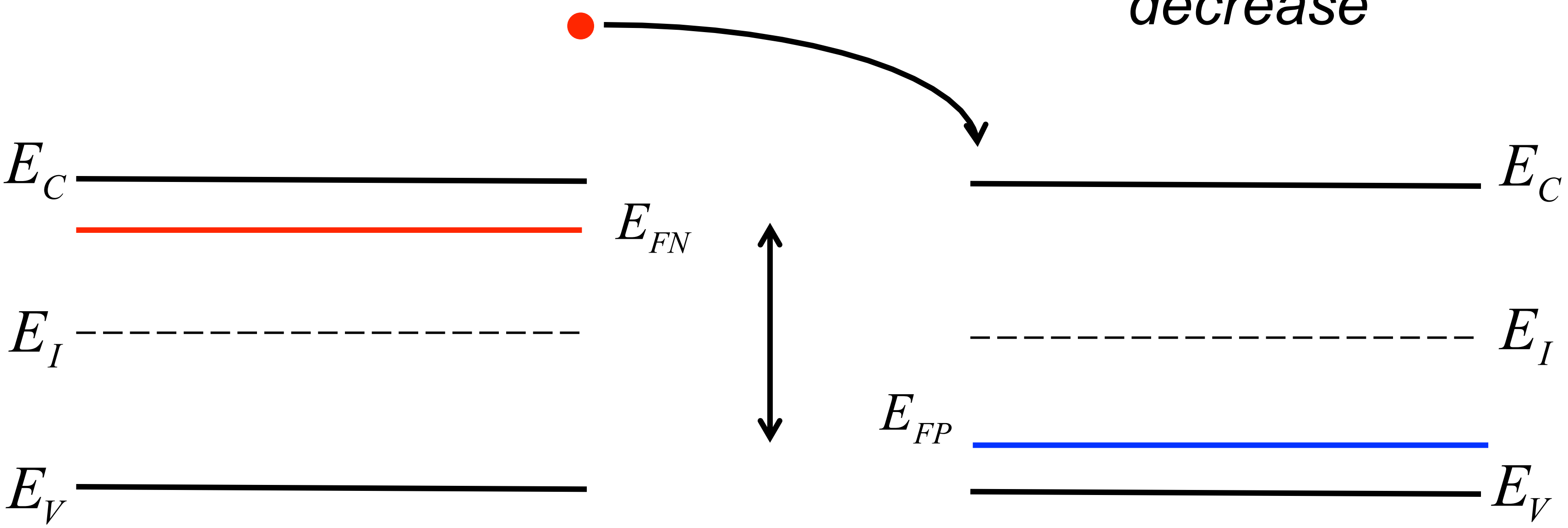
Outline

1) Review of energy band diagrams
2) Heterojunctions
3) General heterostructure
4) DD equation for heterostructures
5) Summary

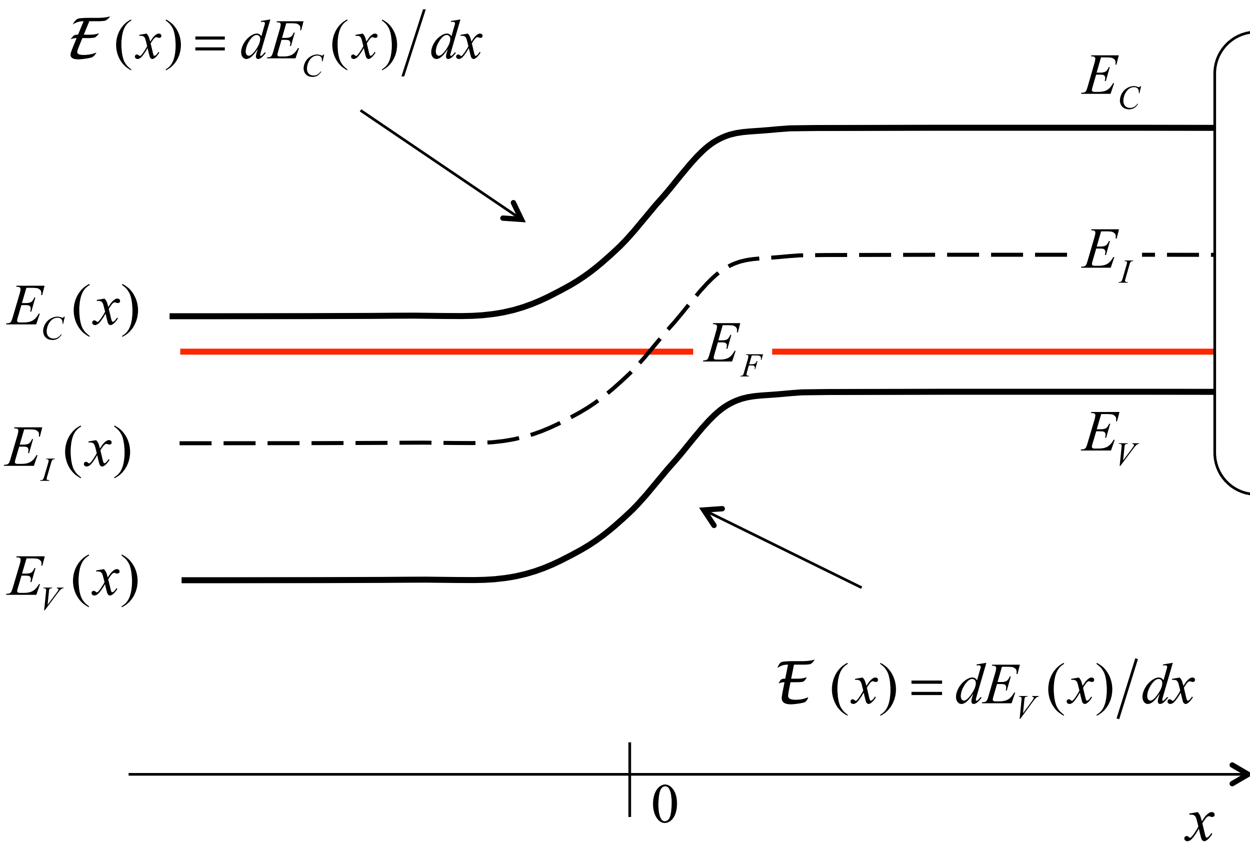
Review: pn homojunctions

$E = E_0 - qV$
potential must decrease



$$qV_{BI} = \left(E_{FN} - E_{FP}\right)/q$$

Review: pn homojunctions

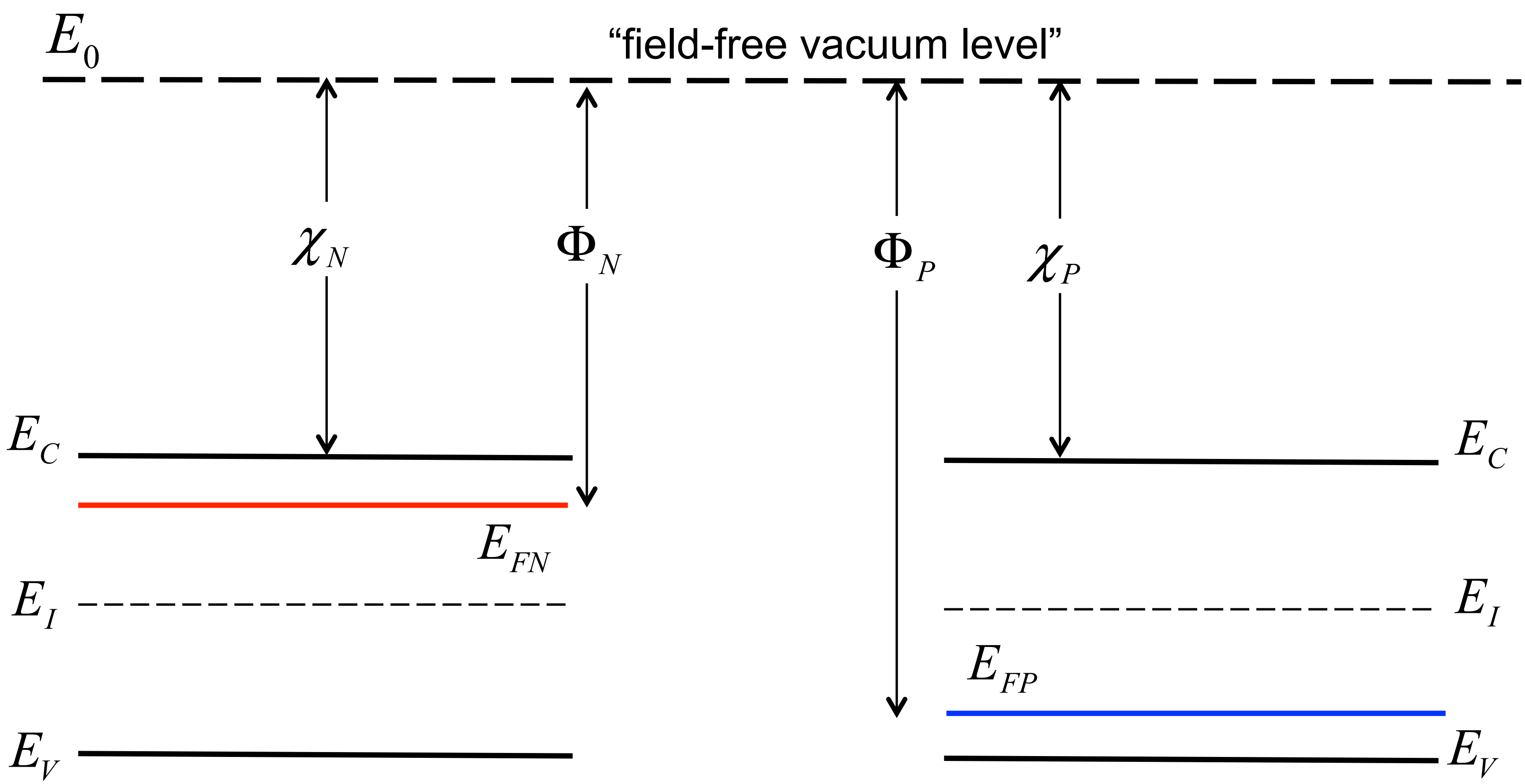


$$V(x) = -E_C(x) + V_{ref}$$

$$n_o(x) = N_C e^{\left(E_F - E_C(x)\right)/k_B T}$$

$$p_o(x) = N_V e^{\left(E_V(x) - E_F\right)/k_B T}$$

Reference for the energy bands

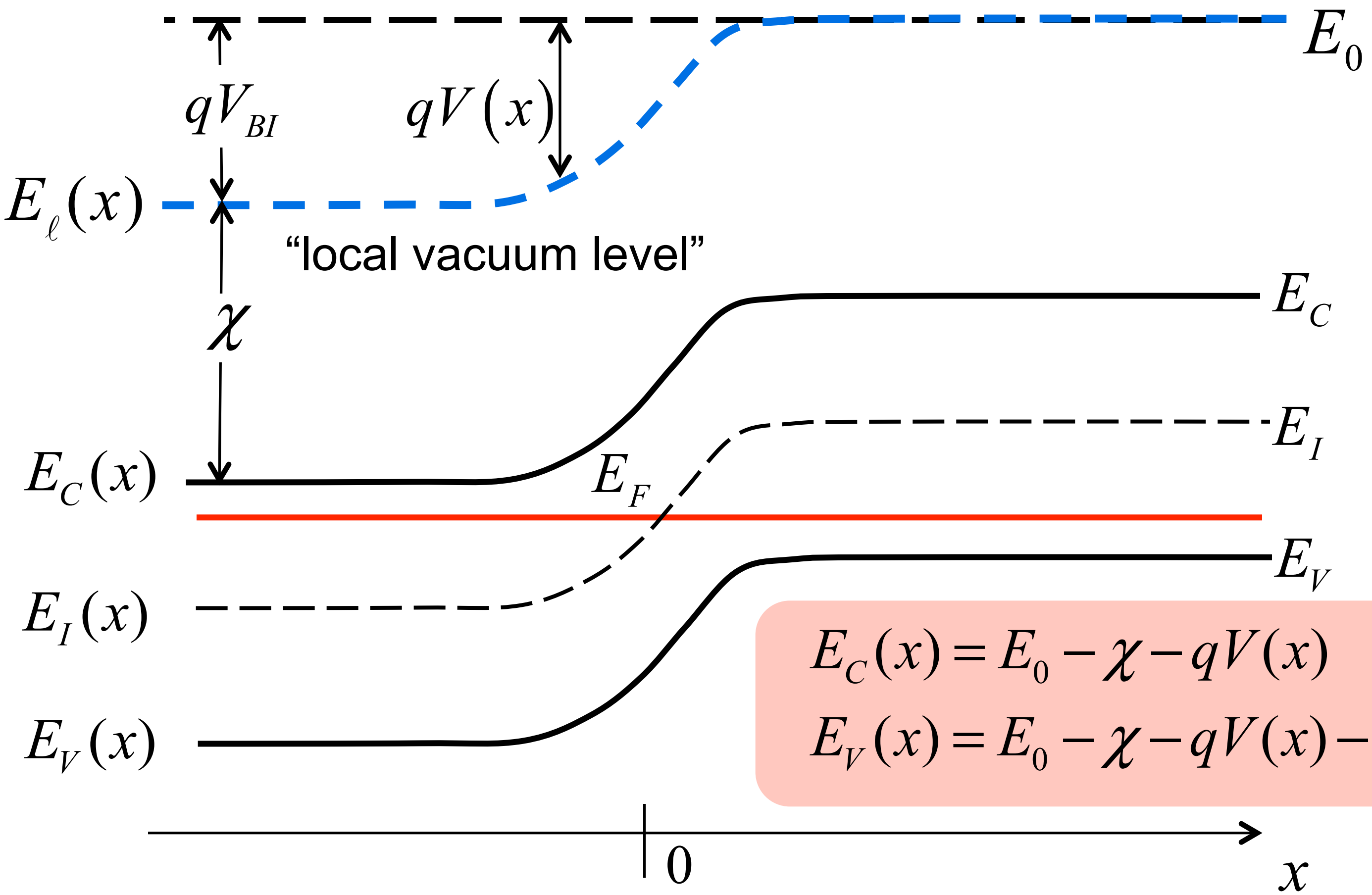


$$E_C = E_0 - \chi$$

$$E_V = E_0 - \chi - E_G$$

$$qV_{BI} = \left(\Phi_P - \Phi_N\right)$$

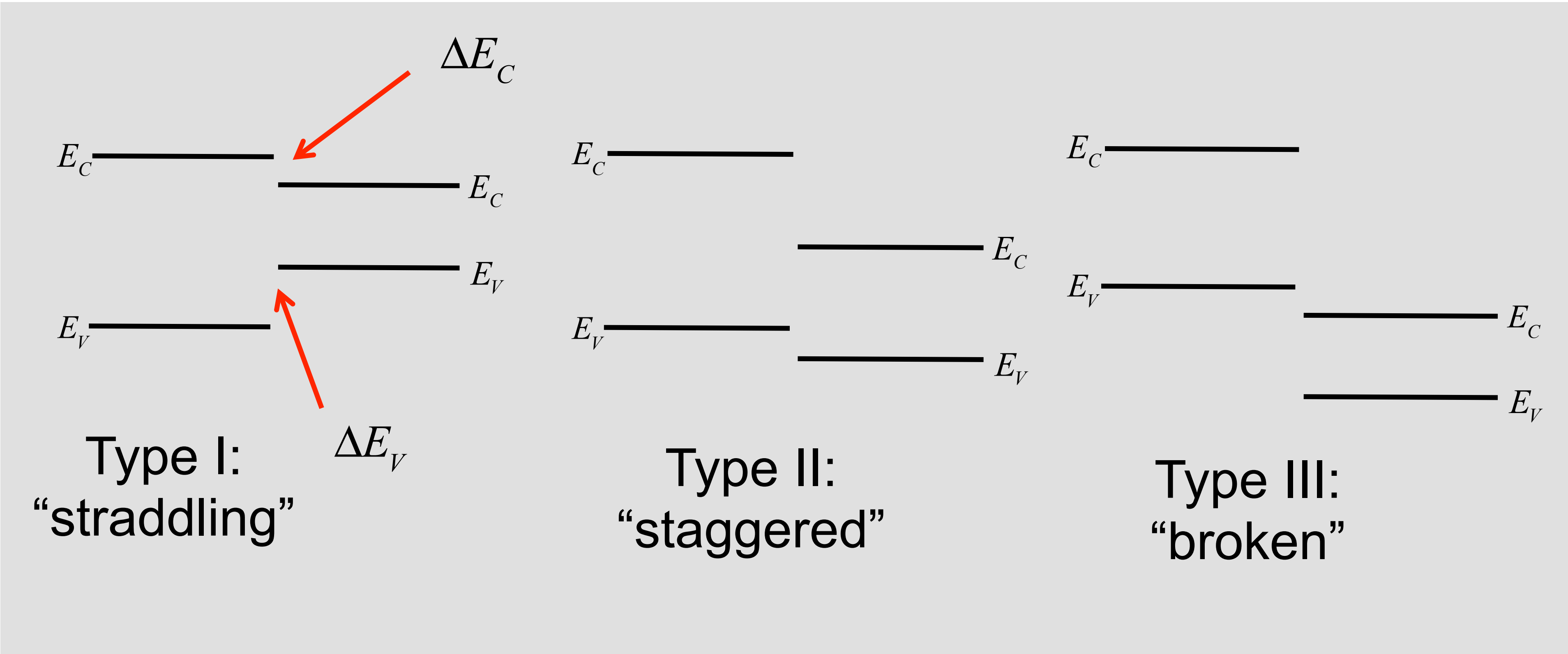
Local vacuum level



$$E_C(x) = E_0 - \chi - qV(x)$$

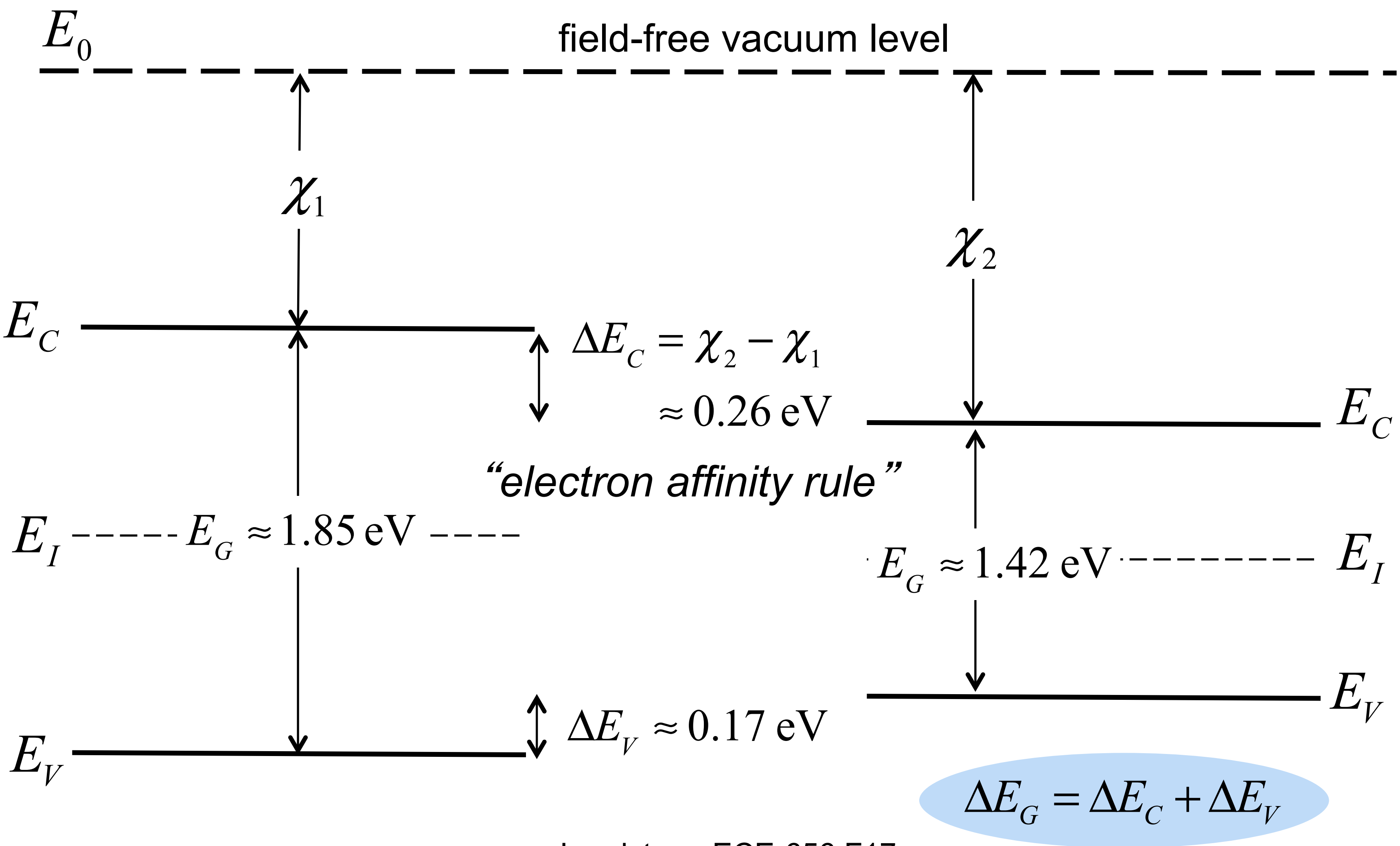
$$E_V(x) = E_0 - \chi - qV(x) - E_G$$

Types of heterojunctions

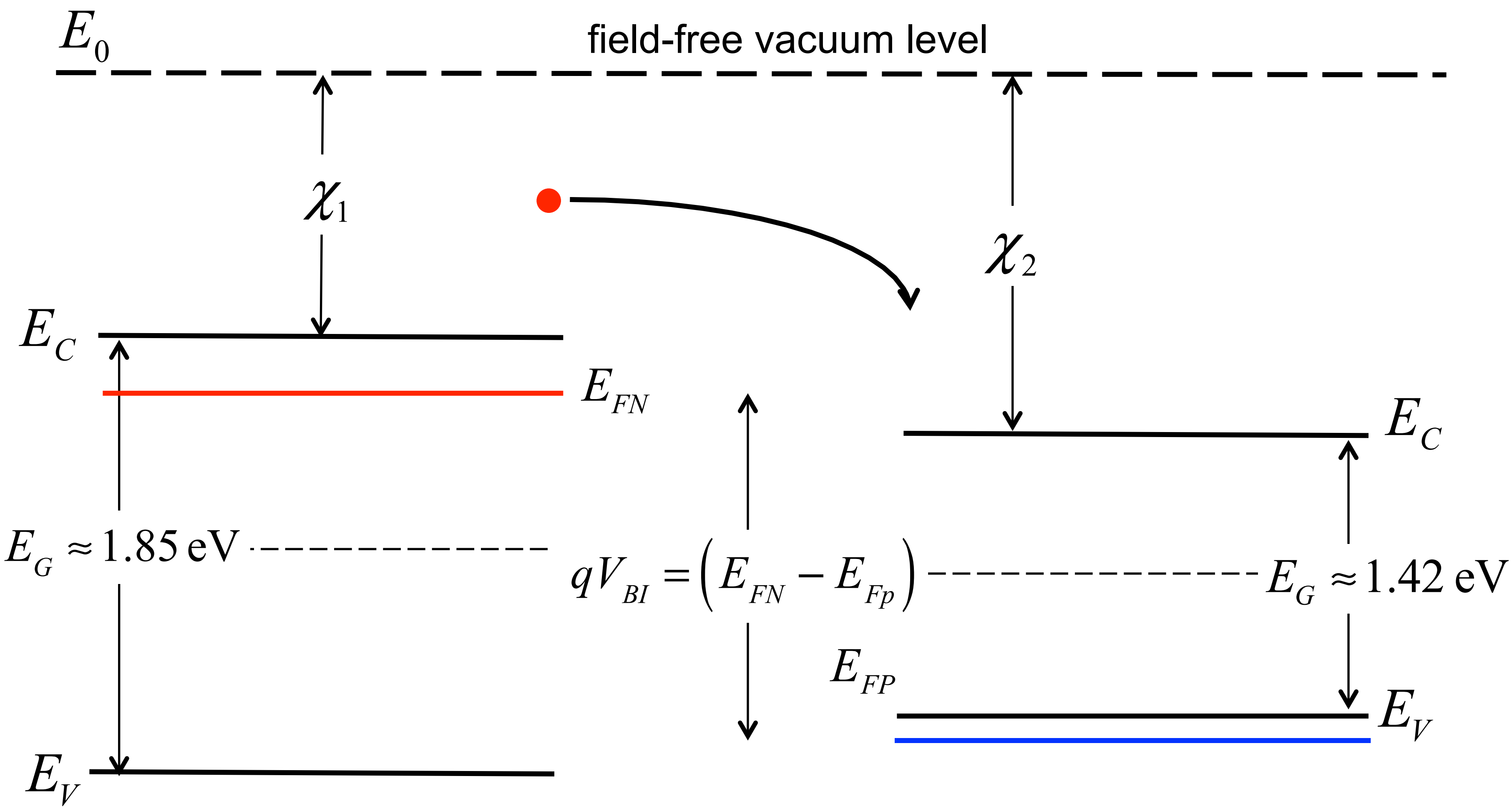


“band alignment” is a critical factor.

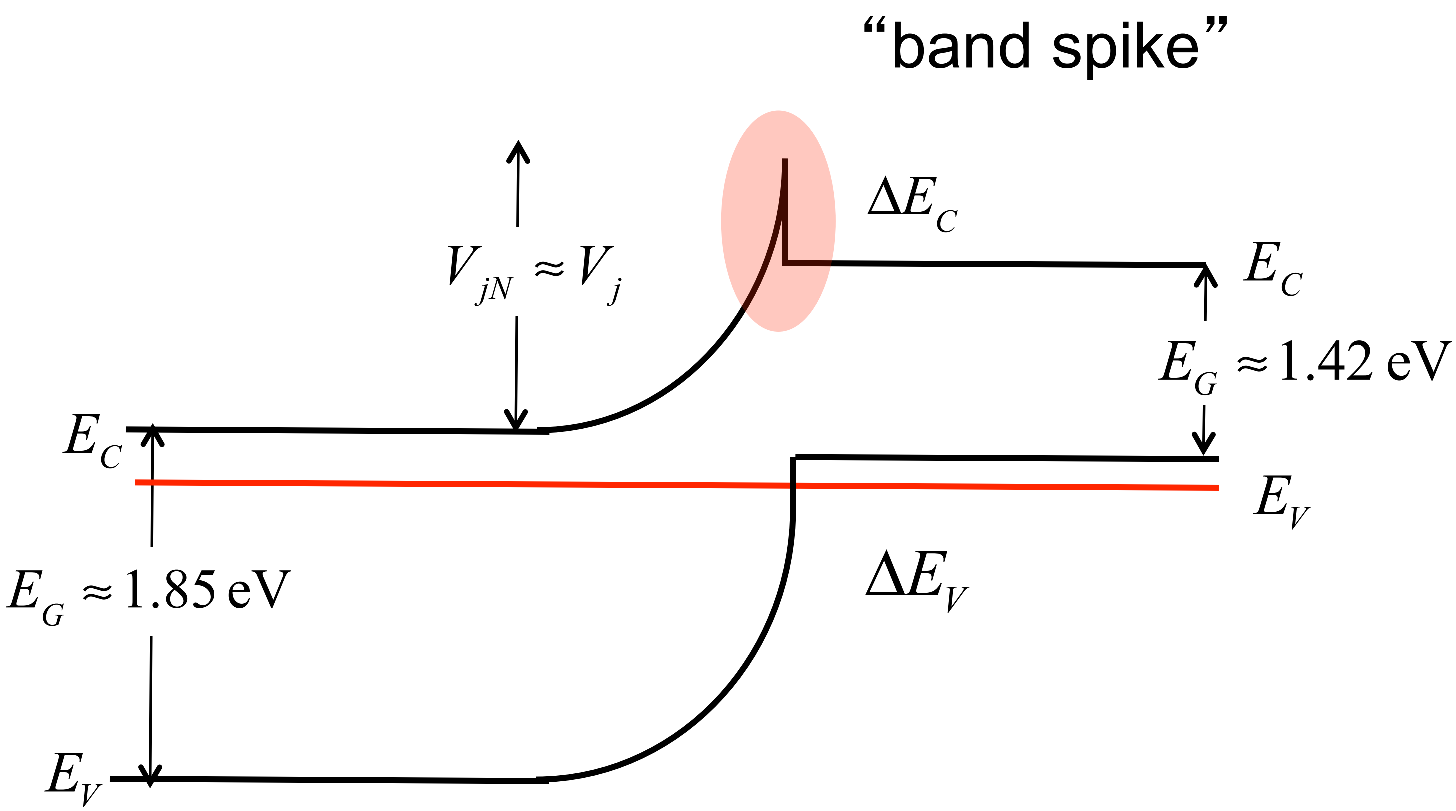
$Al_{0.3}Ga_{0.7}As$: GaAs (Type I HJ)



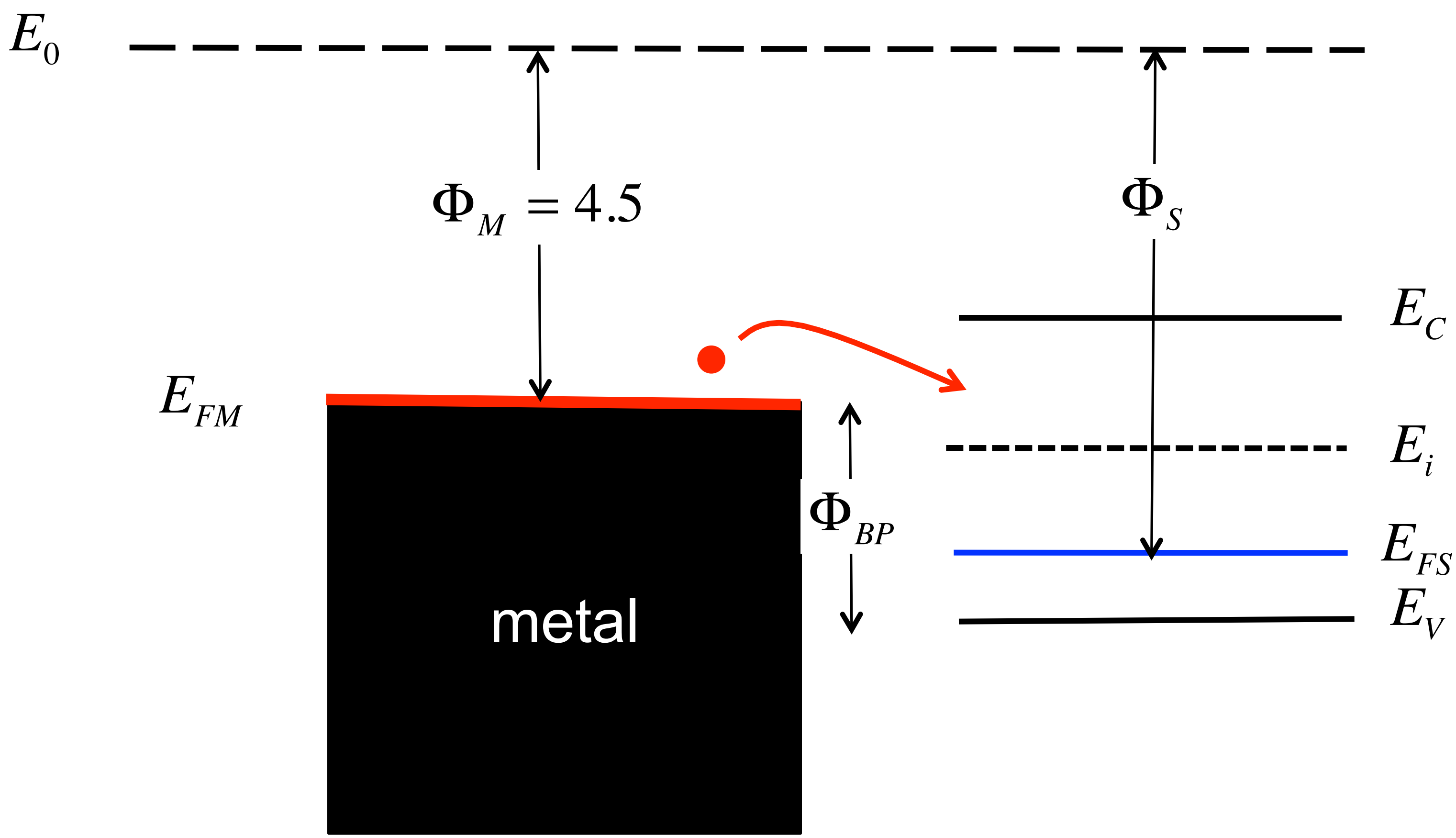
N-$Al_{0.3}Ga_{0.7}As$: p^+-GaAs (Type I HJ)



N-$Al_{0.3}Ga_{0.7}As$: p^+-GaAs (Type I HJ)

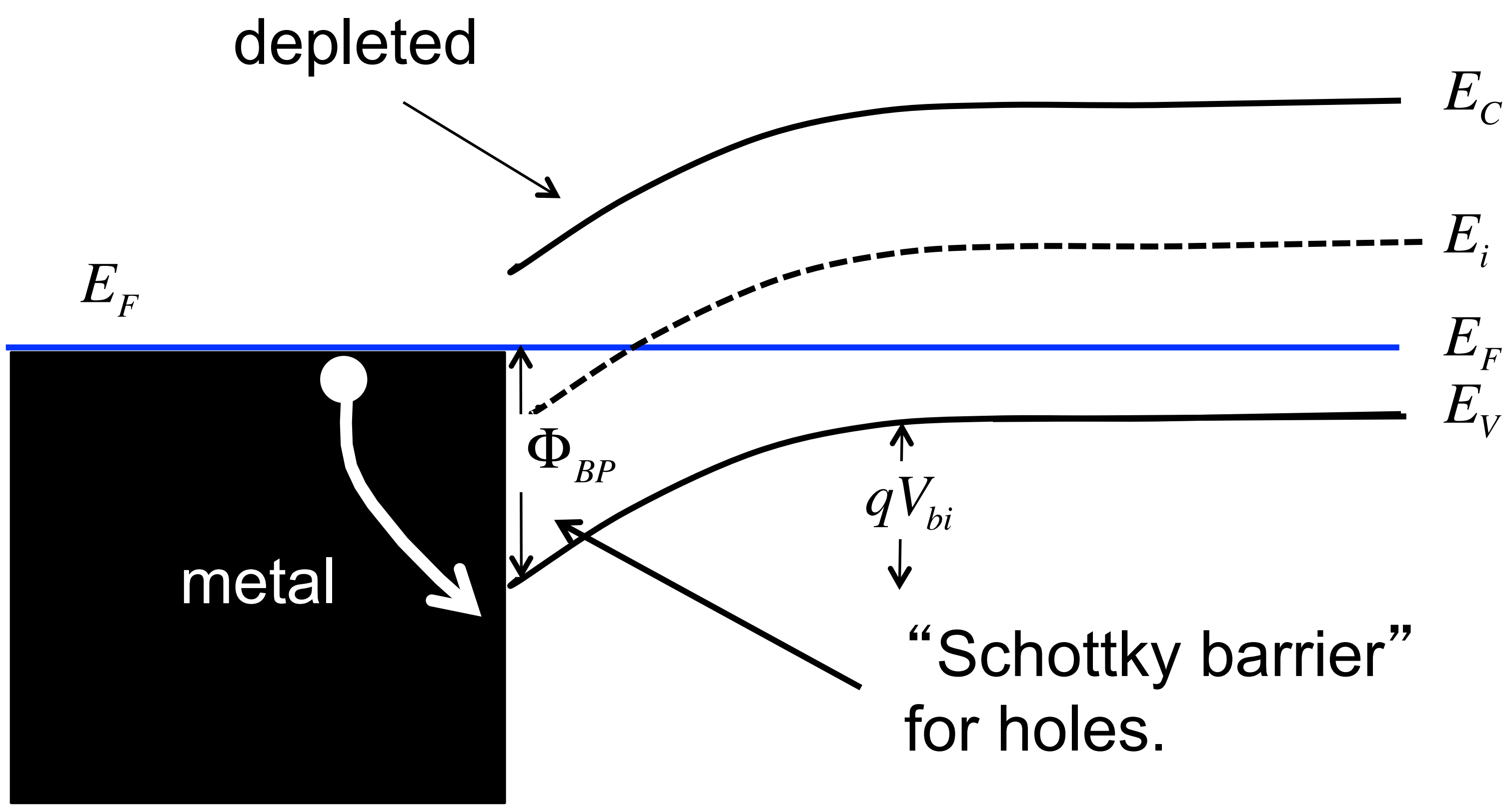


Metal-Semiconductor heterojunctions

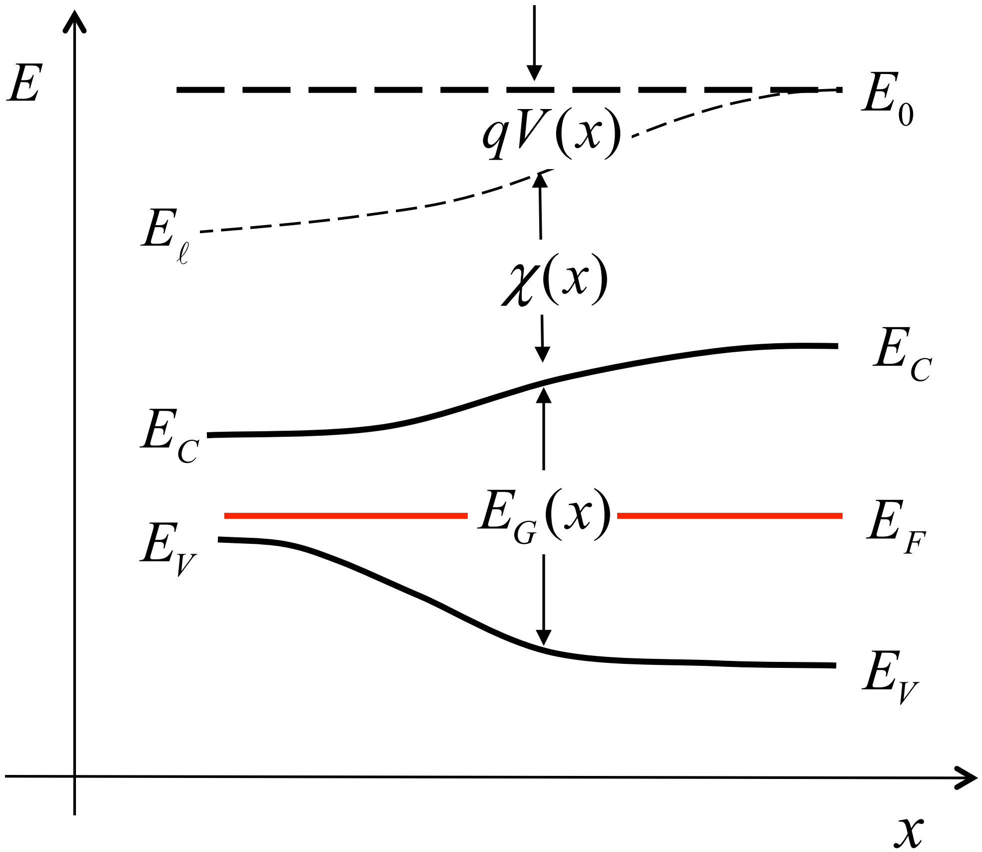


MS diode: equilibrium band diagram

from the band diagram….potential, e-field, p(x), rho(x)



General, graded heterostructure

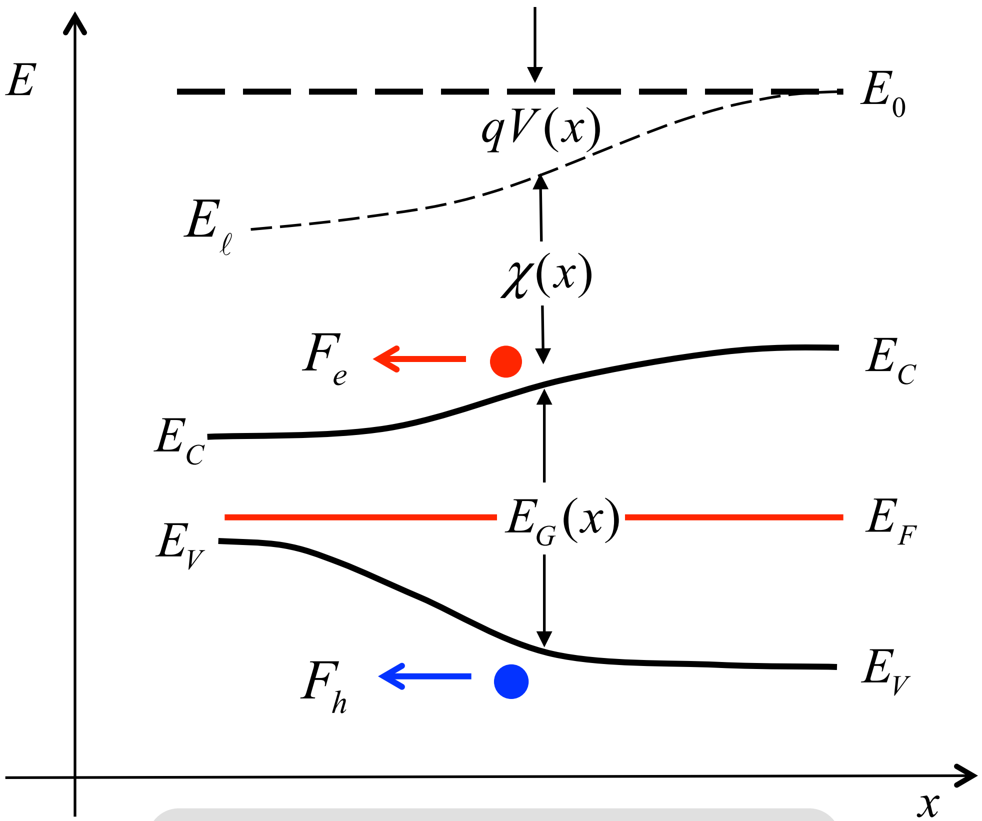


$$E_C(x) = E_0 - \chi(x) - qV(x)$$

$$E_V(x) = E_C(x) - E_G(x)$$

A smooth and slow variation of the composition is assumed.

"Quasi-electric fields"



$$E_C(x) = E_0 - \chi(x) - qV(x)$$
$$E_V(x) = E_C(x) - E_G(x)$$

$$F_e = -\frac{dE_C}{dx} = q\frac{dV}{dx} + \frac{d\chi}{dx}$$

$$F_e = -q\mathcal{E}(x) - q\mathcal{E}_{QN}(x)$$

$$\mathcal{E}_{QN} \equiv -\frac{1}{q}\frac{d\chi}{dx}$$

$$F_h = +\frac{dE_V}{dx} = -q\frac{dV}{dx} - \frac{d(\chi + E_G)}{dx}$$

$$F_h = +q\mathcal{E}(x) + q\mathcal{E}_{QP}(x)$$

$$\mathcal{E}_{QP} \equiv -\frac{1}{q}\frac{d(\chi + E_G)}{dx}$$

DD equation for heterostructures

$$J_p = p\mu_p \frac{dF_p}{dx} \qquad p = N_V(x)\, e^{\left(E_V - F_p\right)/k_B T} \qquad F_p = E_V(x) - k_B T \ln\left(p/N_V\right)$$

$$\frac{dF_p}{dx} = \frac{dE_V(x)}{dx} - k_B T\left[\frac{1}{p}\frac{dp}{dx} - \frac{1}{N_V}\frac{dN_V}{dx}\right]$$

$$J_p = p\mu_p\left[\frac{dE_V(x)}{dx} + \frac{k_B T}{N_V}\frac{dN_V}{dx}\right] - k_B T \mu_p \frac{dp}{dx}$$

$$\frac{dE_V(x)}{dx} = \frac{d}{dx}\left[E_0 - \chi(x) - qV(x) - E_G(x)\right] = q\left(\mathcal{E}(x) + \mathcal{E}_{QP}\right)$$

Hole and electron currents

$$J_p = pq\mu_p\left[\mathcal{E} + \mathcal{E}_{QP} + \frac{k_B T}{q}\frac{1}{N_V}\frac{dN_V}{dx}\right] - qD_p\frac{dp}{dx}$$

"DOS effect"

$$J_n = nq\mu_n\left[\mathcal{E} + \mathcal{E}_{QN} - \frac{k_B T}{q}\frac{1}{N_C}\frac{dN_C}{dx}\right] + qD_n\frac{dn}{dx}$$

quasi-electric fields

$$\mathcal{E}_{QP} \equiv -\frac{1}{q}\frac{d\left(\chi + E_G\right)}{dx} \qquad \mathcal{E}_{QN} \equiv -\frac{1}{q}\frac{d\chi}{dx}$$

Summary

1) Band offsets are critical parameters.

2) In graded heterostructures, we need to consider electric fields and quasi-electric fields.

3) The slope of the conduction band gives the quasi-electric field for electrons – not the electric field.

4) The slope of the valence band gives the quasi-electric field for holes − not the electric field.