ECE-656: Fall 2011

Lecture 33:

Heterostructures

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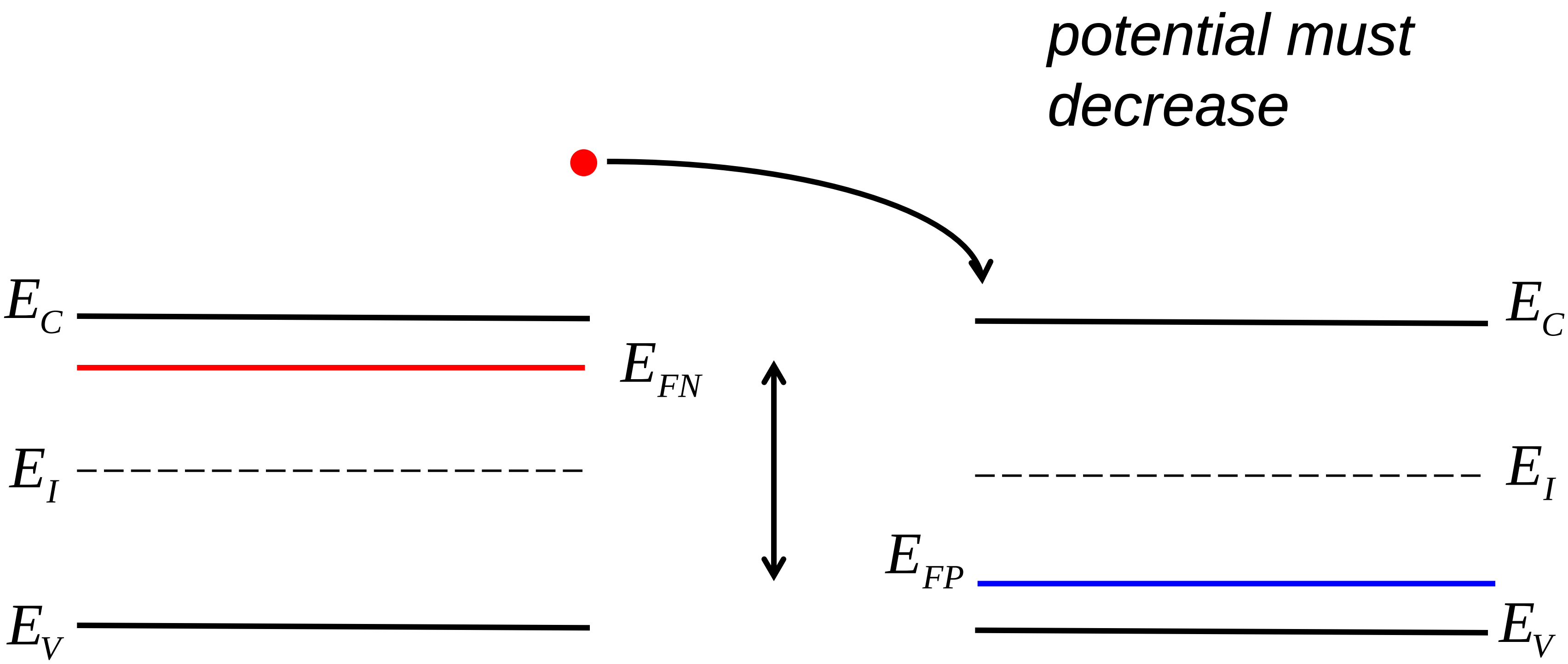
L32 outline

1) Review of L31
2) Carrier temperature and heat flux
3) **Heterostructures**
4) Summary

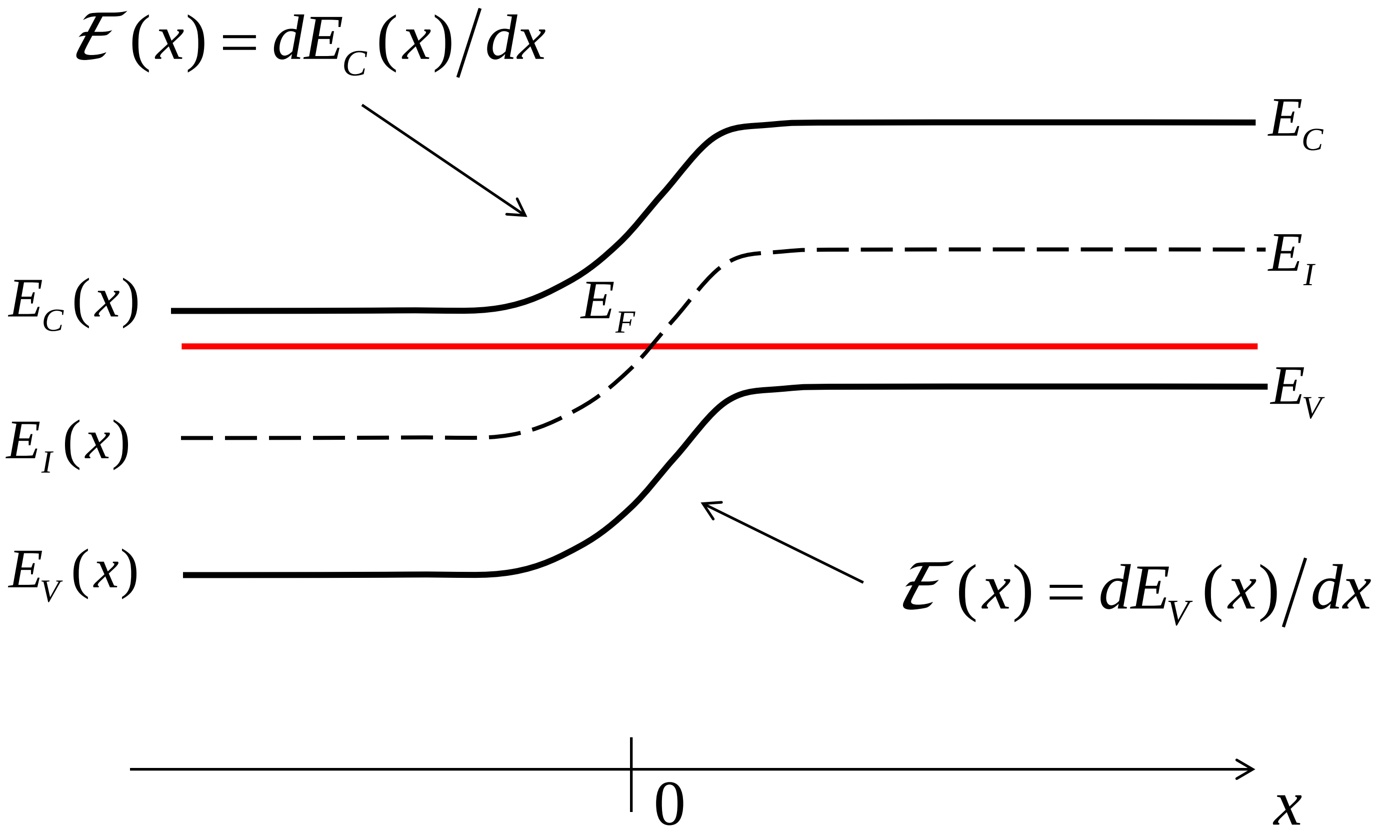
(Reference: Chapter 5, Lundstrom, FCT)

review: pn homojunctions

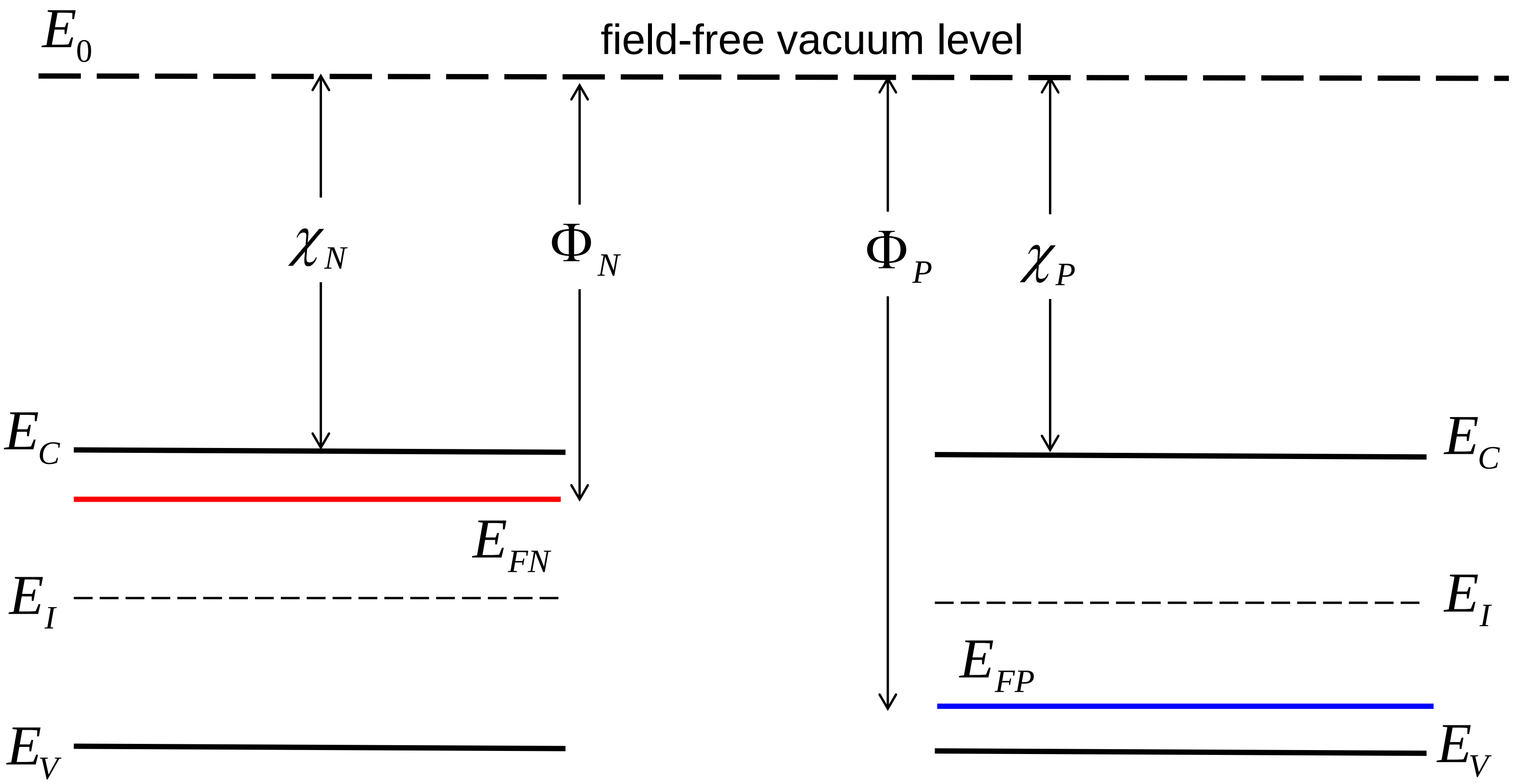


$$qV_{BI} = \left(E_{FN} - E_{FP}\right)/q$$

review: pn homojunctions



reference for the energy bands

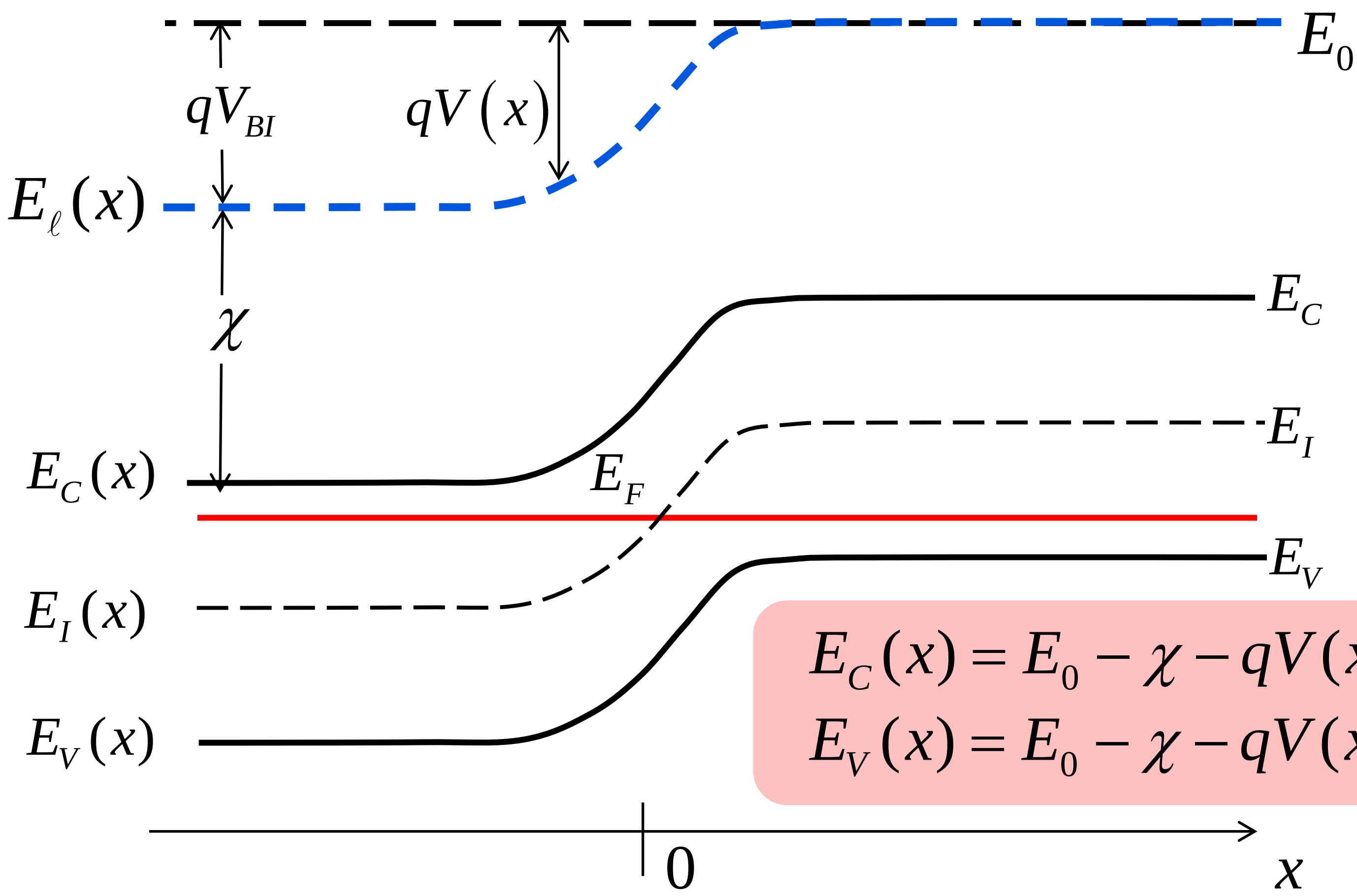


$$E_C = E_0 - \chi$$

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

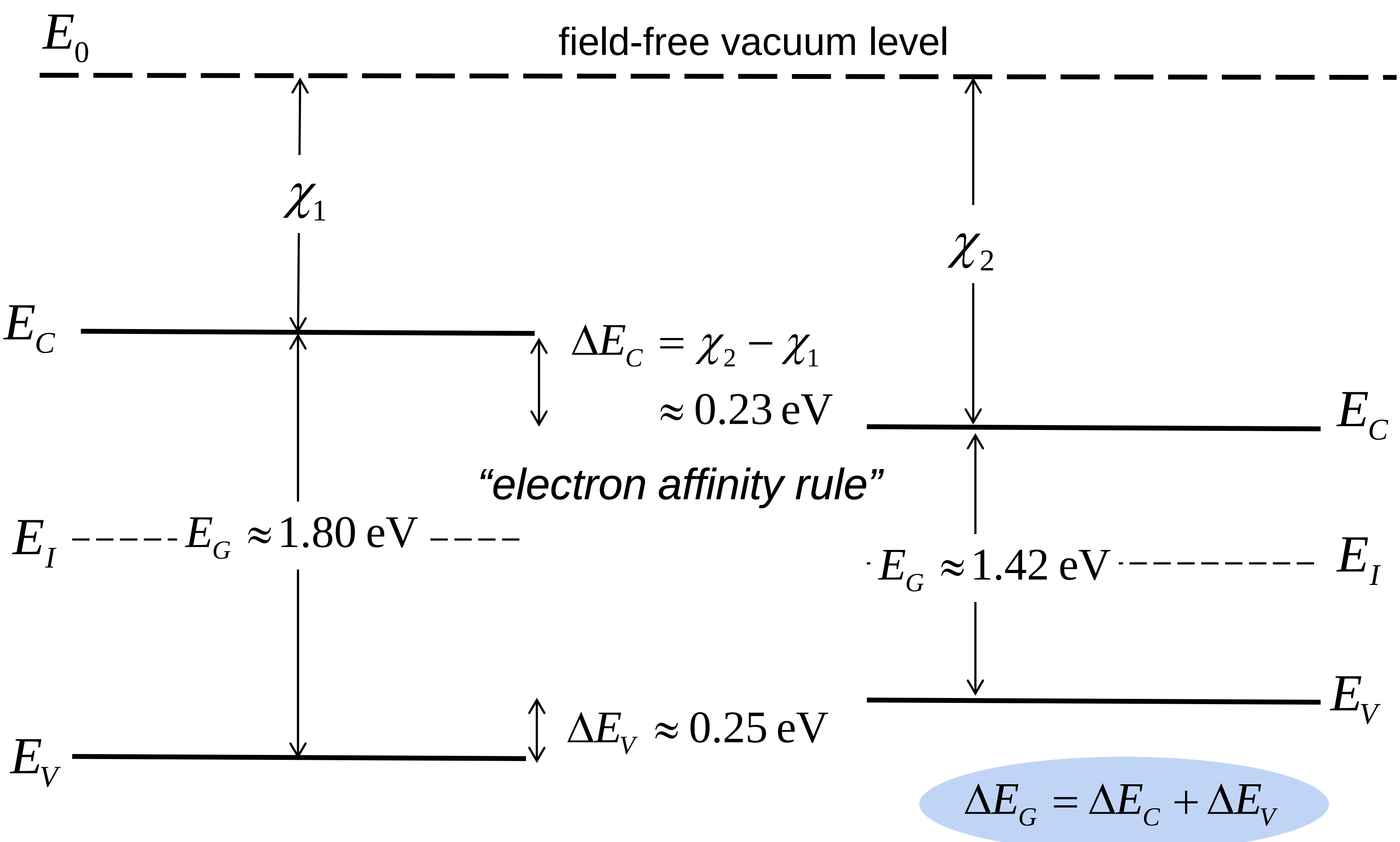
$$qV_{BI} = \left(\Phi_P - \Phi_N\right)$$

local vacuum level

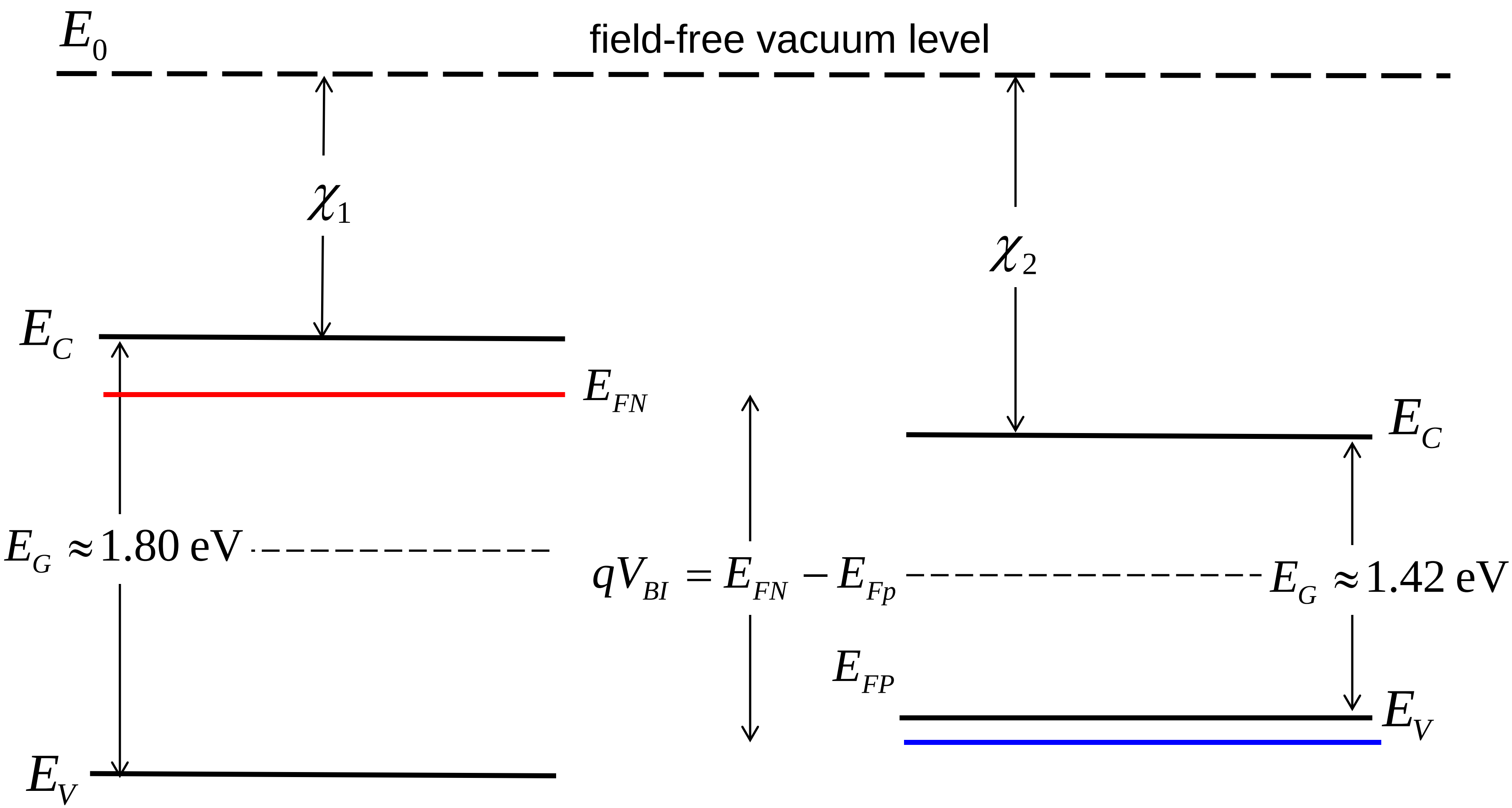


$$E_C(x) = E_0 - \chi - qV(x)$$
$$E_V(x) = E_0 - \chi - qV(x) - E_G$$

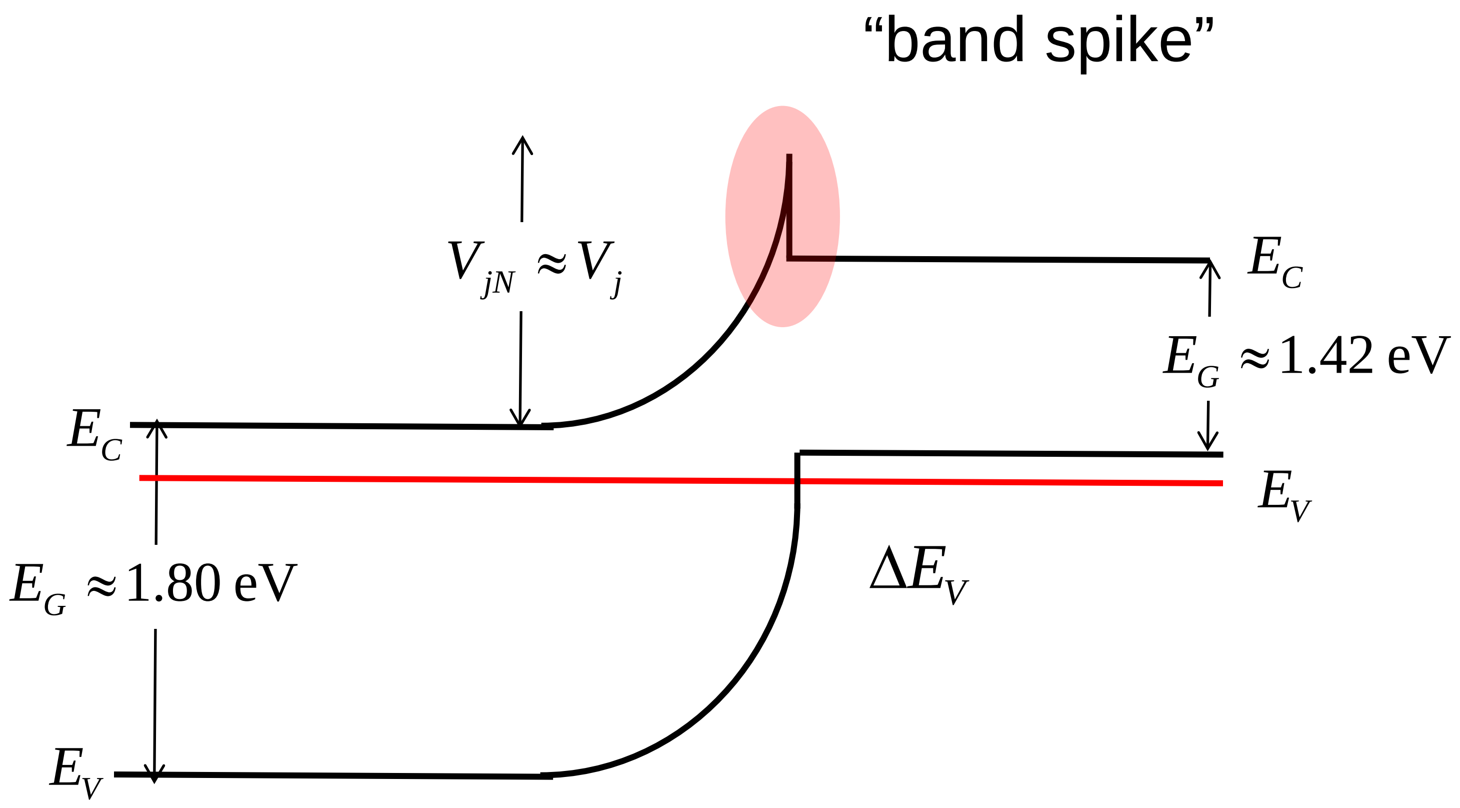
$Al_{0.3}Ga_{0.7}As$: GaAs (Type I HJ)



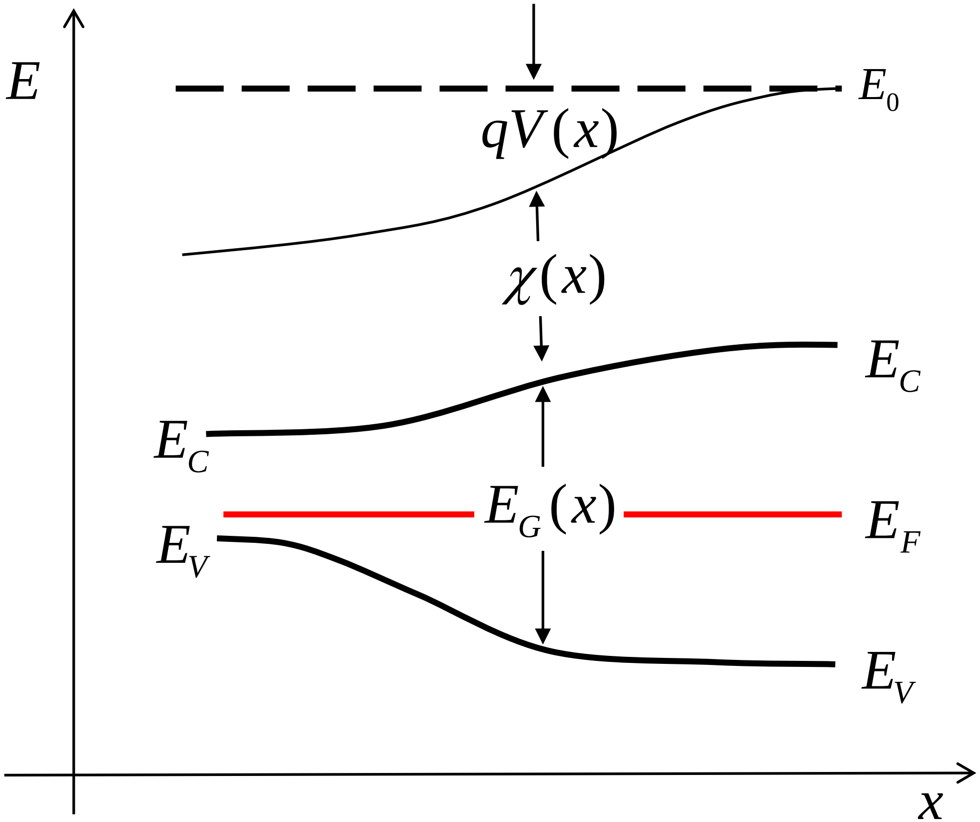
N-$Al_{0.3}Ga_{0.7}As$: p^+-GaAs (Type I HJ)



N-Al$_{0.3}$Ga$_{0.7}$As : p^{+}-GaAs (Type I HJ)



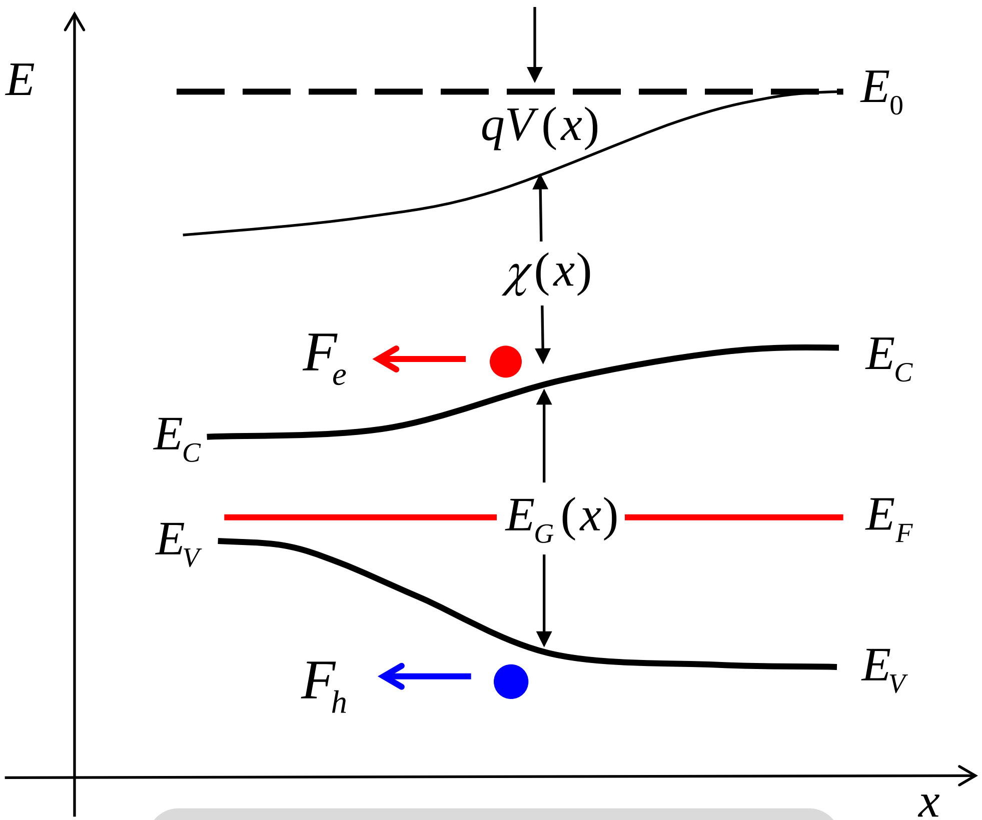
general, graded heterostructure



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

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

"quasi-electric fields"



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

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

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

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

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

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

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

BTE

$$\frac{\partial f}{\partial t}+\vec{\upsilon}\bullet\nabla_r f+\frac{d\,\vec{p}}{dt}\bullet\nabla_p f=0$$

$$\frac{d\,\vec{p}}{dt}=\frac{d\left(\hbar\vec{k}\right)}{dt}=-\nabla_r E_C(\vec{r})=-q\vec{\mathcal{E}}(\vec{r})$$

(constant effective mass)

These equations do not hold when the effective mass is position dependent. Lundstrom, FCT, Sec. 5.8.

alternative approach: hole current

$$J_p = p\mu_p \frac{dF_p}{dx}$$

$$p = N_V(x)\, e^{(E_V - F_p)/k_B T_L} \qquad F_p = E_V(x) - k_B T_L \ln\left(p/N_V\right)$$

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

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

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

hole and electron currents

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

"DOS effect"

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

quasi-electric fields

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

outline

1) Review of L31
2) Carrier temperature and heat flux
3) Heterostructures
4) **Summary**

(Reference: Chapter 5, Lundstrom, FCT)

balance equation summary

1) The four balance equations can be reduced to two continuity equations and two constitutive relations.

2) We can write them as two equations in two unknowns.

3) The unknowns are n and W or n and T_e.

the simplified equations

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \bullet \vec{J}_n$$

cont. eqn. for electrons

$$\vec{J}_n = nq\mu_n\vec{\mathcal{E}} + \frac{2}{3}\mu_n\nabla W$$

current equation

$$\frac{\partial W}{\partial t} = -\nabla \bullet \vec{F}_W + \vec{J}_n \bullet \vec{\mathcal{E}} - \frac{(W - W_0)}{\langle \tau_E \rangle}$$

continuity eqn. for energy

$$\vec{F}_W = ?$$

current eqn. for energy

energy current equation

First approach:

$$\vec{F}_W = -\frac{2}{3}\mu_E W \vec{\mathcal{E}} - \left\langle \tau_{F_W} \right\rangle \nabla \bullet \overleftrightarrow{X} \qquad X_{ij} \approx \frac{5}{3}\frac{k_B T_e}{q}\mu_E W \delta_{ij}$$

Second approach:

$$\vec{F}_W = W\vec{\upsilon}_d + nk_B T_e \vec{\upsilon}_d + \vec{Q} \qquad \vec{Q} \approx -\kappa_e \nabla T_e$$

questions?

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