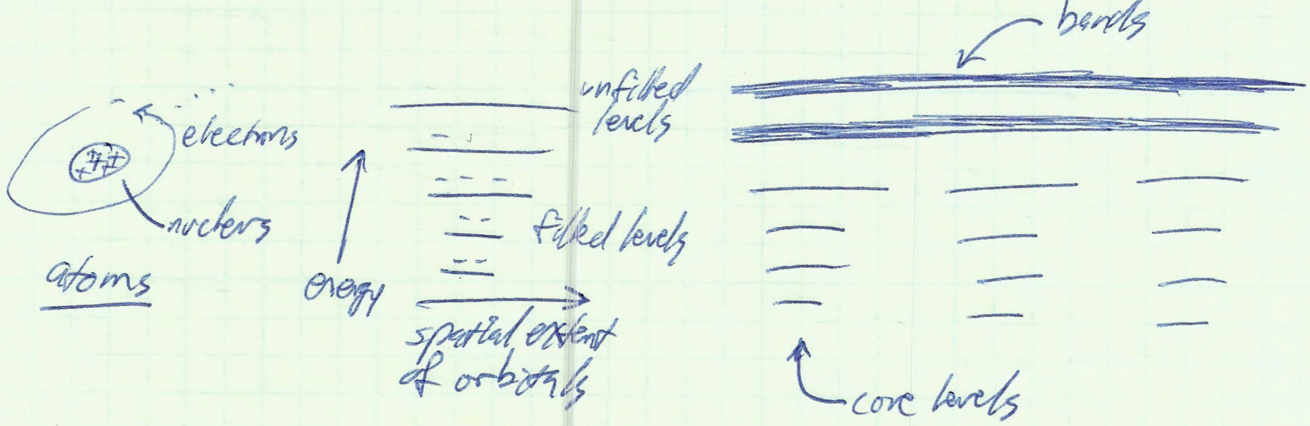
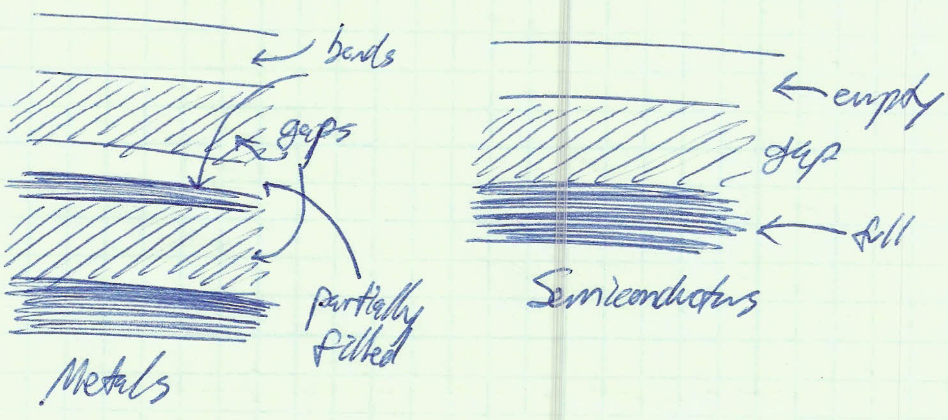
# Diodes

## Basic Semiconductor Physics




- Electrons in the atom can occupy discrete states
- In a solid crystal, the upper states merge into bands
- Properties of solids depend on these bands

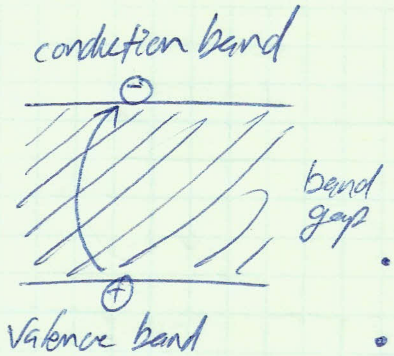



also cover 0k, 300k, (semiconductors) and insulators

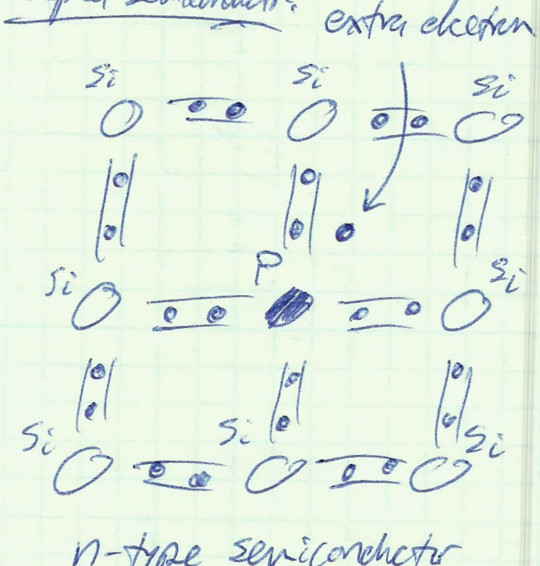
- Conducting current means electrons moving within the band
  - if the band is full, there is no net current

Most semiconductors are group IV : C, Ge, Si

or III-V : GaAs, InP, AlGaAs, GaN, etc.

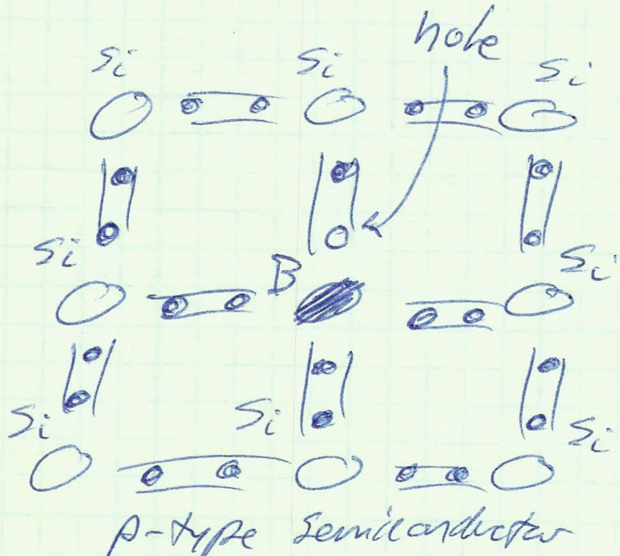



- Thermal excitation promotes some electrons from lower (valence) band to upper (conduction) band leaving a hole.
- Both electron and hole can move (conducts electricity)
- Carrier densities:
  - Metals ~ $10^{28}$-$10^{29}$ $cm^{-3}$
  - Semiconductors ~ $10^{16}$-$10^{19}$ $cm^{-3}$
  - Insulators ~ $10^{7}$ $cm^{-3}$

- Insulators are just like semiconductors, but with a much larger gap
- Doped semiconductors:


n-type semiconductor

Add group V elements




p-type semiconductor

Add group III elements

## Thermal excitation of carriers

$n = p = n_i$ (in intrinsic - undoped - semiconductor)

$n_i = BT^{3/2} e^{-E_g/2kT}$    $T$ = temperature

- $E_g$ ← band gap energy
- $B$ ← material-dependent constant

for any semiconductor (even doped) $n \cdot p = n_i^2$ ← equal numbers of electrons + holes

(in thermal equilibrium)

- Balance between thermal generation and recombination

## Doped Semiconductors

$N_D$ = density of donors
$N_A$ = density of acceptors

for n-type:

$$p_n n_n = n_i^2 \;,\; n_n \simeq N_D \longrightarrow p_n \simeq \frac{n_i^2}{N_D}$$

for p-type

$$p_p n_p = n_i^2 \;,\; p_p \simeq N_A \longrightarrow n_p \simeq \frac{n_i^2}{N_A}$$

- $p_p$ ← majority carriers
- $n_p$ ← minority carriers

## Current flow in Semiconductors

- Drift current - motion in response to electric field

$v_{p\text{-}drift} = \mu_p E$ ← electric field

- $\mu_p$ ← mobility (material dependent)
- $v_{p\text{-}drift}$ ← drift velocity of holes

$v_{n\text{-}drift} = -\mu_n E$

## Drift Current - continued

$$J = q(p\mu_p + n\mu_n)E$$

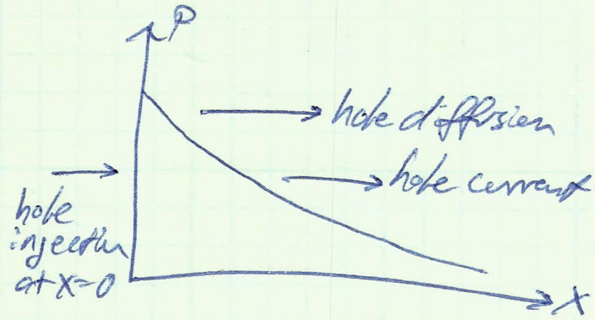
- $q$ ← electronic charge
- $p$, $n$ ← carrier densities

$$J = \sigma E \longrightarrow \sigma = q(p\mu_p + n\mu_n) \quad \text{conductivity}$$

- Diffusion current - motion due to concentration gradient

$$J_p = -qD_p \frac{dp(x)}{dx}$$

$D_p$ ↑ diffusion constant (material dependent)



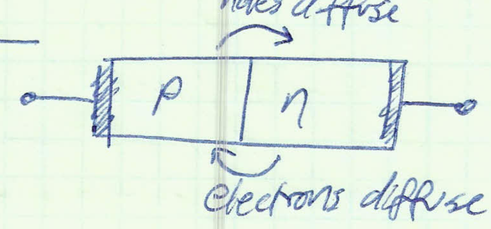

$$J_n = qD_n \frac{dn(x)}{dx}$$

Relationship between D and $\mu$ (not derived here):

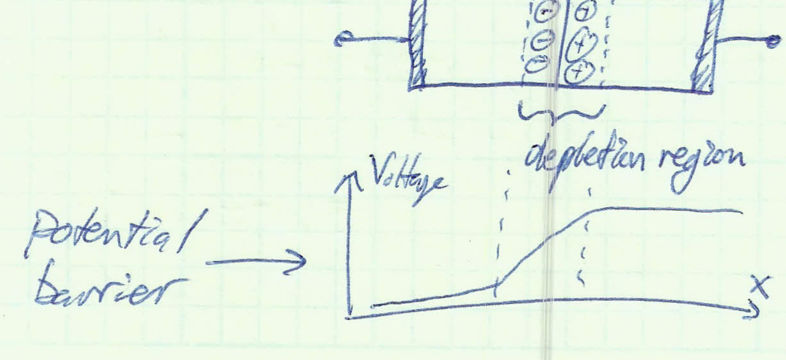
$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T = \frac{kT}{q}$$

$V_T$ ← thermal voltage

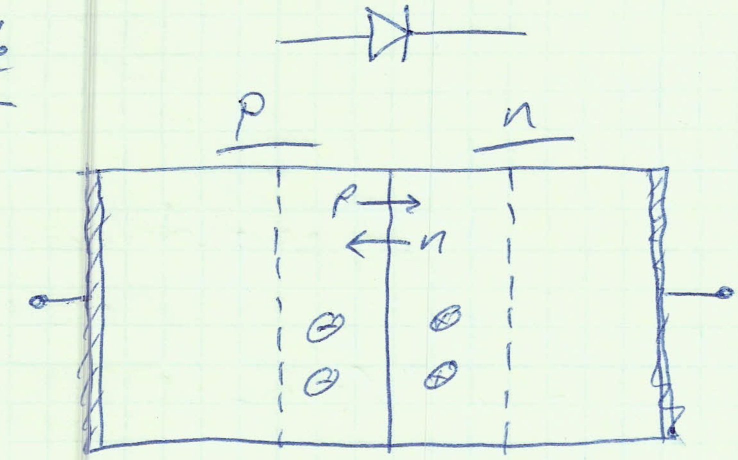
## Junction Diode:



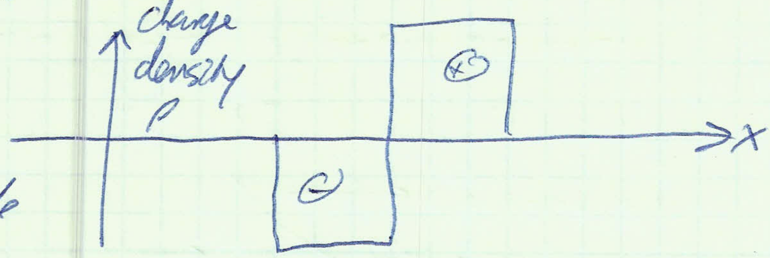

Carriers diffuse to the opposite side and deplete majority carriers near the junction
- called "depletion region"
- creates "built-in voltage" that counters the flow of charge



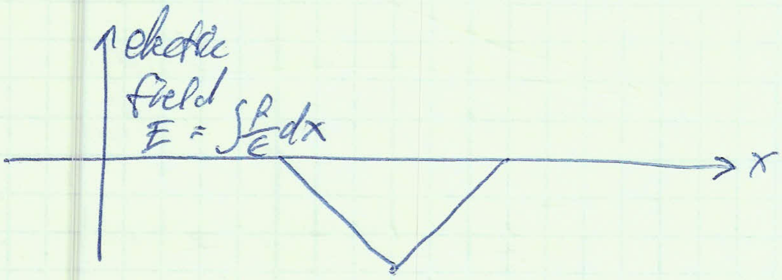
## The Junction Diode



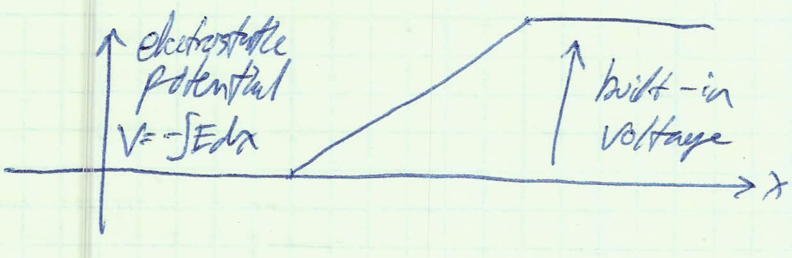

- holes diffuse to n-side
- electrons diffuse to p-side
- these minority carriers recombine, and deplete the majority carriers in a narrow (~0.5 μm) region called "depletion region"




- width is related to dopant density in each side
- charge density creates electric field in depletion region, and built in voltage



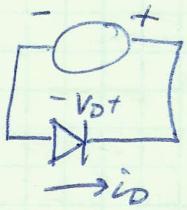

- Charge is not due to presence of diffused minority carriers (which have recombined) but due to "uncovered" ions that are exposed

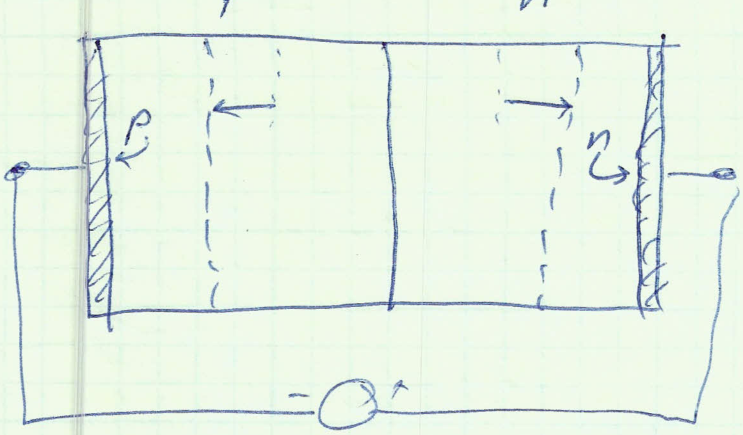



- this cannot be used as a battery or voltage source.
  - if attached to a load with no other sources, there will be other voltage drops such as across the contacts, so no current will flow

# I-V characteristics of Diodes

- Reverse Bias

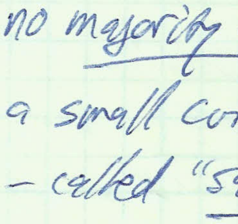



- Some majority carriers flow to the terminals
- p-side becomes more negatively charged, n-side becomes more positively charged
- width of depletion region becomes <u>wider</u>
- potential barrier becomes <u>higher</u>

- no majority carriers can cross the depletion region
- a small current will flow due to minority carriers
  - called "saturation current", typically ~$10^{-9}$ A (nA)
  - $i_D = -I_S$
  - $I_S$ is temperature dependent - related to thermal electron-hole pair production
  - $I_S$ doubles every ~7°C in temperature

- Forward Bias




- majority carriers move toward depletion region
- depletion region gets narrower
- potential barrier is reduced
- at high enough voltage, carriers can flow through the depletion region

$$i_D = I_S \left( e^{v_D / n V_T} - 1 \right)$$

- reverse current due to minority carriers
- $V_T = kT/q \approx 26mV$ at $T = 300K$

$q = 1.6 \times 10^{-19}$ C

$k = 1.38 \times 10^{-23}$ J/K

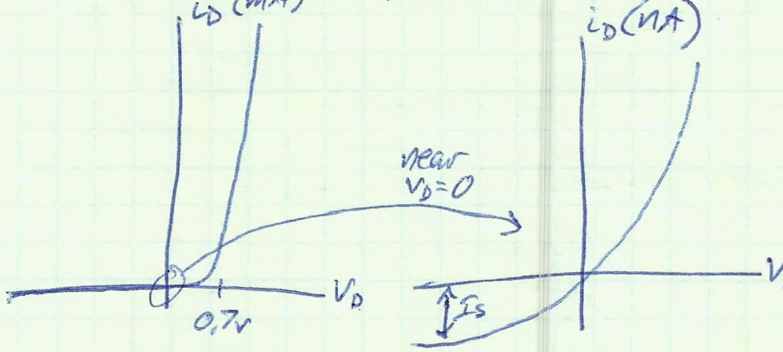
$n$ = emission coefficient

($n = 2$ for Si diodes, $1 \leq n \leq 2$ in ICs)

- note at $v_D = 0$, $i_D = I_S(1-1) = 0$

$I_S$ is ~ nA range

Although $I_S$ is very small, $e^{v_D/0.05}$ compensates, current rises sharply at $V_D = 0.6$ to $0.7V$




__Power__ $P = i_D v_D$ is dissipated as __heat__

at high enough currents this can damage the diode

__Reverse Breakdown__

- At high enough bias voltage, minority carriers are accelerated through the depletion region
- Impact ionization can create new electron-hole pairs
- Avalanche process leads to sharp increase in current
- Can destroy the diode (except Zener diodes)