

Lecture 13: Optical properties of semiconductors

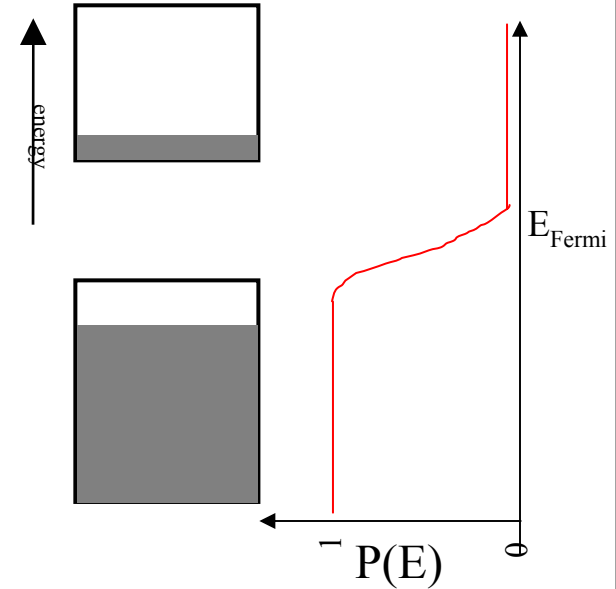
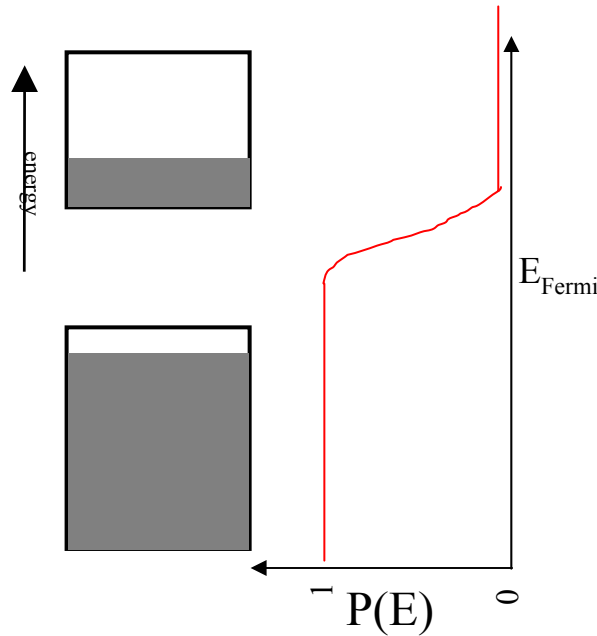
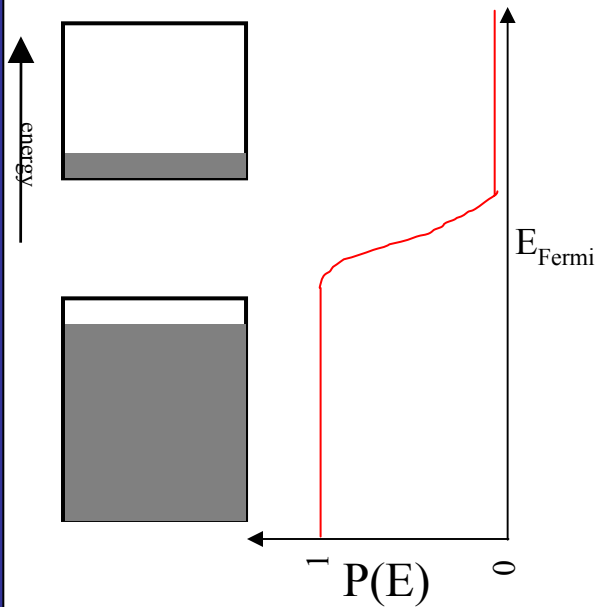
- Quasi-Fermi levels
- Optical properties
- pn junctions

Last time:

Intrinsic:

n-type:

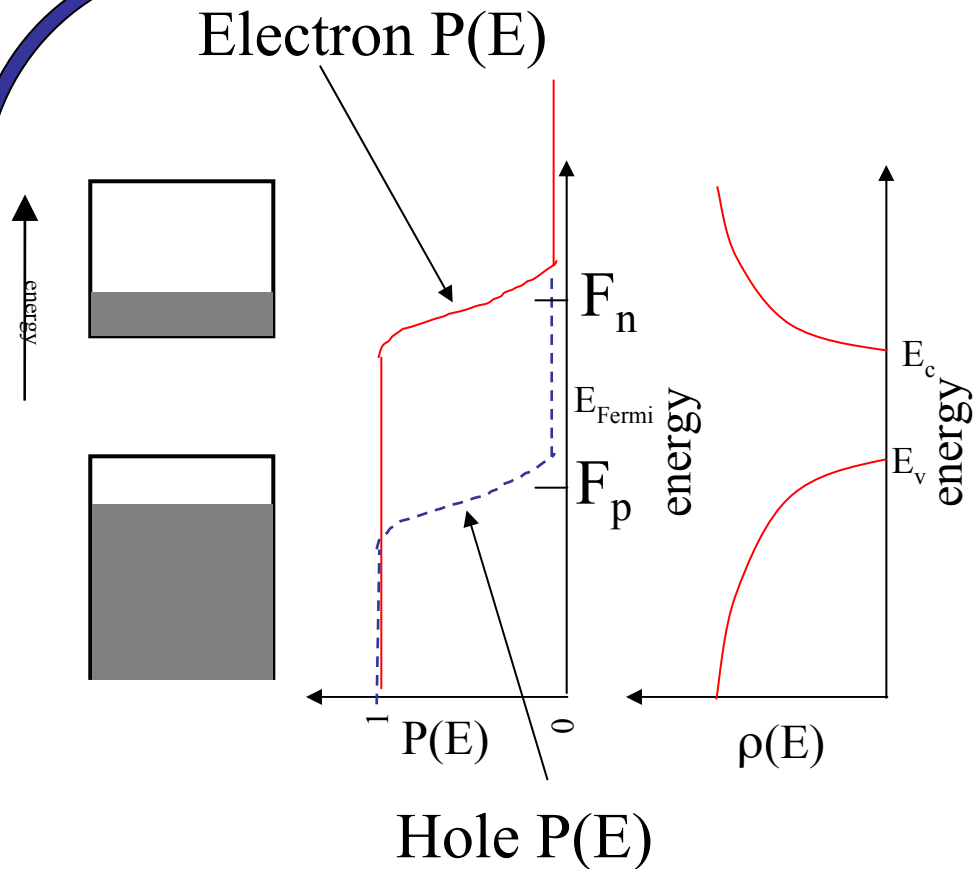
p-type:



$$n = p$$

$$n > p$$

$$n < p$$

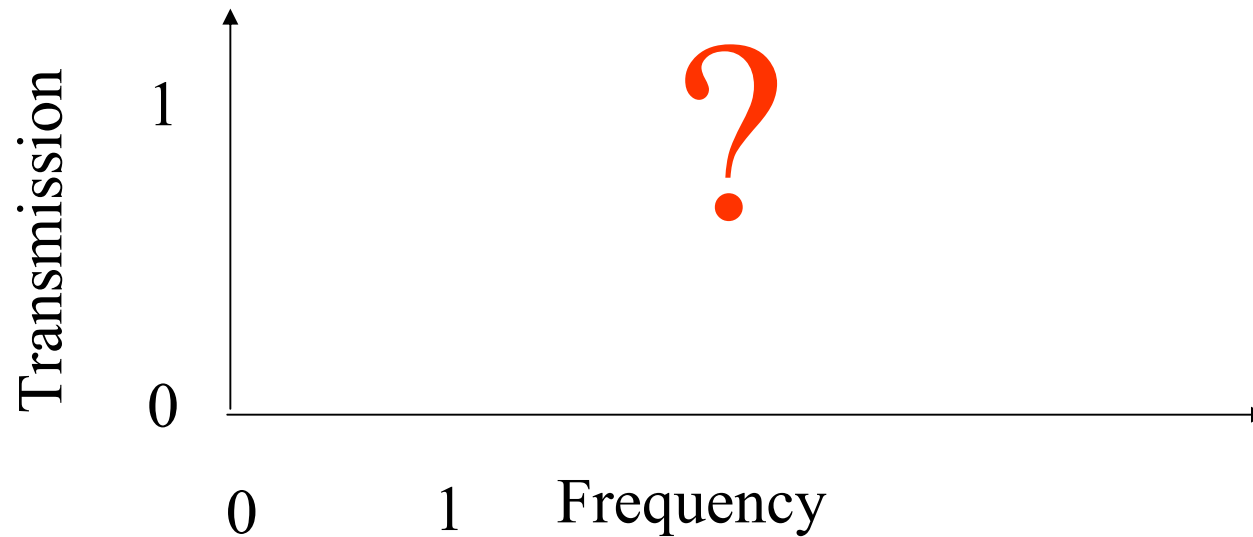
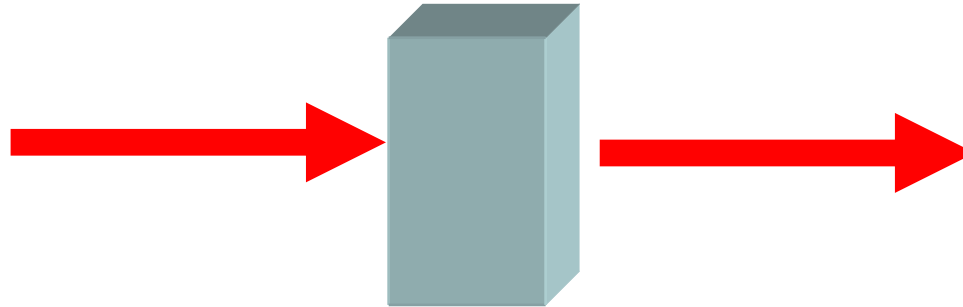


Quasi-Fermi levels:

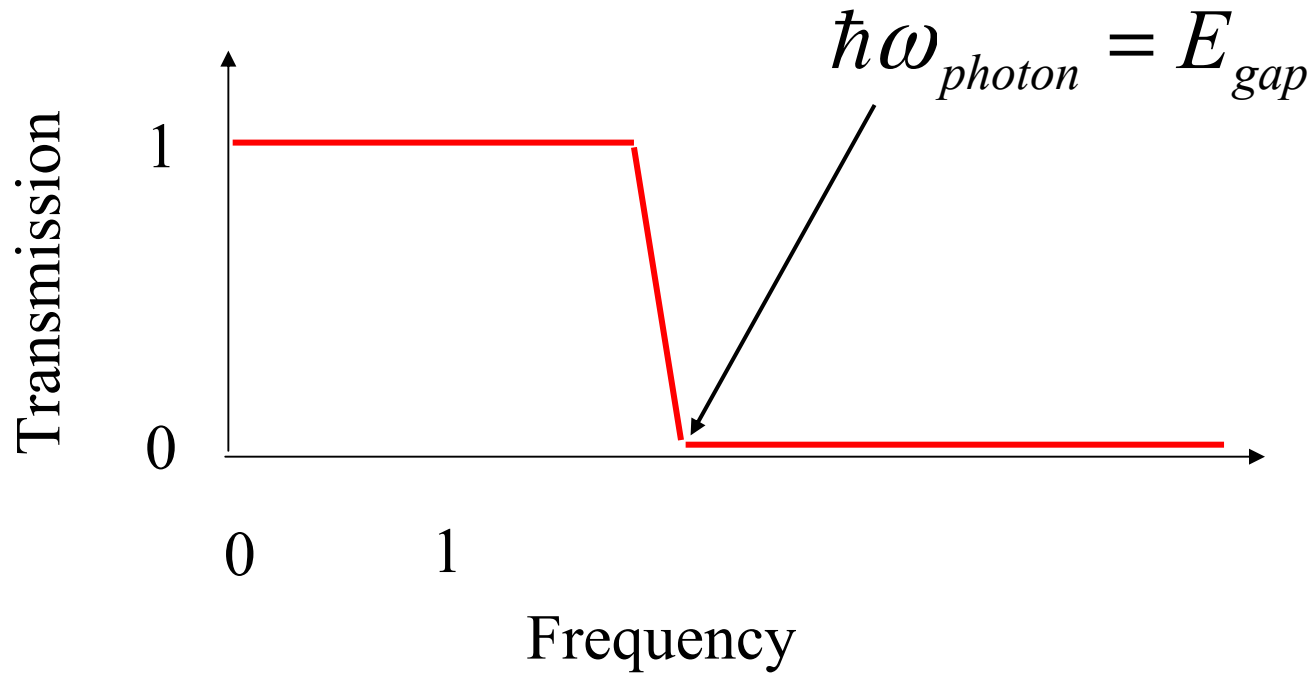
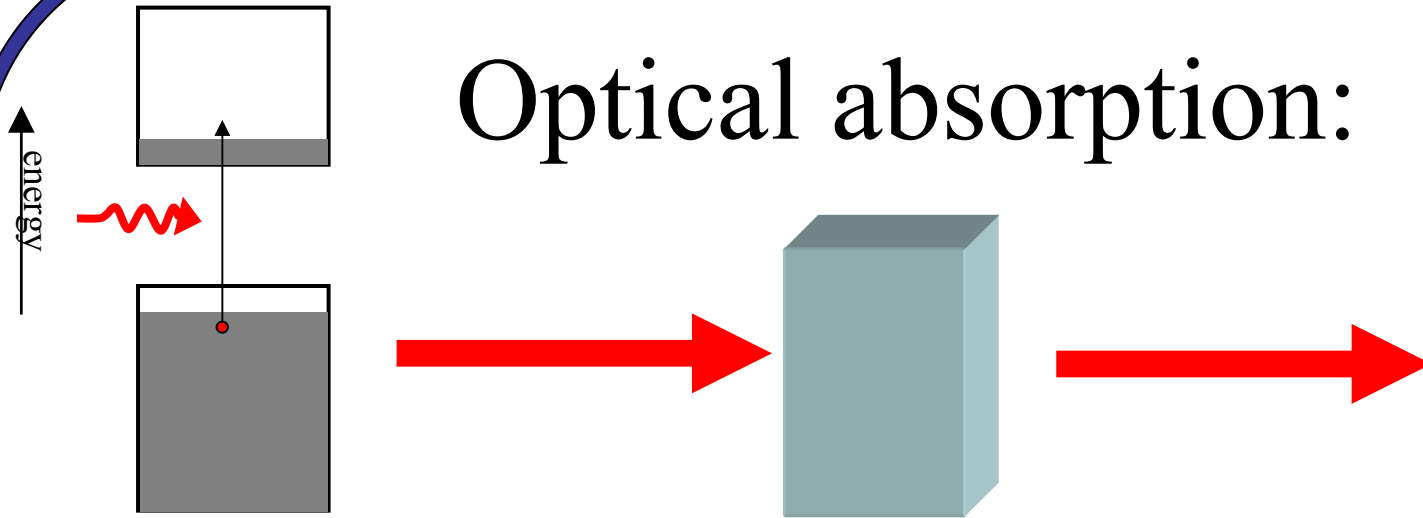
If we achieve this, electrons would spontaneously emit photons and tend to make $F_n = F_p$.

By injecting electrons from the n-side of a p-n diode, we can “pump” electrons into the system, thus maintaining the population inversion.

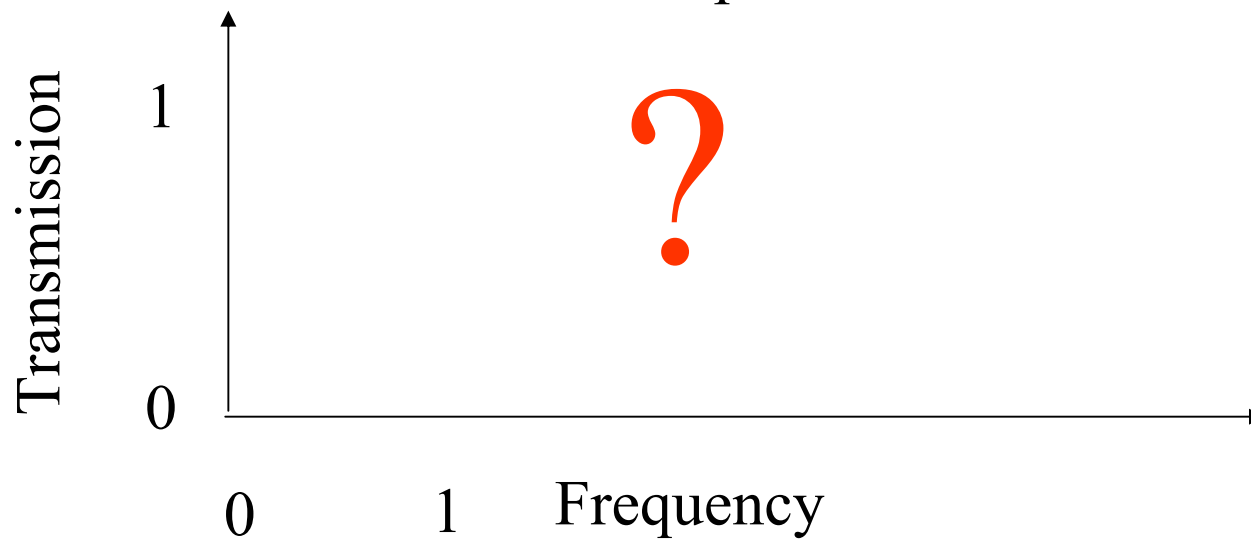
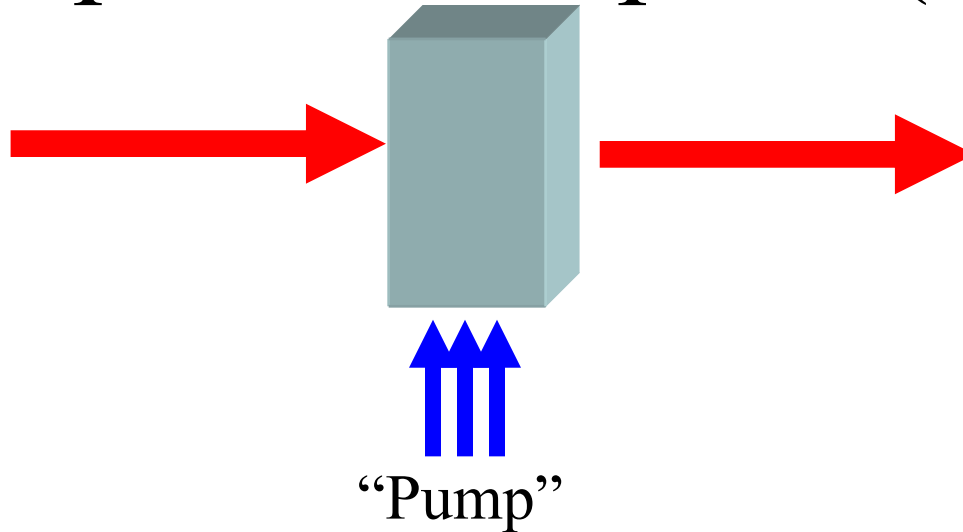
Optical absorption:



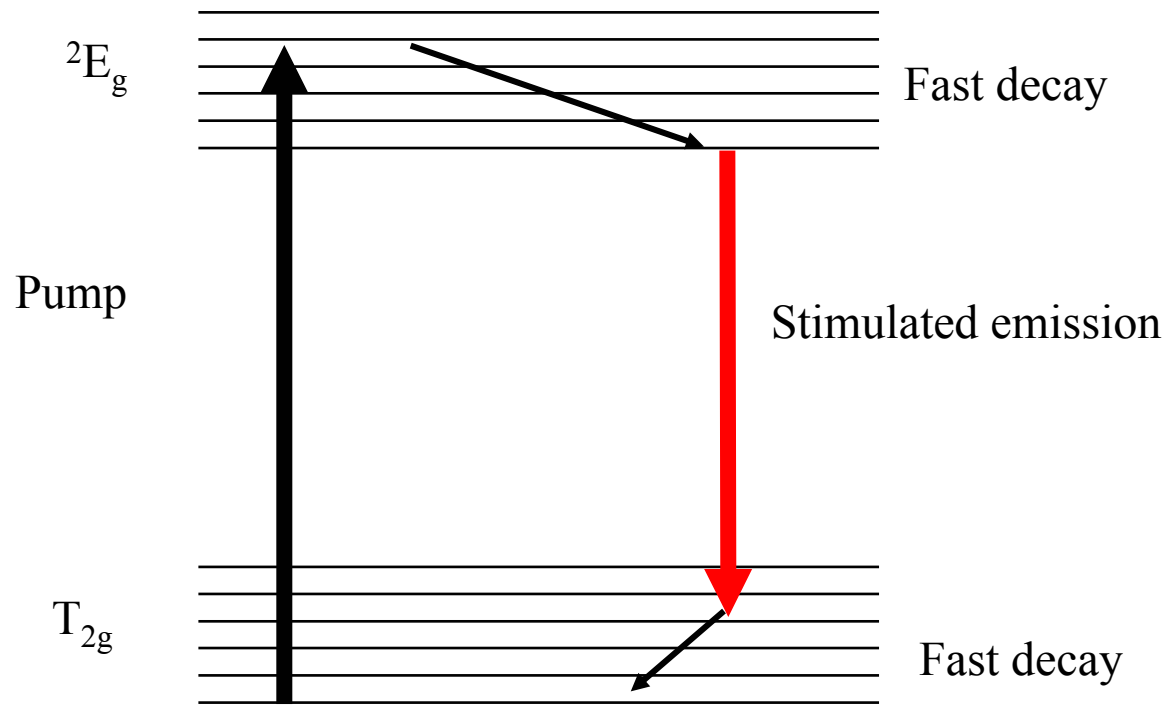
Optical absorption:



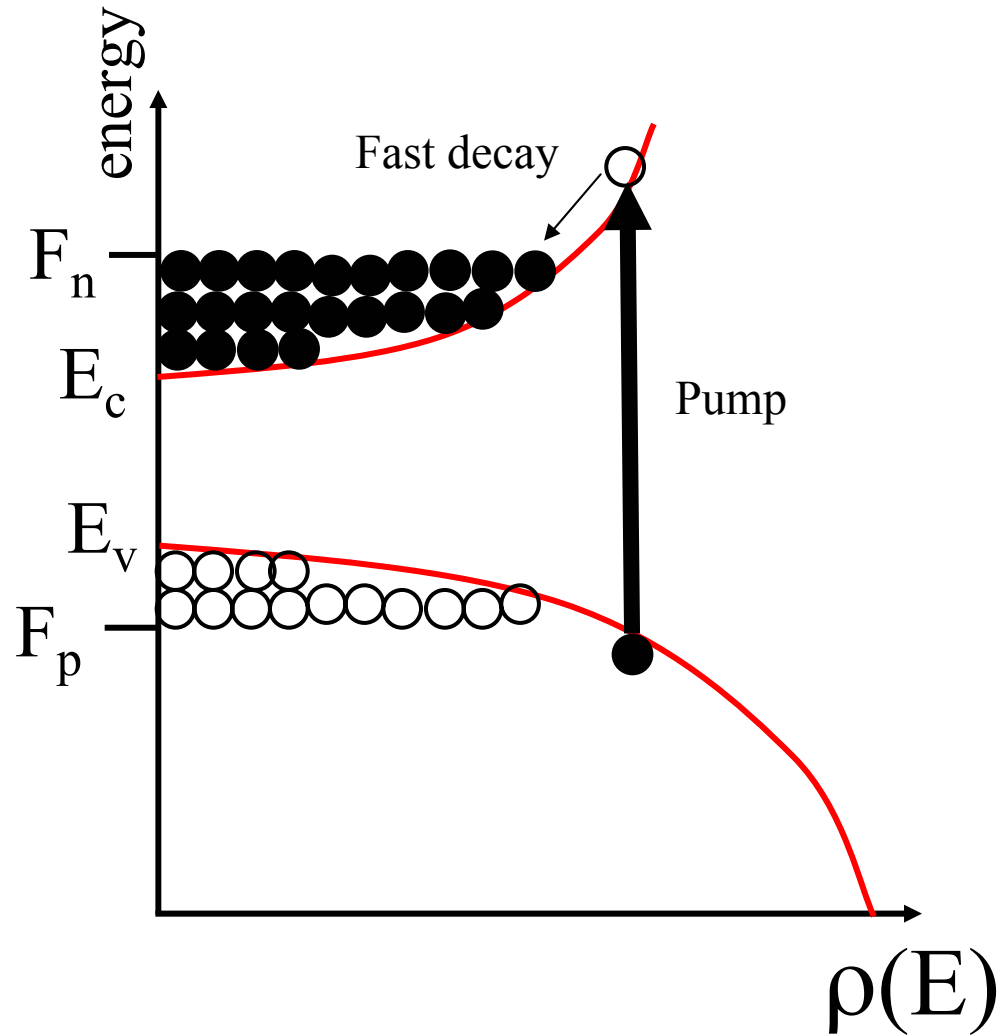
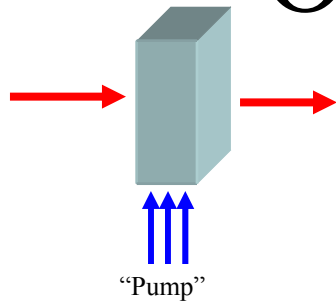
Optical absorption (?):



Recall Ti:Sapphire

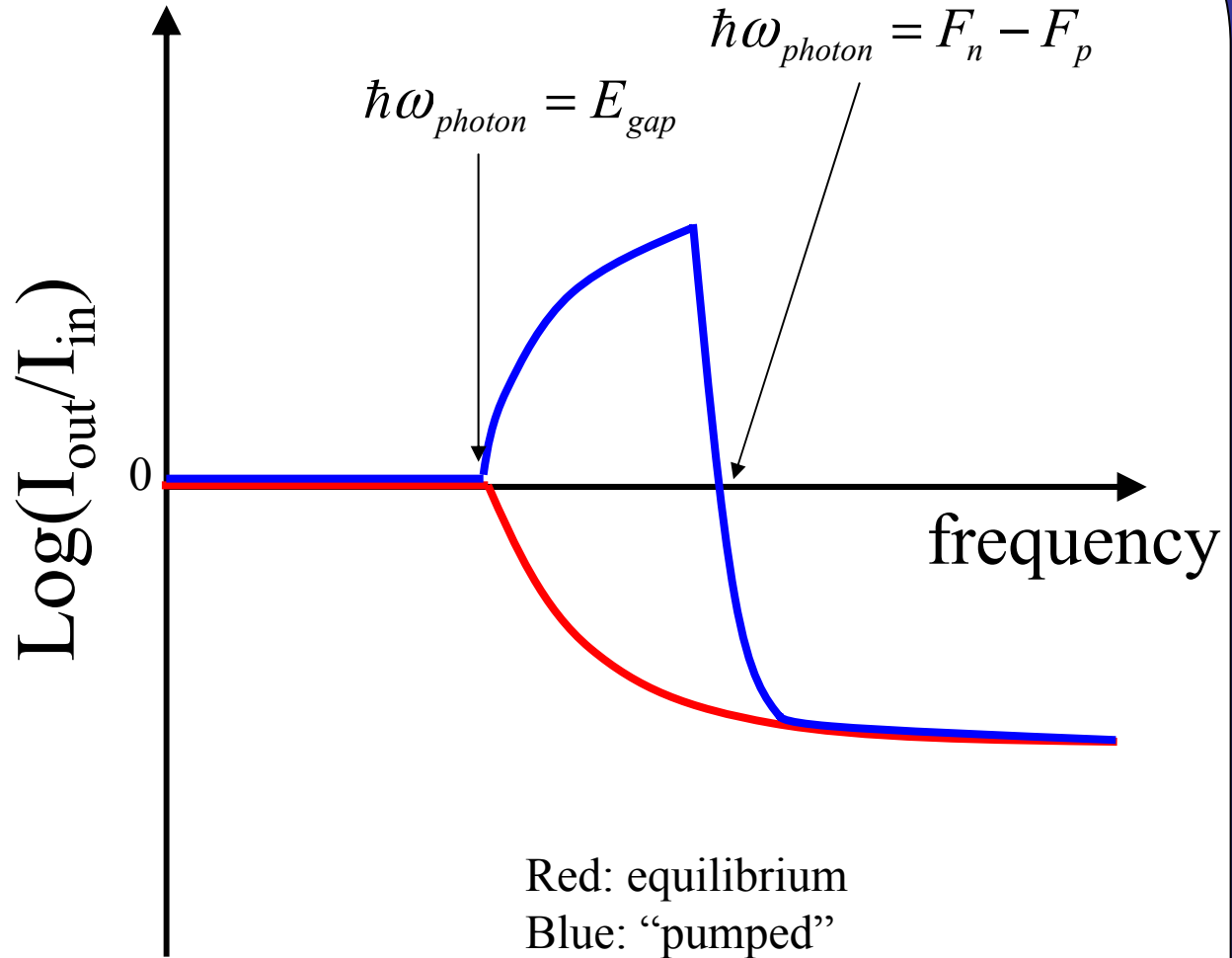
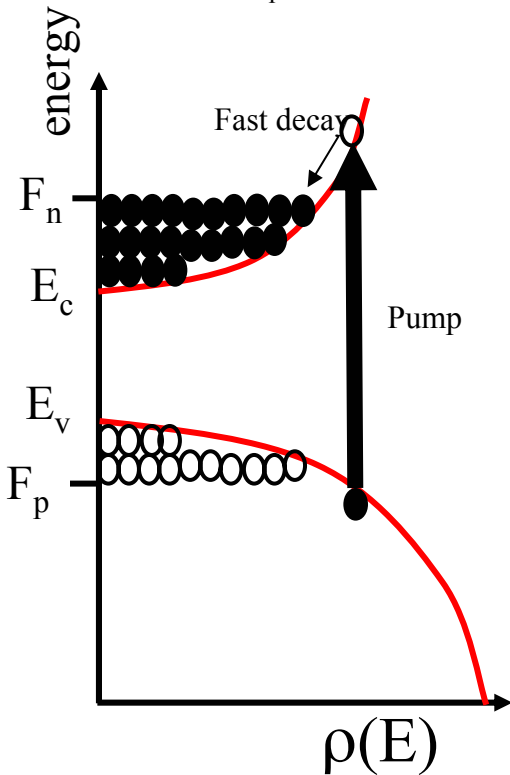
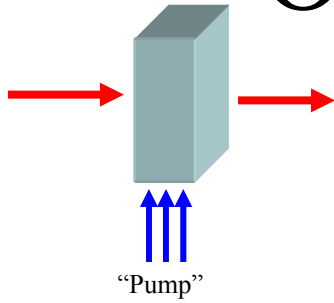


Optical absorption (?):



Discuss diagram in detail, including overlay of density of states, photon energy, and

Optical absorption (?):

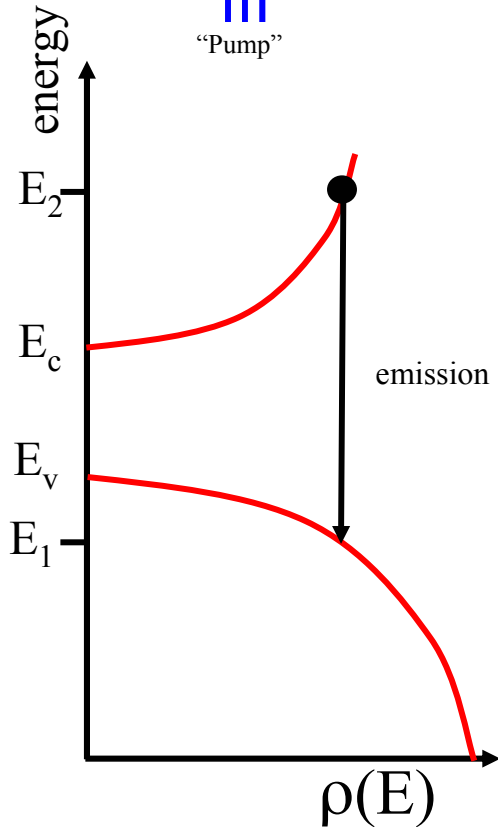
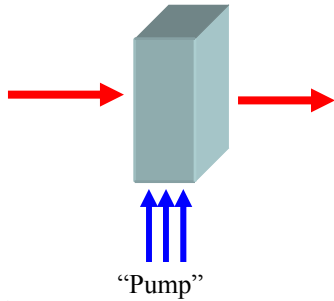


Red: equilibrium
Blue: "pumped"

Discuss log scale
on board (0).

Our goal in the next slides is to calculate quantitatively the blue curve.

Optical emission:



$$\hbar\omega_{\text{photon}} = E_2 - E_1$$

$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

$$\hbar k_v = \sqrt{2m_h^*(E_v - E_1)}$$

$$\hbar k_v = \hbar k_c$$

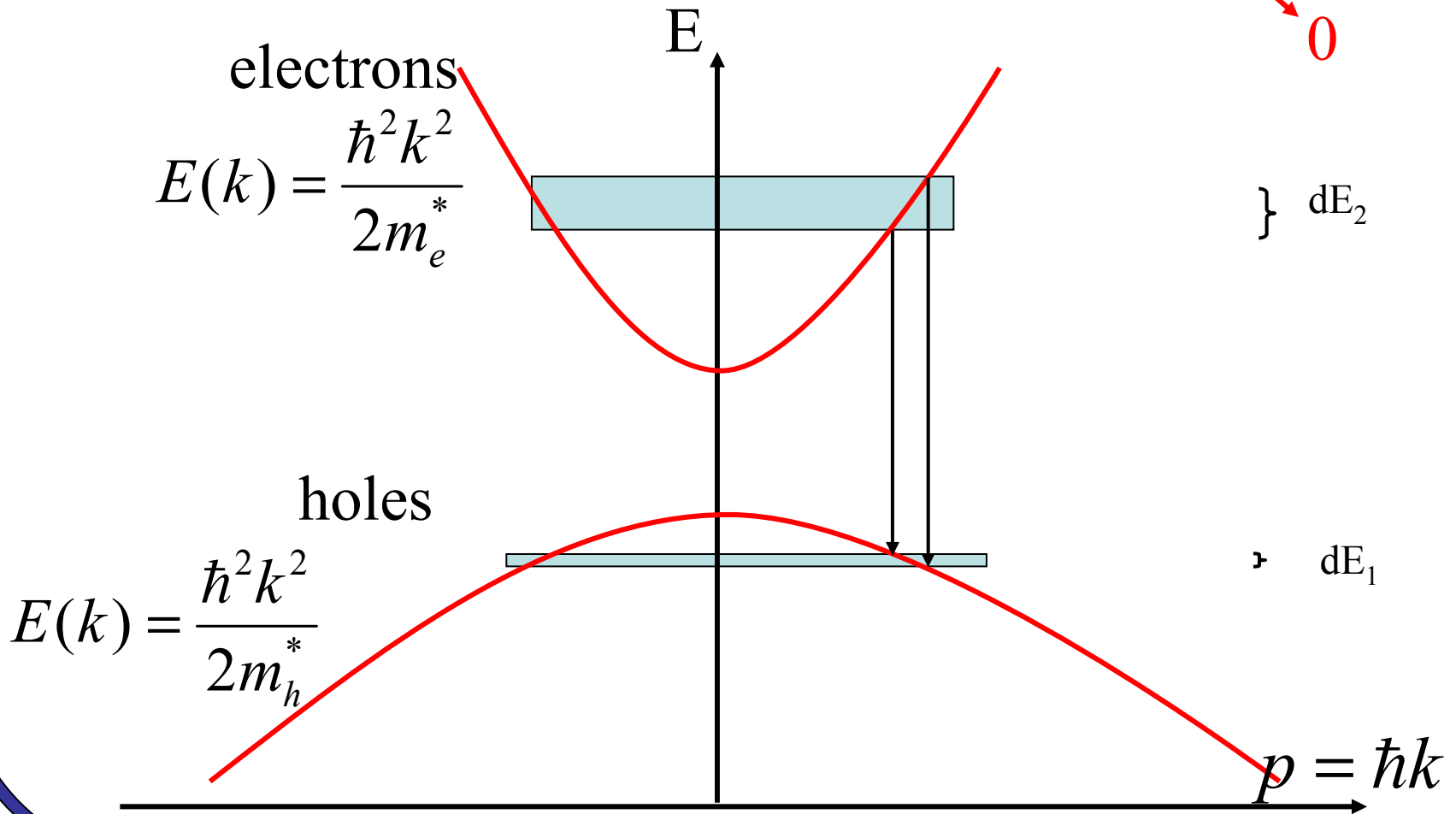
$$\Rightarrow E_2 - E_c = \frac{m_h^*}{m_e^*} (E_v - E_1)$$

E_2 and E_1 are *not* centered around midgap.

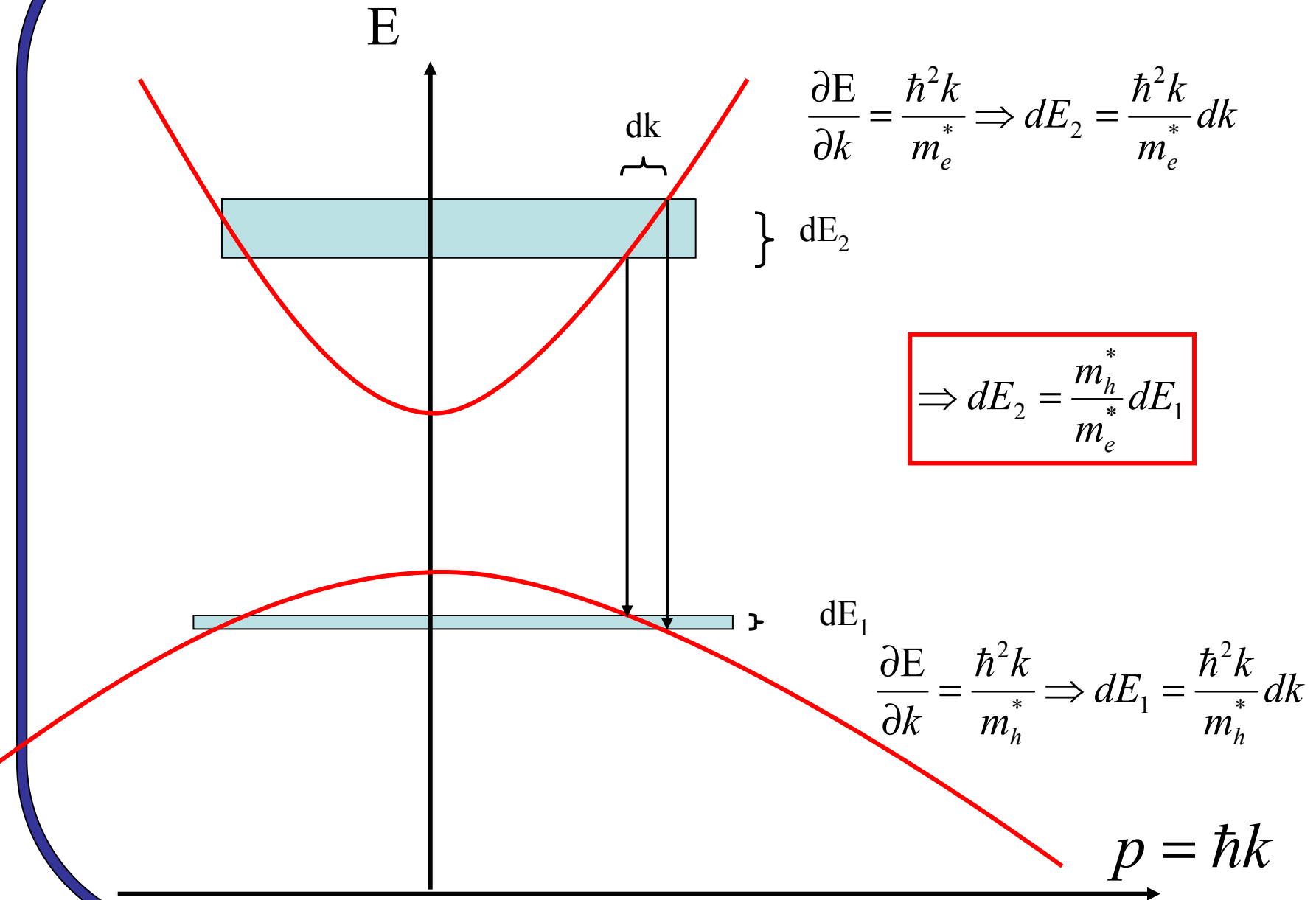
Optical emission:

$$E_{electron} (before) = E_{electron} (after) + \hbar\omega_{photon}$$

$$p_{electron} (before) = p_{electron} (after) + p_{photon}$$



Optical emission:



So far:

$$E_2 - E_c = \frac{m_h^*}{m_e^*} (E_v - E_1)$$

$$dE_2 = \frac{m_h^*}{m_e^*} dE_1$$

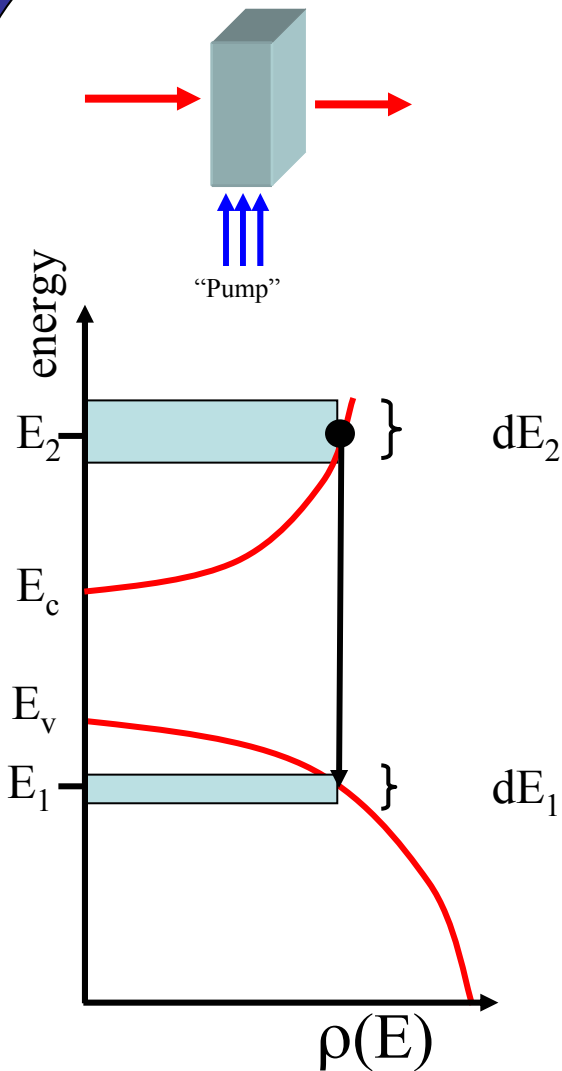
So far, we have assumed:

$$\hbar\omega_{\text{photon}} = E_2 - E_1$$

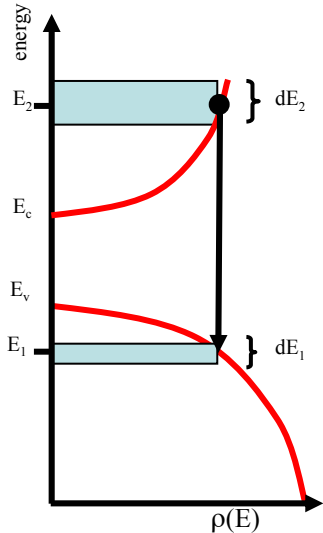
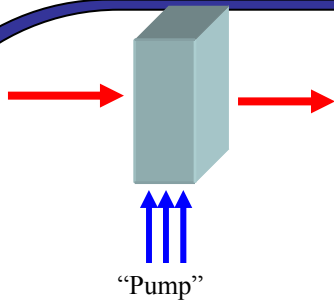
What if the incoming intensity is distributed in frequency such that $I(\nu)d\nu$ is the intensity between ν and $\nu+d\nu$?

How many states are there such that an incident intensity with total intensity $I(\nu)d\nu$ participates?

$$\rho_{\text{int}}(h\nu) = \frac{1}{2} \left[\frac{1}{\rho_c(E_2)} - \frac{1}{\rho_v(E_1)} \right]$$



So far:



$$R_{1 \rightarrow 2} = B_{1-2} \cdot \frac{1}{c} I(\nu) d\nu \cdot \rho_{jnt}(\nu) \cdot [f_\nu(E_1)(1 - f_c(E_2))]$$

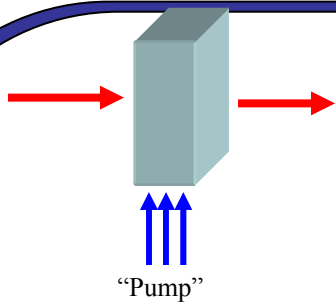
$$R_{2 \rightarrow 1} = B_{2-1} \cdot \frac{1}{c} I(\nu) d\nu \cdot \rho_{jnt}(\nu) \cdot [f_c(E_2)(1 - f_\nu(E_1))]$$

$$R_{2 \rightarrow 1} - R_{1 \rightarrow 2} = B_{2-1} \cdot \frac{1}{c} I(\nu) d\nu \cdot \rho_{jnt}(\nu) \cdot [f_c(E_2) - f_\nu(E_1)]$$

Power emitted = $h\nu$ * number of transitions/time = $h\nu$ * $(R_{21} - R_{12})$

$$\gamma(\nu) \equiv \frac{dI(\nu)/dz}{I(\nu)} = \frac{\text{power/volume}}{I(\nu)} = \frac{h\nu \cdot [R_{2 \rightarrow 1} - R_{1 \rightarrow 2}]}{I(\nu) d\nu}$$

$$\gamma(\nu) = B_{2-1} \cdot \frac{1}{c} \cdot \rho_{jnt}(\nu) \cdot [f_c(E_2) - f_\nu(E_1)]$$

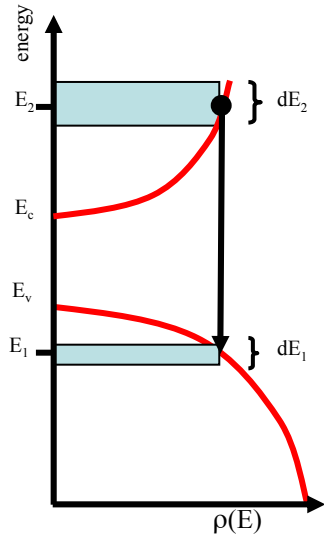


So far:

$$\gamma(\nu) = B_{2-1} \cdot \frac{1}{c} \cdot \rho_{jnt}(\nu) \cdot [f_c(E_2) - f_v(E_1)]$$

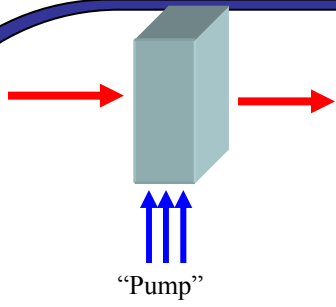
$$\rho_{jnt}(\nu) = \left(\frac{2m_e^* m_h^*}{m_e^* + m_h^*} \right)^{1/2} \sqrt{h\nu - E_{gap}}$$

$$\gamma(\nu) = K \cdot \sqrt{h\nu - E_{gap}} \cdot [f_c(E_2) - f_v(E_1)]$$



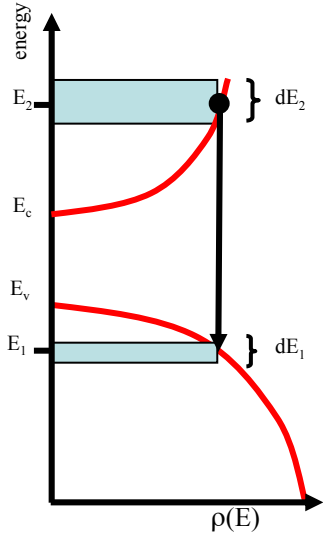
Three cases:

- 1) $h\nu < E_{gap}$
- 2) $E_{gap} < h\nu < F_n - F_p$
- 3) $h\nu > F_n - F_p$



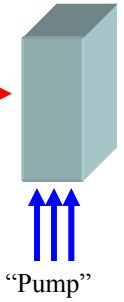
Case one: $h\nu < E_{\text{gap}}$

$$\gamma(\nu) = K \cdot \sqrt{h\nu - E_{\text{gap}}} \cdot [f_c(E_2) - f_v(E_1)]$$

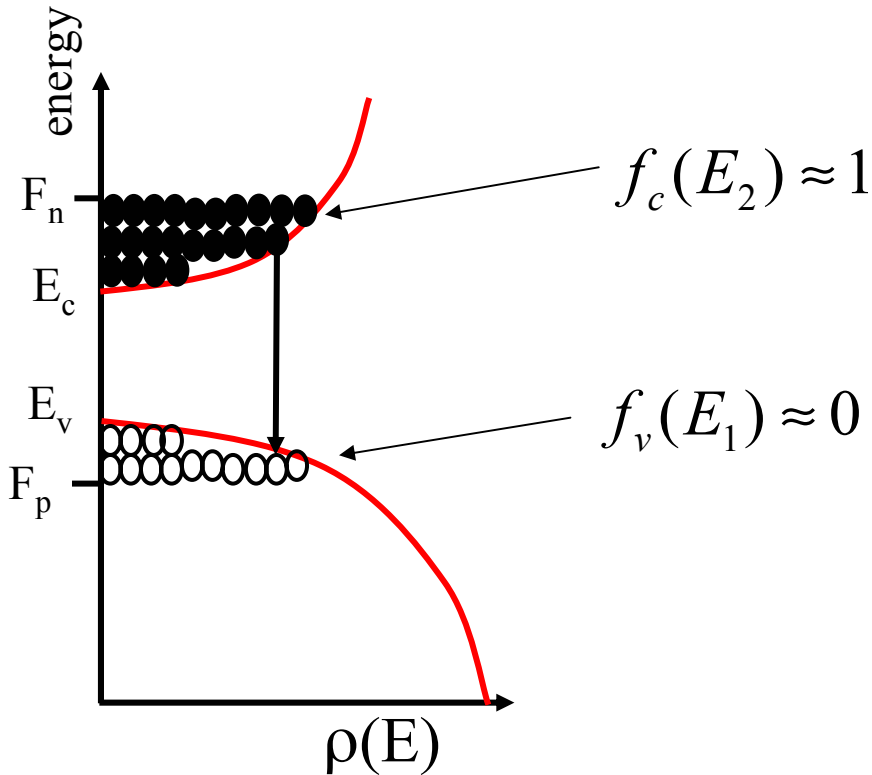


No absorption
No emission
 $\gamma=0$

Case two: $E_{\text{gap}} < h\nu < F_n - F_p$



$$\gamma(\nu) = K \cdot \sqrt{h\nu - E_{\text{gap}}} \cdot [f_c(E_2) - f_v(E_1)]$$

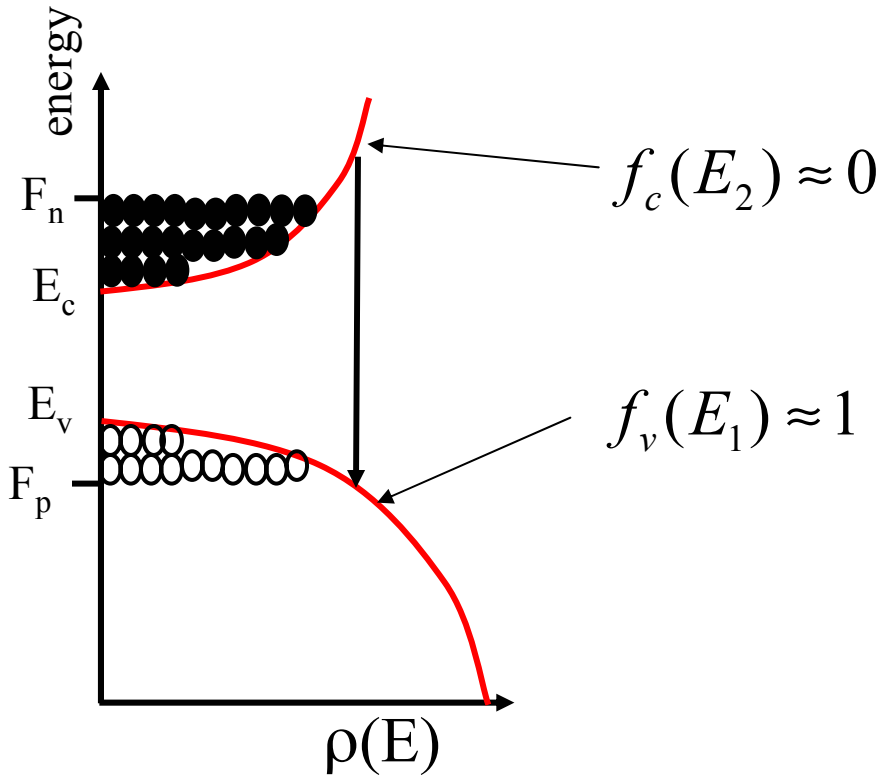
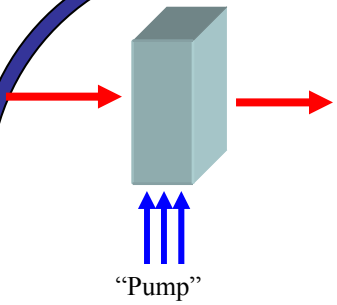


$$\gamma(\nu) \approx K \cdot \sqrt{h\nu - E_{\text{gap}}}$$

GAIN

Case three: $> F_n - F_p$

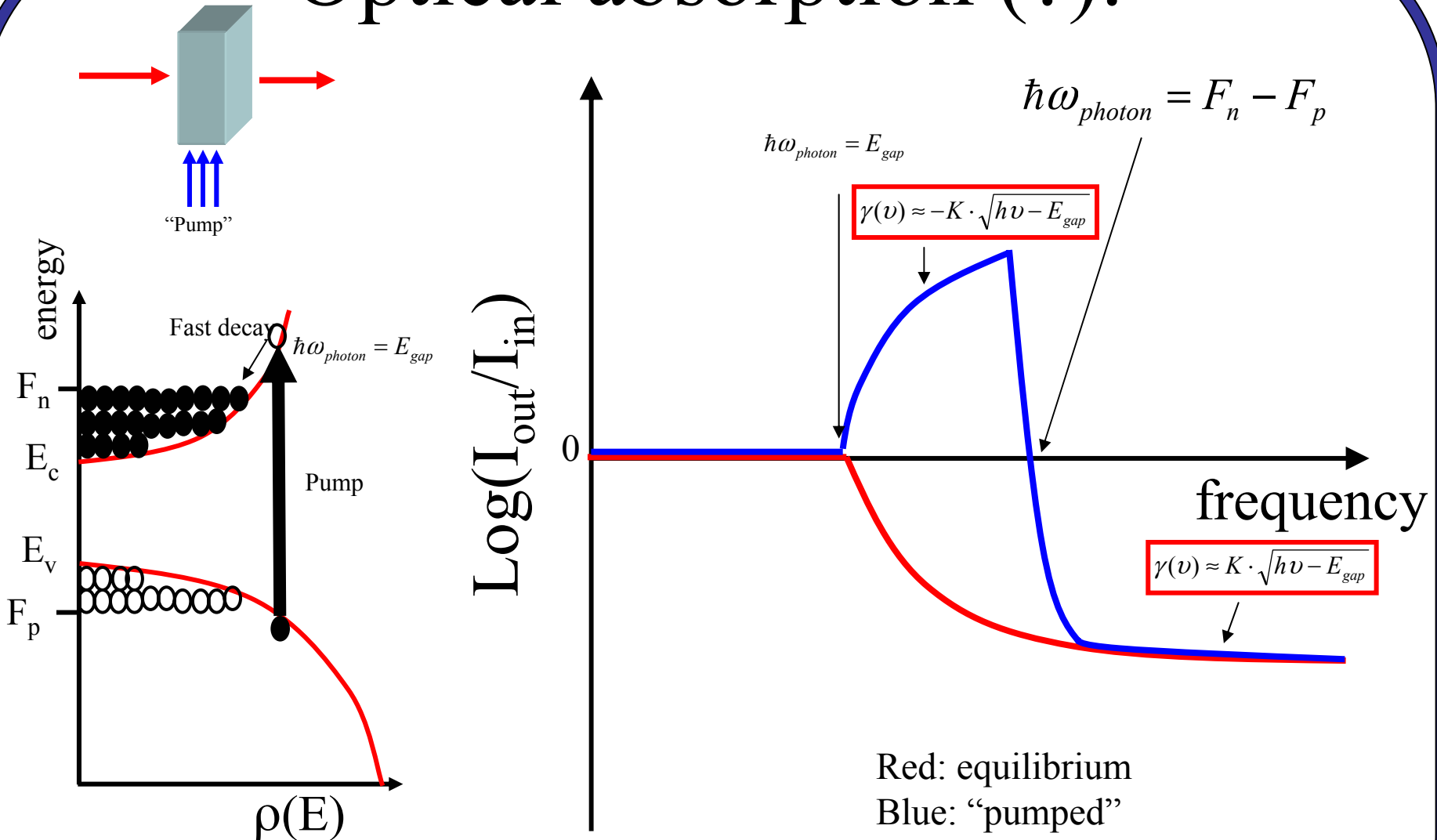
$$\gamma(\nu) = K \cdot \sqrt{h\nu - E_{gap}} \cdot [f_c(E_2) - f_v(E_1)]$$



$$\gamma(\nu) \approx -K \cdot \sqrt{h\nu - E_{gap}}$$

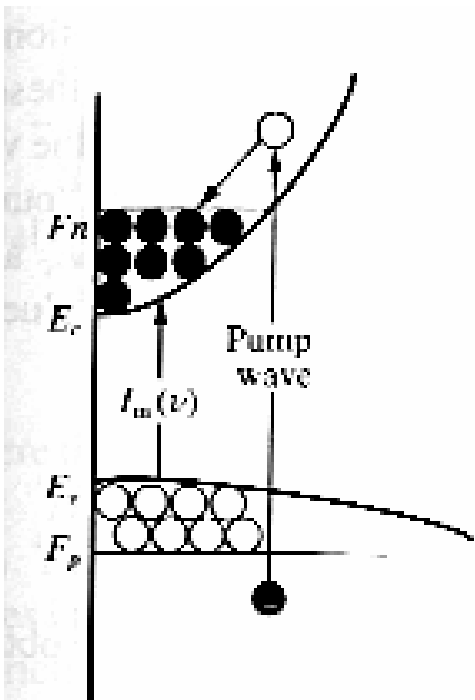
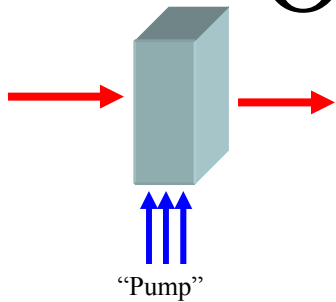
LOSS

Optical absorption (?):

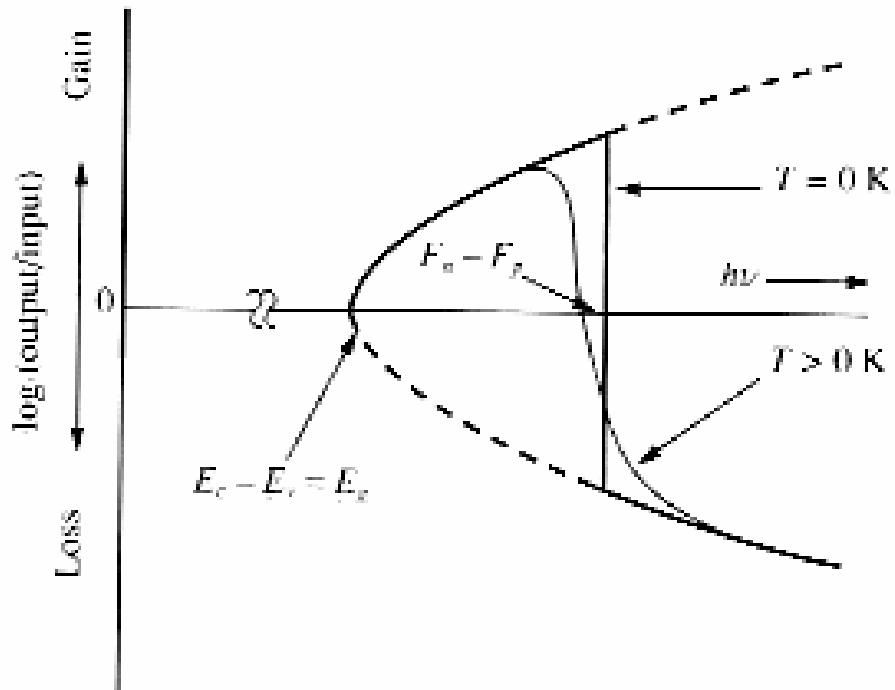


Our goal in the next slides is to calculate quantitatively the blue curve.

Optical absorption (?):



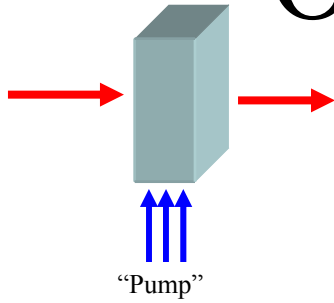
(b) The band diagram



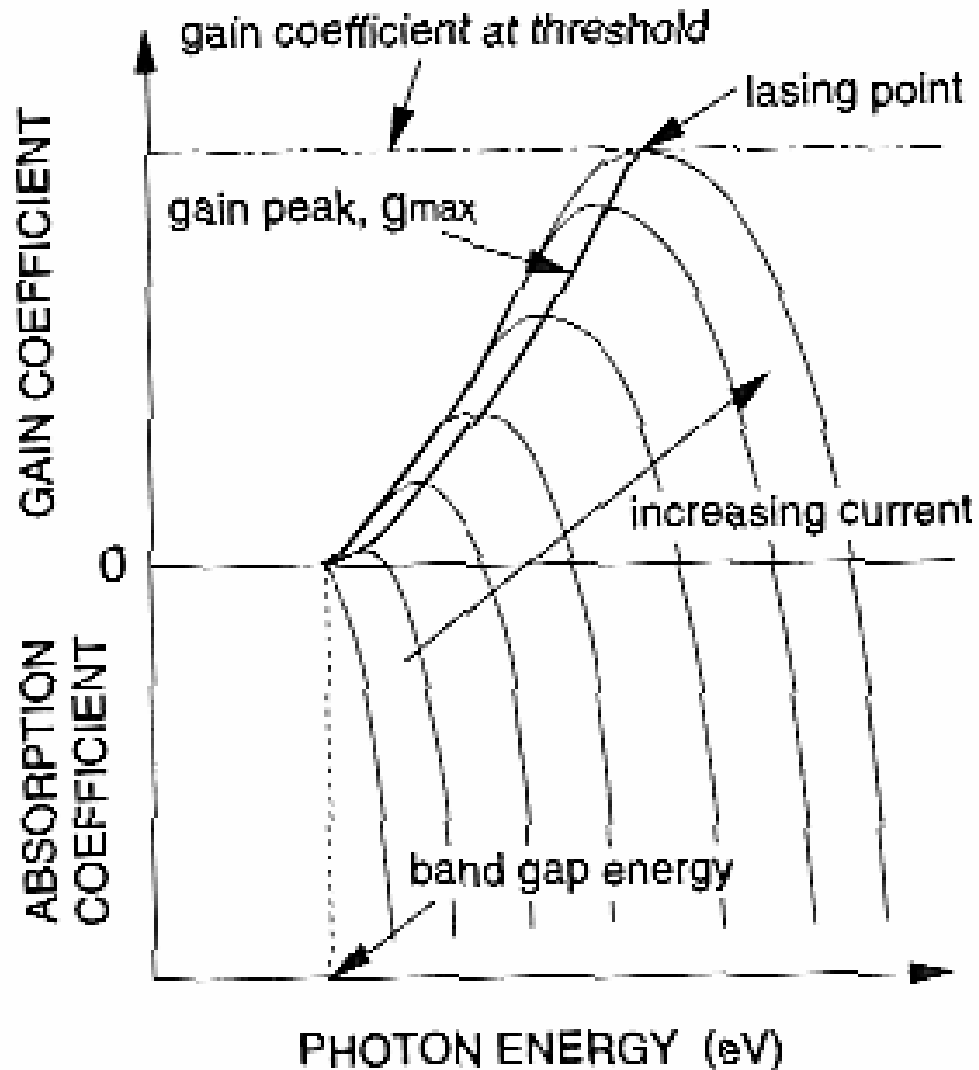
(c) The "data"

From Verdeyen

Optical absorption (?):

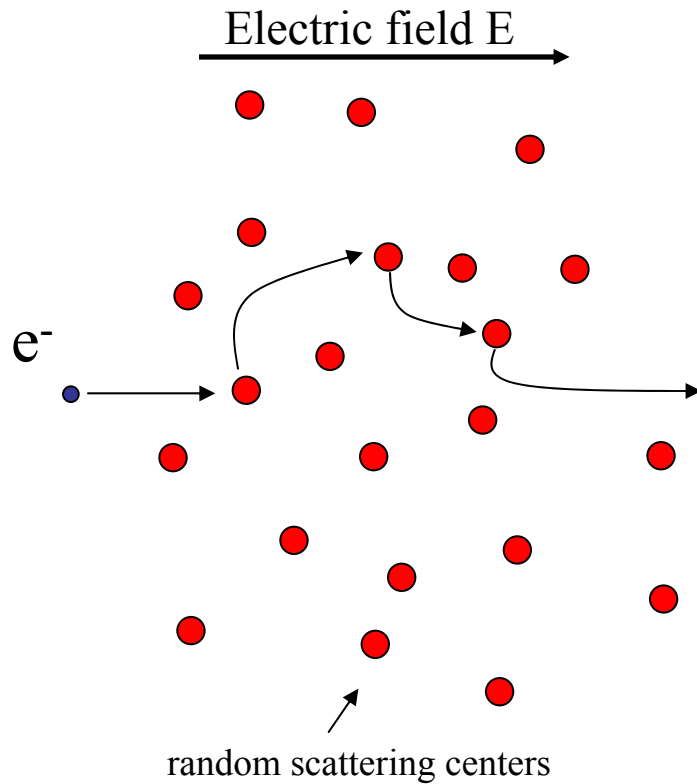


Discuss log scale
on board (0).



From Fukuda, Optical Semiconductor Devices

Drude model: Drift current



$$F = ma$$

$$eE = m \frac{\partial v}{\partial t}$$

$$v_{drift} = \frac{e\tau}{m} E$$

\underbrace{m}_{μ}

$$J = nev = \frac{ne^2\tau}{m} E = e \cdot \mu \cdot n \cdot E$$

Diffusion current

$$J = eD \frac{dn(x)}{dx}$$

Total current

$$J_n = e \cdot \mu_n \cdot n \cdot E + eD_n \frac{dn(x)}{dx}$$

E, n can depend on x!

Holes:

$$J_p = e \cdot \mu_p \cdot p \cdot E - eD_p \frac{dp(x)}{dx}$$

Diffusion equation

Cross section area of length dx : (draw on board)

$$\frac{\partial n}{\partial t} = \frac{1}{e} \frac{J(x) - J(x + \Delta x)}{\Delta x} - \left(\frac{1}{\tau_n} \right) n$$

$$\Rightarrow \frac{\partial n}{\partial t} = \frac{1}{e} \frac{\partial J(x)}{\partial x} - \left(\frac{1}{\tau_n} \right) n$$

$$J = eD \frac{dn(x)}{dx}$$

$$\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2} - \left(\frac{1}{\tau_n} \right) n$$

Steady state

$$\frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2} - \left(\frac{1}{\tau_n} \right) n = 0$$

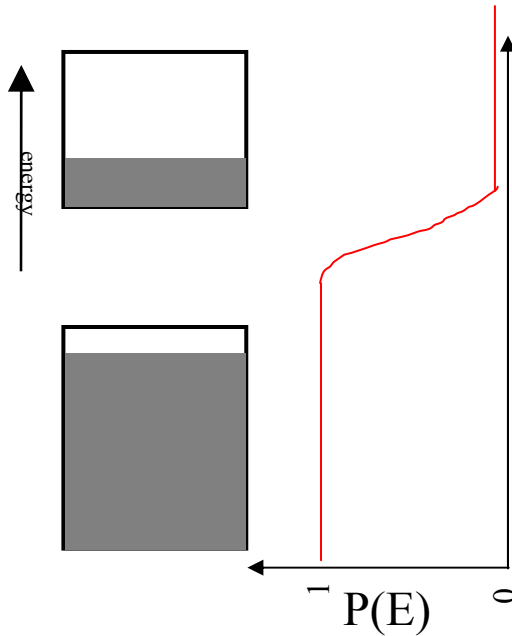
$$\Rightarrow D \frac{\partial^2 n}{\partial x^2} = \left(\frac{1}{\tau_n} \right) n$$

$$\Rightarrow n(x) = n(x=0) \cdot \exp\left(-\frac{x}{\sqrt{D\tau_n}} \right)$$

$$\sqrt{D\tau_n} \equiv \text{diffusion length}$$

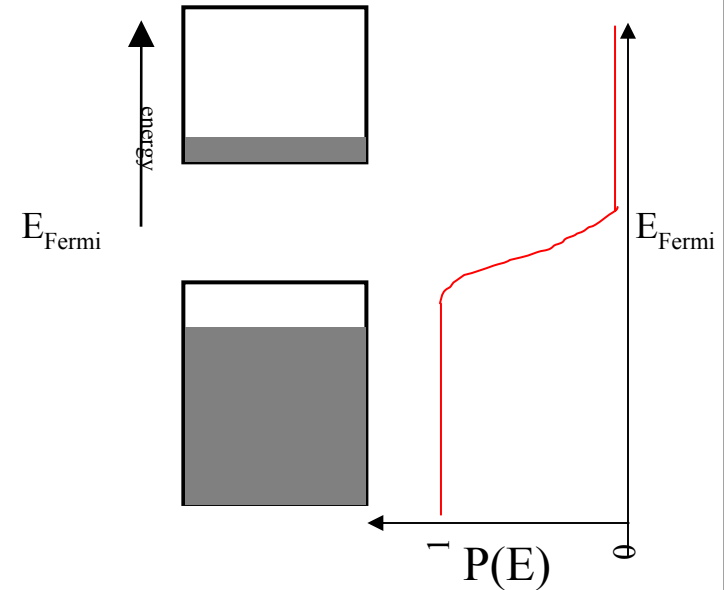
Last time:

n type:



$$n > p$$

p type:

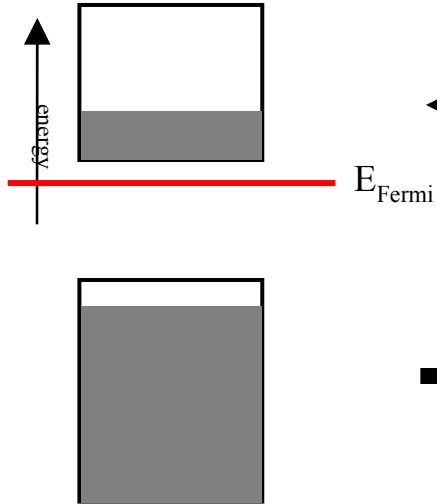


$$n < p$$

What if we bring n and p type together?
p n diode

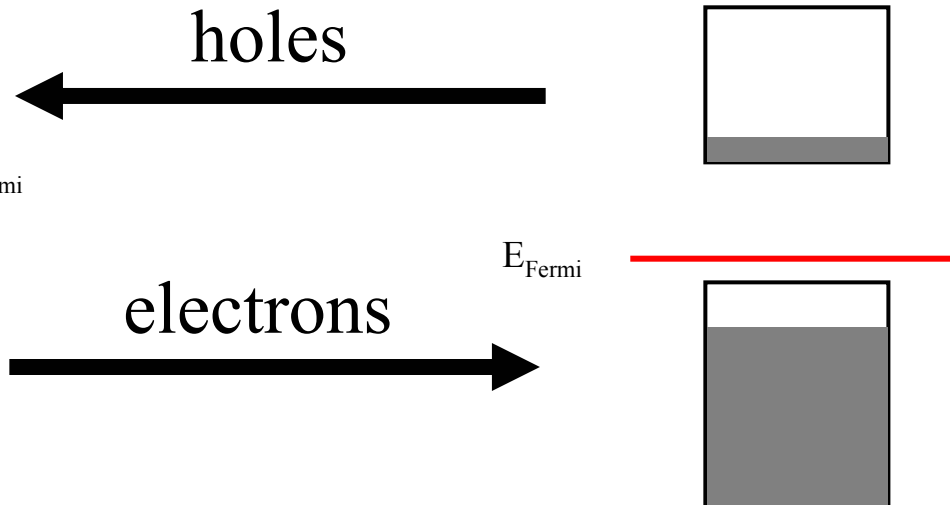
p n diode

n type:



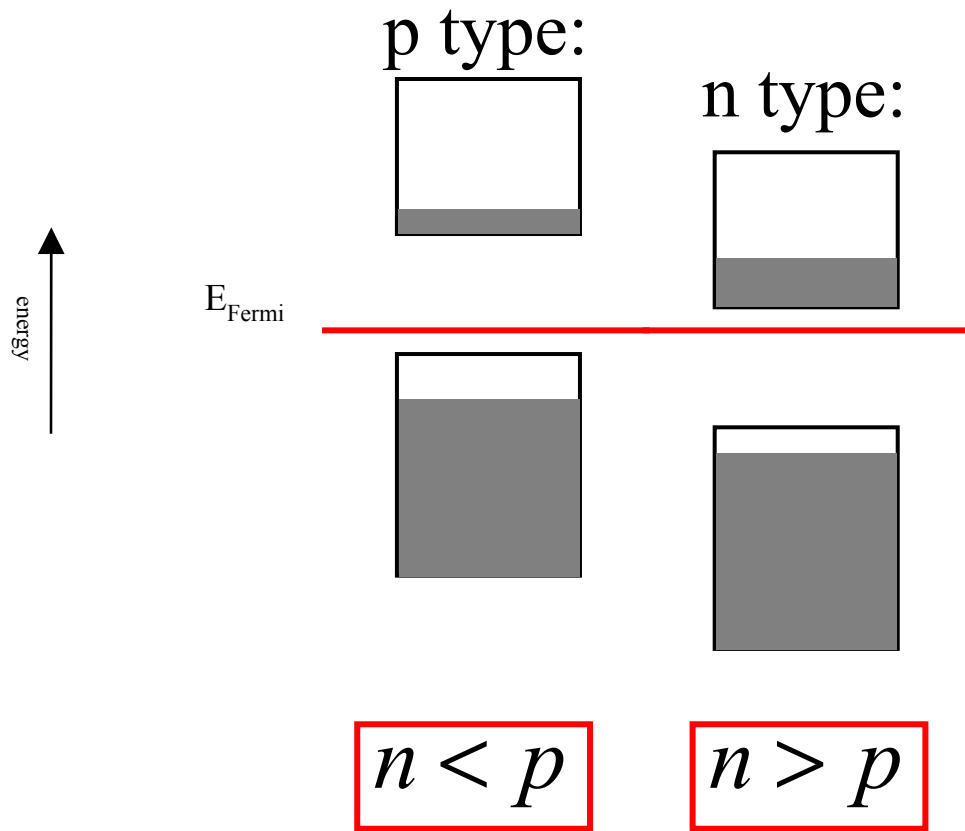
$$n > p$$

p type:



$$n < p$$

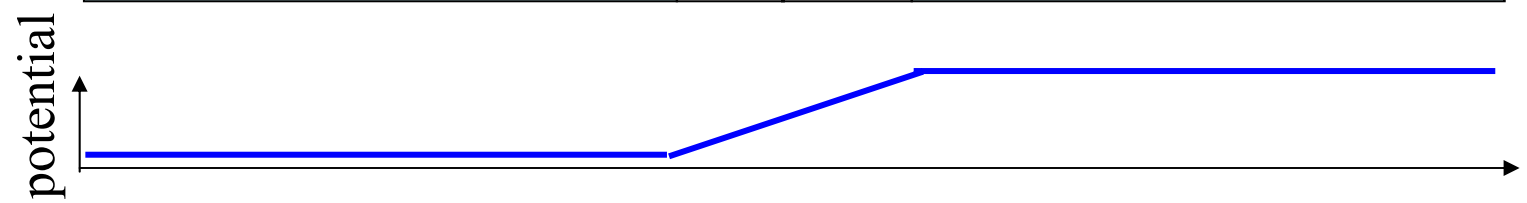
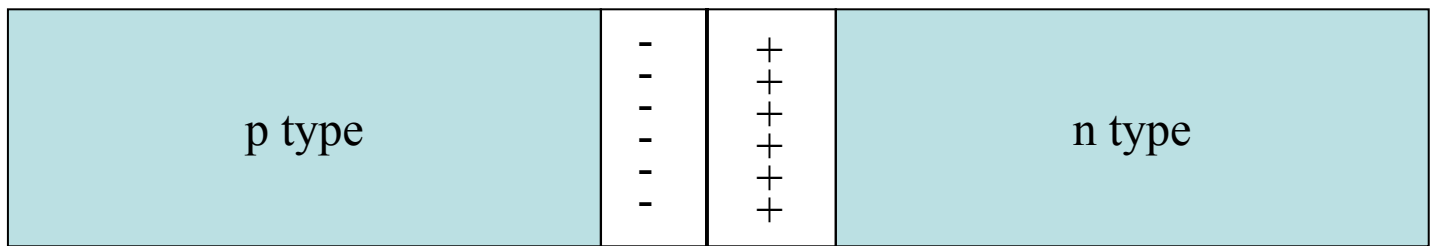
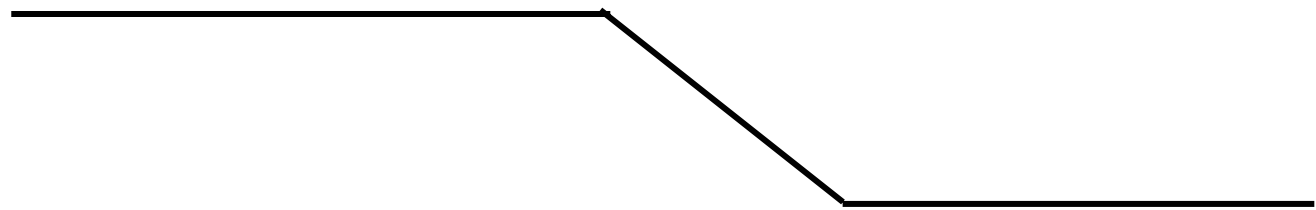
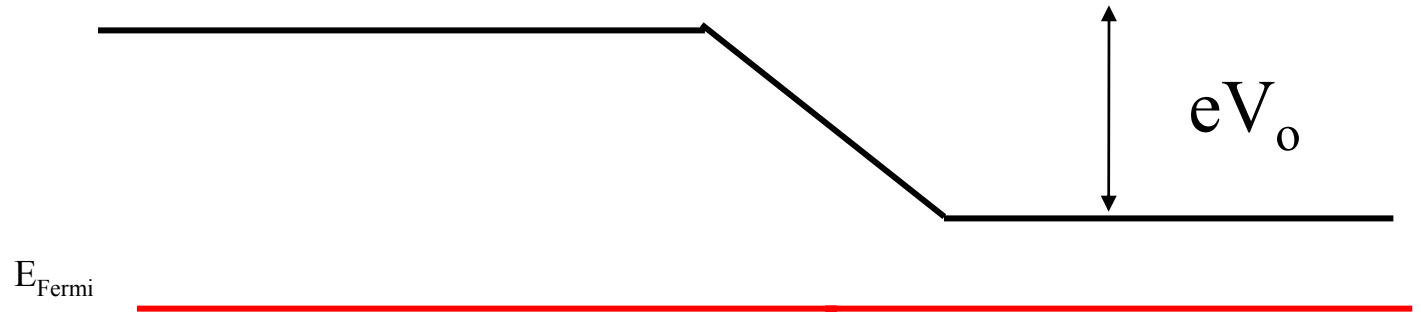
p n diode



p n diode

p type:

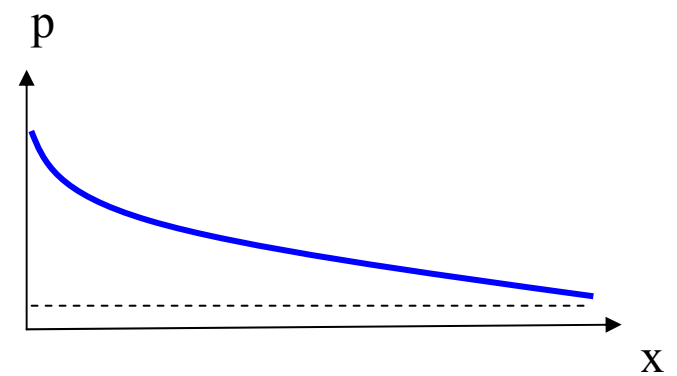
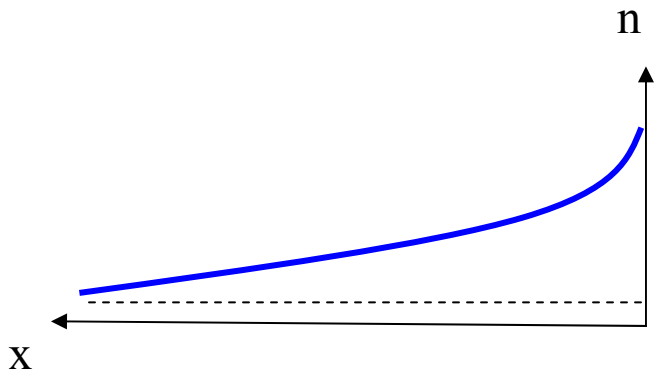
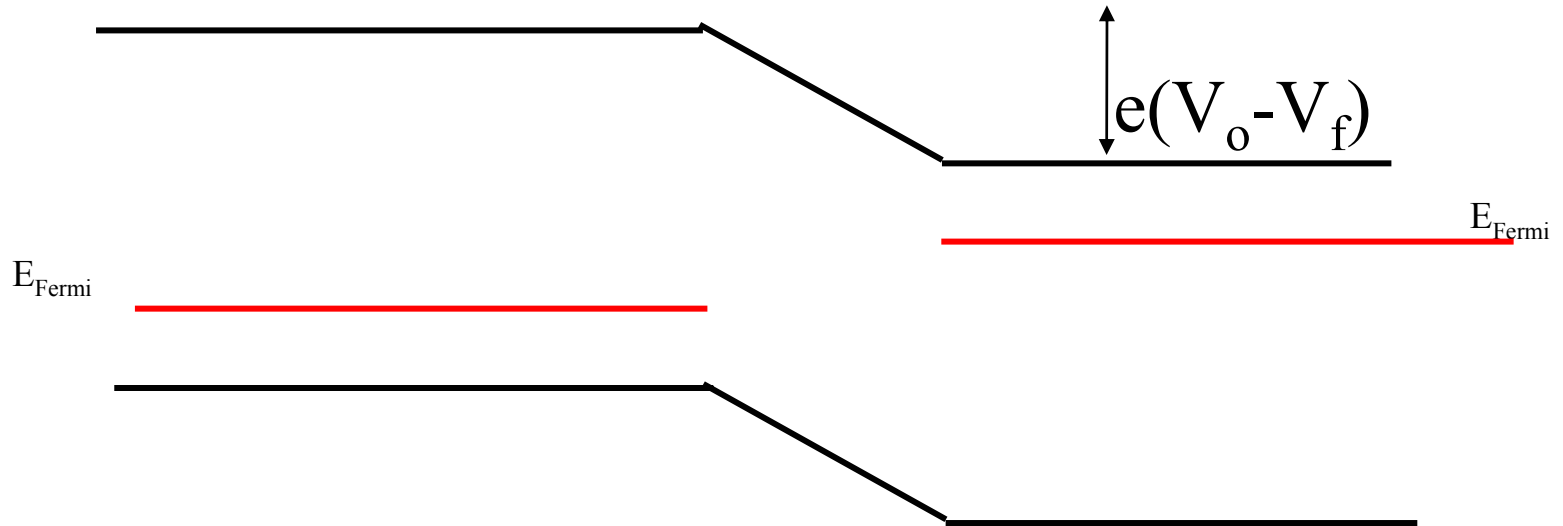
n type:



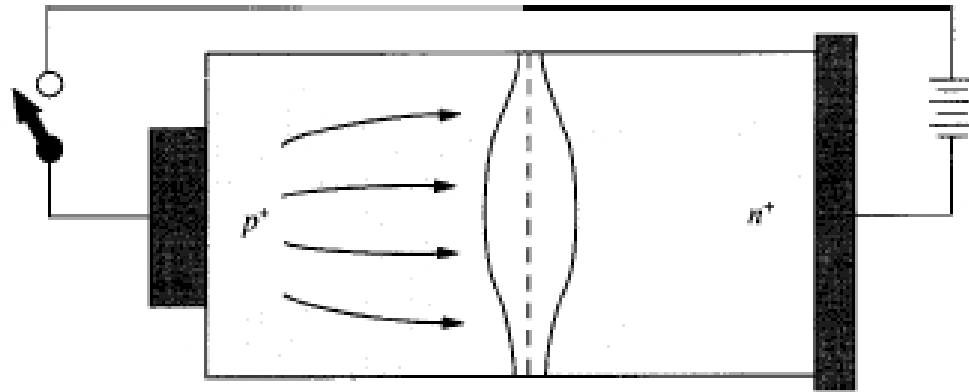
Forward bias

p type:

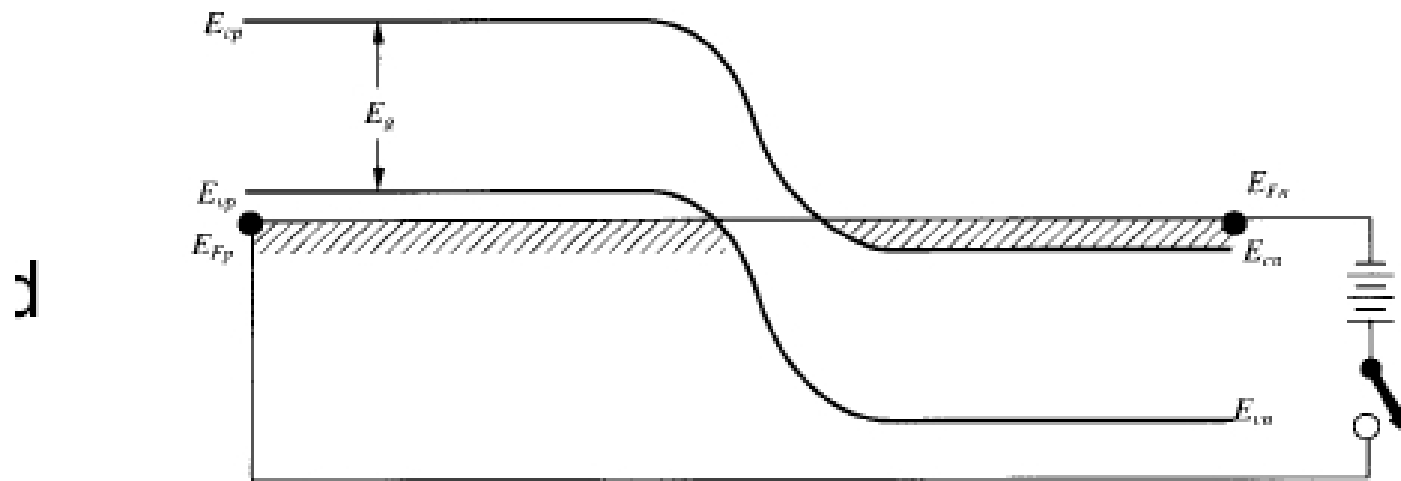
n type:



Laser diode



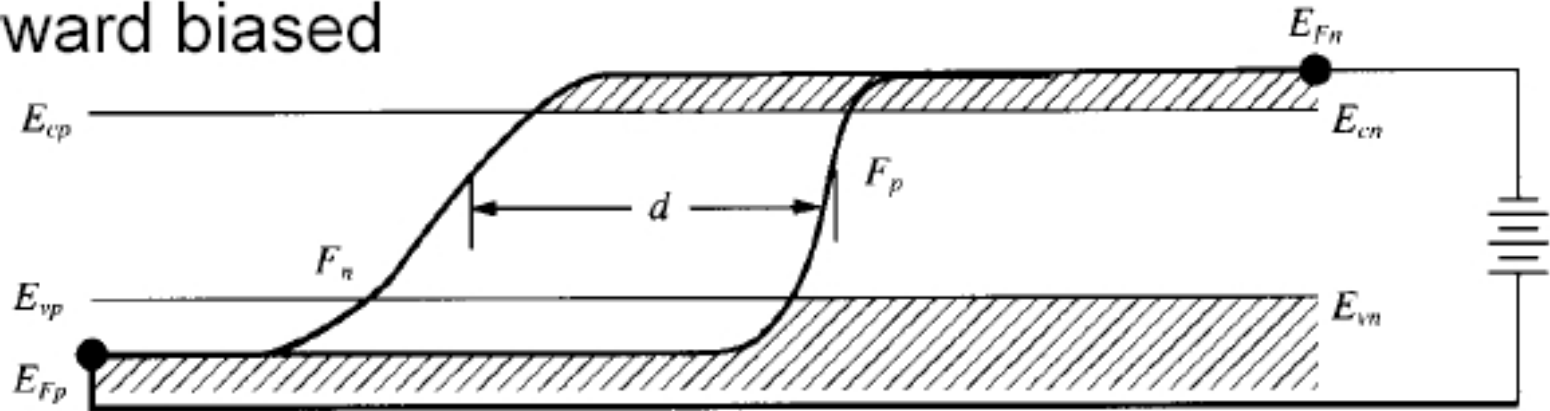
(a)



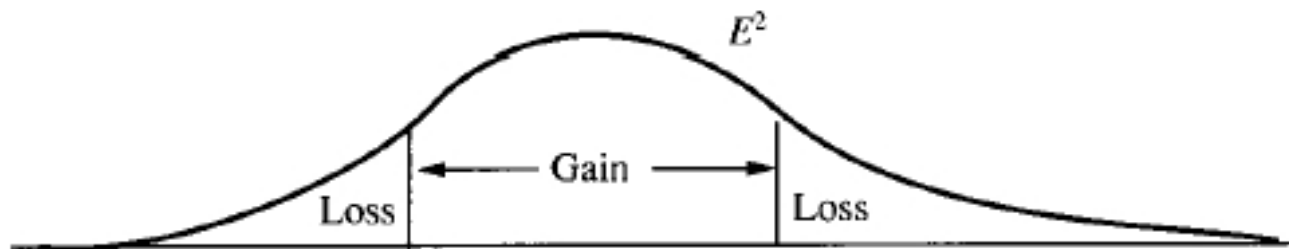
(b)

Laser diode

forward biased



(c)



(d)

Threshold current

- Injected electrons = current
- Recombination rate $\sim n p$
- Need input current = recombination rate (steady state)
- Need $n, p \sim 10^{18} \text{ cm}^{-3}$
- $J \sim 10 \text{ kA/cm}^2$ VERY BIG!