Semiconductors

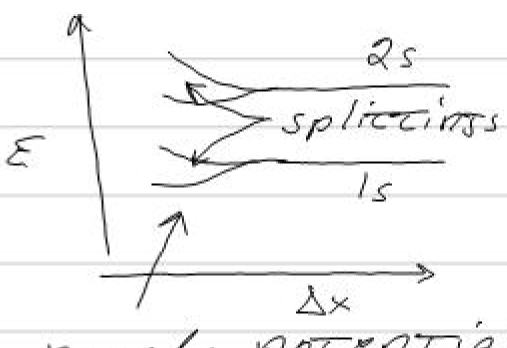
Solids categorized by electrical conductivity,

CPU's, PROM's, FPGA, diodes, transistors

Conductors	$\rho\,(\Omega m)$
metals (Cu)	$\lesssim 10^{-7}$
alloys (Nichrome)	$\sim 10^{-6}$
Semiconductors	
Silicon, Ge	10^{-4} - 10^{3}
Insulators	
Rubber	$\gtrsim 10^{8}$

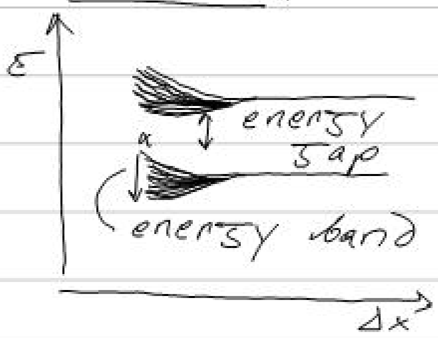
Can be understood by considering impact of large #'s of atoms on individual wave functions.

2 atoms:



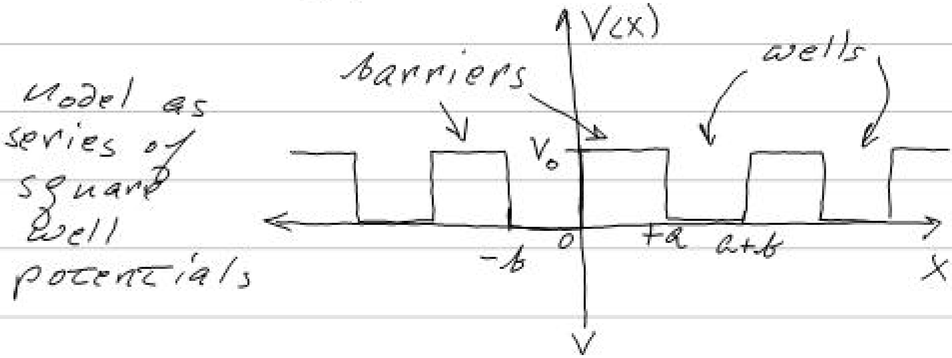
nearby potential well causes splittings

N atoms:



Kronig-Penney Model:

Consider an e^- in a lattice of atoms:



In a particular well, free particle

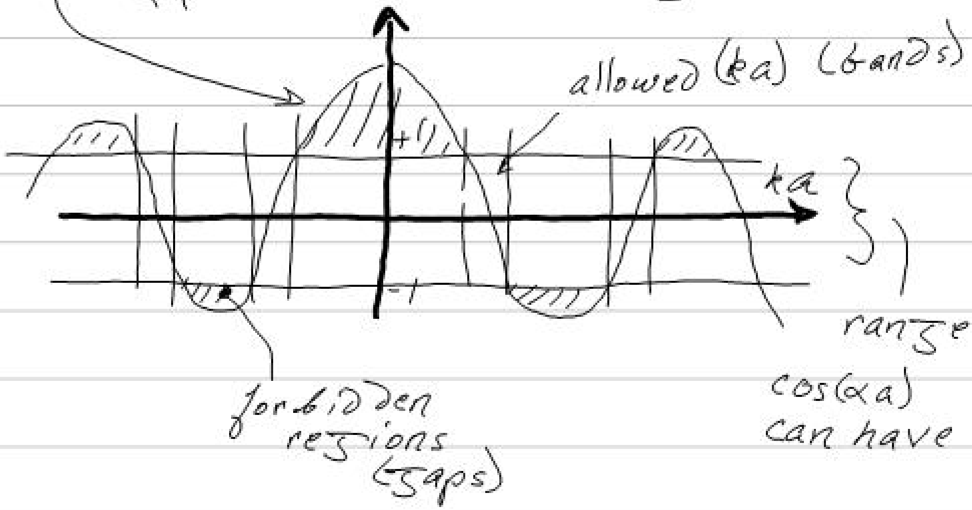
$$\underline{\psi(x) = Ae^{ikx} + Be^{-ikx}} \quad k^2 = \frac{2mE}{\hbar^2}$$

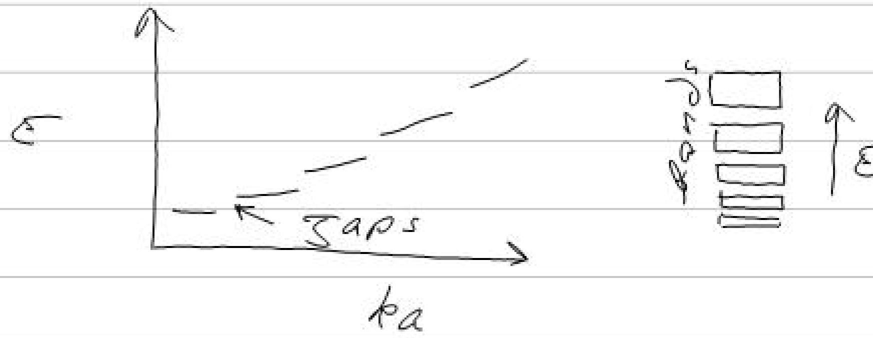
In each barrier $(E < V_0)$

$$\underline{\psi(x) = Ce^{\alpha x} + De^{-\alpha x}} \quad \alpha^2 = \frac{2m(V_0 - E)}{\hbar^2}$$

Boundary conditions give relation

$$\left[\frac{\alpha^2 b}{2k}\sin(ka) + \cos(ka)\right] = \cos(\alpha a)$$

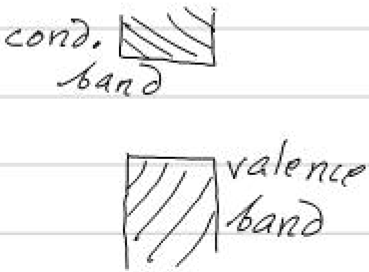




Band theory helps classify materials

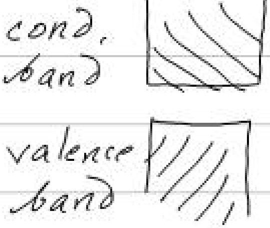
conductors

- easy to move bound e^-s into very high level "conduction band"
- no 'gap' in way of e



insulators

- large (several eV) gap between conduction & valence bands
- cannot get e^-s into conduction band



Semiconductors

- valence & conduction bands close
  $\Delta E \sim 1 eV$
- can get modest current

Fermi - Statistics & Hole Generation

Fermi-Dirac statics gives a scale factor to the # density of states

$$F_{FD} = \left[e^{(\varepsilon - \varepsilon_F)/kT} + 1 \right]^{-1}$$

As T rises:

- increasing fraction of time
  - e^- in conduction band ($\varepsilon > \varepsilon_F$)
  - so ρ decreases → as observed

Holes:

- e^- moving along in conduction band

- leaves behind positively charged 'hole' in valence band
- intrinsic semiconductor

$$N_{-CB} = N_{+CB}$$

n-Type Semiconductors

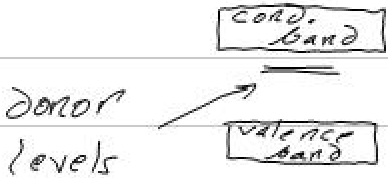
of conduction e^-s controlled by exponential part of F_{FD}

very few $\Rightarrow$ small current

Doping: add a small quantity of certain atoms

- can enhance the e^- that are in conduction band
- will have e^- that are very close to conduction band

Example: Arsenic $4s^2 4p^3$



5th e^- is 0.05 eV from conduction band

$\downarrow$

'donor e^-'

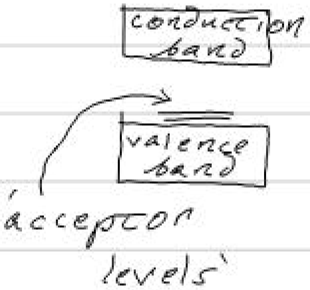
"n(egative)-type"

p-Type Semiconductor

One could also add a dopant having fewer e^- than Si

Example: Indium $5s^2 5p^1$

→ there's an extra hole per Indium atom



- E levels just above valence band ("acceptor levels")
- easily accept e^- from valence band

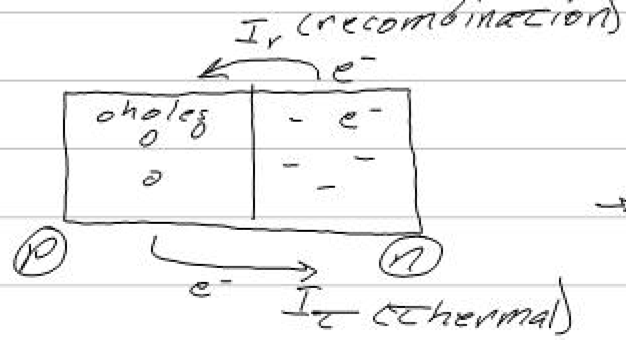
When E-field applied: doping causes an increase in current (decrease in R)

→ observe apparent flow of holes in direction of $\vec{E}$

"positive-type"

p-n Junction Diodes

Join a p-type + n-type semiconductor



No Bias Case

$I_t = -I_r$

→ e^- on n-side want to "recombine" with holes in p-side : I_r

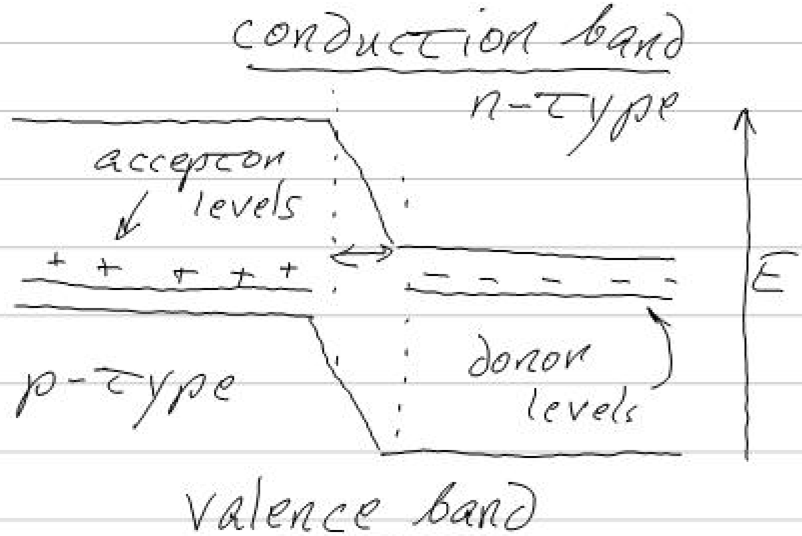
→ small current from thermal e^- which get into acceptor band : $I_{thermal}$

Energy Bands In a Diode:

No Bias

Acceptor + Donor levels

→ @ same E



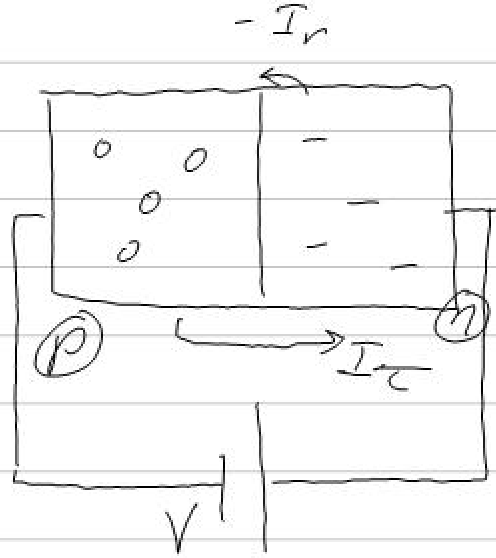
Reverse Bias

I_r reduced due to potential difference

⇓

I_t remains same

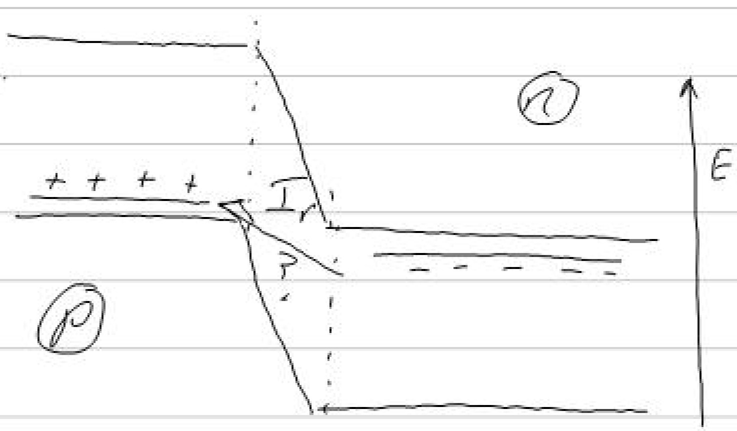
$|I_t| > |I_r|$



Very small net flow of e^-s from p to n : I in opposite direction

Reverse Bias

e^- in n-type no must pass an Energy "hill" to get to p-type acceptors

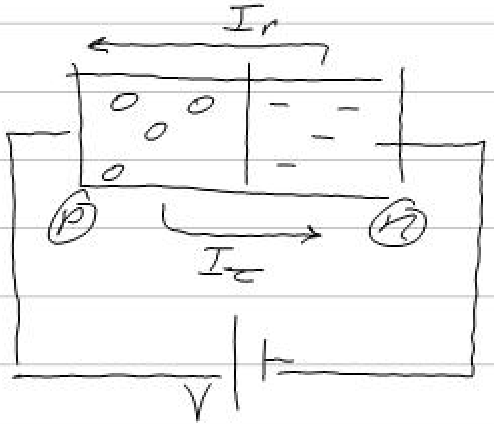


∴ I_r is small

Forward Bias

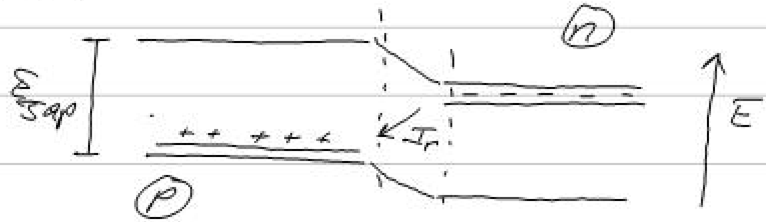
I_t same small value

I_r much larger:
→ e^- already want to go this way



$|I_r| >> |I_t|$ → total I large going from n → p

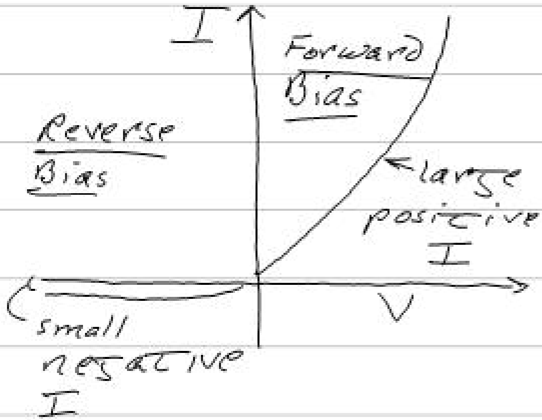
Forward Bias



E barrier is gone
- now e^- donors move thru conduction band and deexcite to acceptor levels
→ can generate heat or light

Light Emitting Diodes

E_γ = gap energy, E_{gap}



@ room Temperature:

$$I^{\text{No Bias}}_{n\to p} \propto N e^{-eV_0/kT} = I_0$$

(# in conduction band

Forward Bias:

$$I \propto N e^{-e(V-V_0)/kT}$$

$$= I_0 e^{eV/kT}$$

- plus motion of holes ($=-I_0$)

$$\boxed{I_{total} = I_0\left(e^{eV/kT} - 1\right)}$$

Example Use of Diodes:

Rectification (AC → DC power)