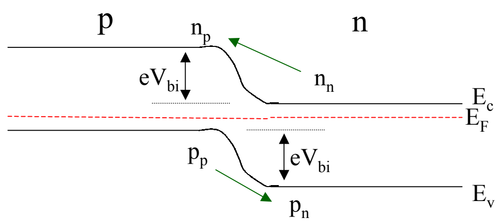
What is the built-in voltage V_{bi}?



$$eV_{bi}=E_{Fn}-E_{Fp}$$

$$E_{Fp}=-k_bT\ln\left(\frac{p}{N_V}\right)=-k_bT\ln\left(\frac{N_a}{N_V}\right) \qquad E_{Fn}=-k_bT\ln\left(\frac{p_n}{N_V}\right)=-k_bT\ln\left(\frac{n_i^2}{N_VN_d}\right)$$

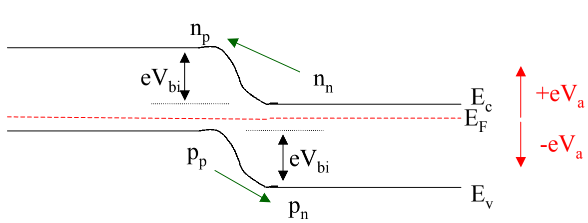
$$\therefore V_{bi}=\frac{k_bT}{e}\ln\left(\frac{N_aN_d}{n_i^2}\right)$$

We can also re-write these to show that eV_{bi} is the barrier to minority carrier injection:

$$p_n=p_pe^{\frac{-eV_{bi}}{k_bT}} \qquad n_p=n_ne^{\frac{-eV_{bi}}{k_bT}}$$

Qualitative Effect of Bias

- Applying a potential to the ends of a diode does NOT increase current through drift
- The applied voltage upsets the steady-state balance between drift and diffusion, which can unleash the flow of diffusion current
- "Minority carrier device"



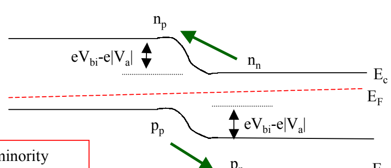
$$n_p=n_ne^{\frac{-e(V_{bi}-V_a)}{k_bT}} \qquad p_n=p_pe^{\frac{-e(V_{bi}-V_a)}{k_bT}}$$

Current Flow - Recombination, Generation

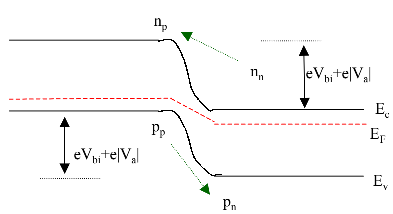
Qualitative Effect of Bias

- Forward bias (+ to p, - to n) decreases depletion region, increases diffusion current exponentially
- Reverse bias (- to p, + to n) increases depletion region, and no current flows ideally

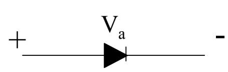
Forward Bias

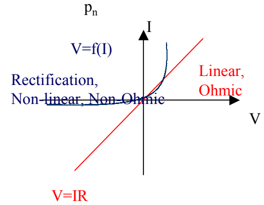


Reverse Bias



Solve minority carrier diffusion equations on each side and determine J at depletion edge





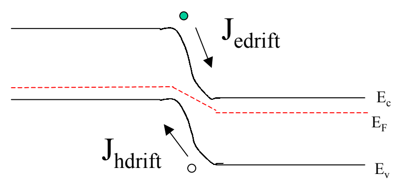
$$J = q\left(\frac{D_e}{L_e}\frac{n_i^2}{N_a} + \frac{D_h}{L_h}\frac{n_i^2}{N_d}\right)\left(e^{\frac{qV_a}{k_bT}} - 1\right) = J_o\left(e^{\frac{qV_a}{k_bT}} - 1\right)$$

$$\frac{D_i}{\ } = \frac{k_bT}{\ } \qquad L_i = \sqrt{D_i\tau_i}$$

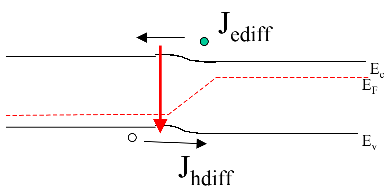
Devices

Solar Cell/Detector

Reverse Bias/Zero Bias



LED/Laser



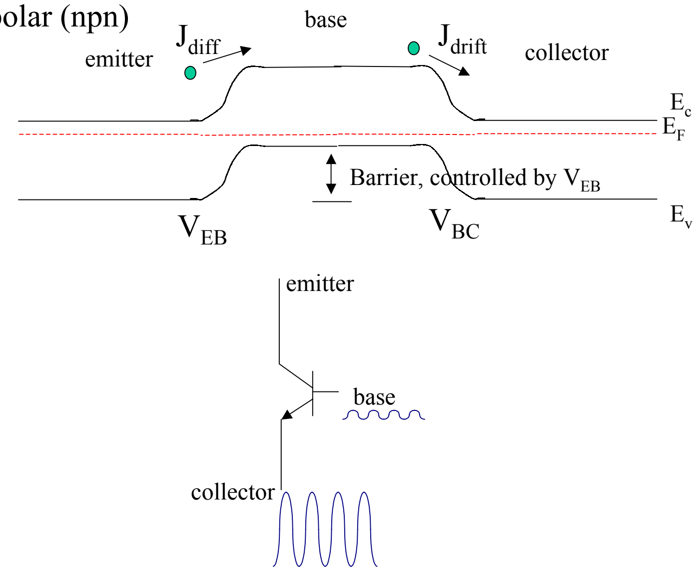
Laser
- population inversion
- reflectors for cavity

Potential Wells - Heterojunction Lasers

Energy bands of a light-emitting diode under forward bias for a double heterojunction AlGaAs-GaAs-AlGaAs structure.

Transistors

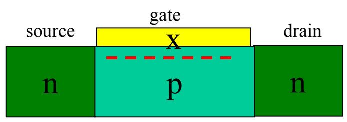
Bipolar (npn)



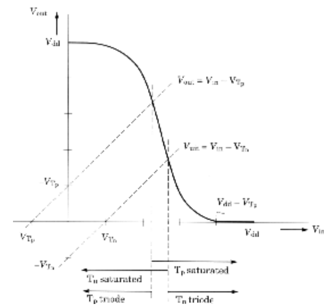
Field Effect

Transistors

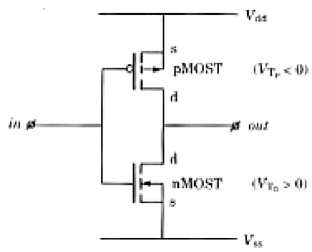
FET

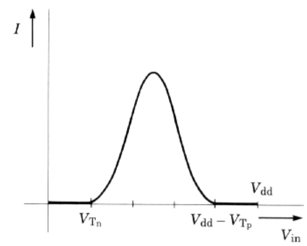


x=metal is a MESFET
x=metal/poly Si/oxide is a MOSFET

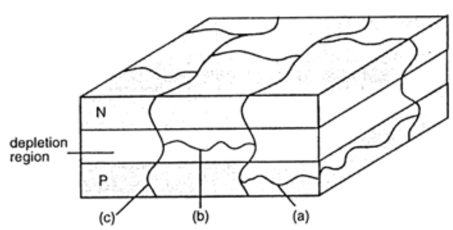


CMOS





Polycrystalline Solar Cells



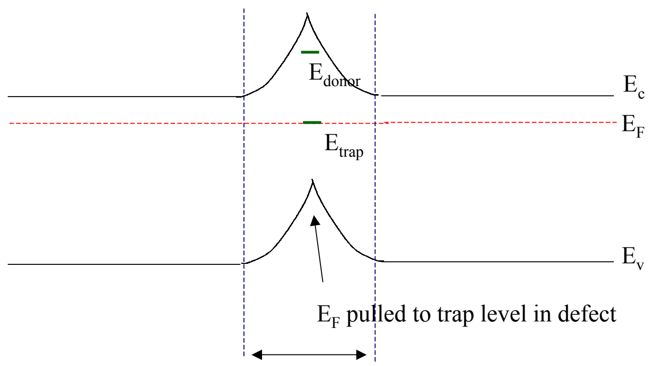
- Local field enhances minority carrier capture → reduced minority carrier lifetime
- majority carriers experience potential barrier → increased resistivity; reduced effective mobility
- boundaries intersecting p-n junction provide shorting paths → increase I_o, decrease V_{oc}.

Effect of Traps (Defects) on Bands

- Trapping (Fermi level in defect) creates depleted regions around defect

$$E_F = E_g + k_b T \ln\left(\frac{N_d}{N_C}\right)$$

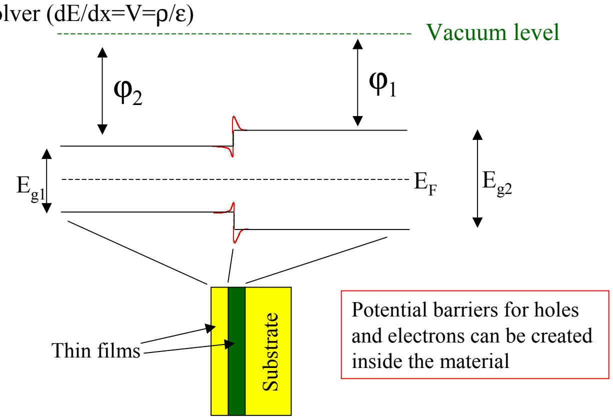
- E_F position in semiconductor away from traps in n-type material
- E_F pulled to mid-gap in defect/trap area



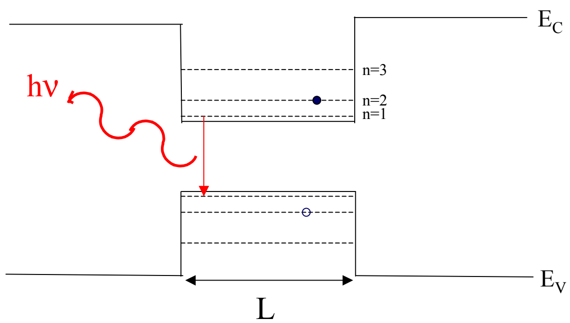
Other Means to Create Internal Potentials:

Heterojunctions

- Different semiconductor materials have different band gaps and electron affinity/work functions
- Internal fields from doping p-n must be superimposed on these effects: Poisson Solver (dE/dx=V=ρ/ε)



Quantum Wells



If we approximate well as having infinite potential boundaries:

$k = \frac{n\pi}{L}$ for standing waves in the potential well

$$E = \frac{\hbar^2 k^2}{2m^*} = \frac{h^2 n^2}{8m^* L^2}$$

We can modify electronic transitions through quantum wells

Artificially Modulated Structures

Photodetectors/Solar Cells

E-h pairs generated by photons with energy

$$h\gamma \geq E_g$$

are separated by the built-in potential gradient at the p-n junction.

The current voltage characteristics are given by

$$I = I_o\left[\exp\left(qV/kT\right) - 1\right] - I_p$$

where I_p is the photo-induced "reverse current."

Junctions/Functions

Junction	Function	Application
P/n Metal/semiconductor	Injection/diffusion/collection Blocking (reverse bias)	p-n rectifier, switch p-n-p transistor
	Acceleration/breakdown Tunneling	Avalanche and tunnel diodes
	Injection/confinement/recombination	LED, injection laser
	Generation/separation	Solar cell, photodiode
	Separation/confinement	High electron mobiity devices Quantum devices
M/I/S	Inversion/depletion/accumulation	MOSFET