Frequently, two species,

$q_1 = e$, M_+ $\quad q_2 = -e$, M_- ← mass

density same, $n = \frac{\#}{\text{volume}}$

then $\vec{J} = \vec{J}_+ + \vec{J}_-$

$$= e n \vec{v}_+ - e n \vec{v}_-$$

$$= e n \left[\frac{e}{M_+} \langle \Delta t_+ \rangle - \frac{(-e)}{M_-} \langle \Delta t_- \rangle \right] \vec{E}$$

$$\vec{J} = e^2 n \left[\frac{\langle \Delta t_+ \rangle}{M_+} + \frac{\langle \Delta t_- \rangle}{M_-} \right] \vec{E}$$

$$\sigma = e^2 n \cdot \left[\frac{\langle \Delta t_+ \rangle}{M_+} + \frac{\langle \Delta t_- \rangle}{M_-} \right]$$

$\langle \Delta t \rangle$ → called τ or T in book!

e^2 ↑ $\left(\frac{\text{charge}}{\text{ion}}\right)^2$

n ↑ volume density of charges

$\langle \Delta t \rangle$ = time between collisions

M = mass

may be different for

+ → ions, usually

− → electrons, usually

Types of conductors

① Like Glass, NaCl

→ structure less constraining as Temperature rises, $\langle \Delta t \rangle \uparrow$

② Conductors, like Copper, Gold, etc

→ lots of electrons available to move when field applied

→ if $T \to 0$, motion of atoms (not electrons) vanishes

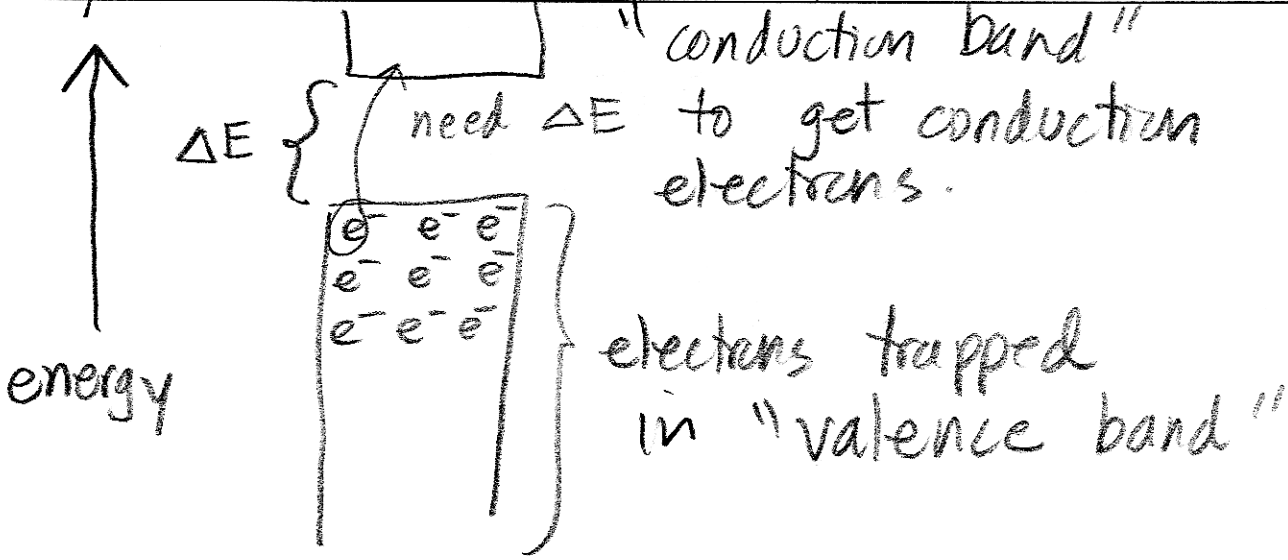
→ due to quantum mechanics, electrons can pass through a stationary forest of atoms almost unimpeded!

→ $\langle \Delta t \rangle \to \infty$ as $T \to 0$

motion of atoms messes this up as T increases

→ σ decreases as T increases!

③ Semiconductors: electrons cannot easily get free, there is a minimum energy necessary to free an electron



Dominant feature in semiconductors is $\underline{n}$ the density of "carriers"

Influences on n:

(A) Temperature → Boltzman ⇒

$$\frac{n(\text{above gap})}{n(\text{below})} \propto e^{-\frac{\Delta E}{kT}}$$

$kT \simeq \frac{1}{40}$ e.V. at 300 K

(B) Presence of impurities.

Phosphorous or aluminum in Silicon

Phosphorous: frees extra e^-

aluminum: frees extra "holes"

(C) Shine light on semiconductor

Holes:

In crystal, position where electron removed can move around!

→ acts like a particle of mass m^*, where m^* depends on the crystal (!!!)

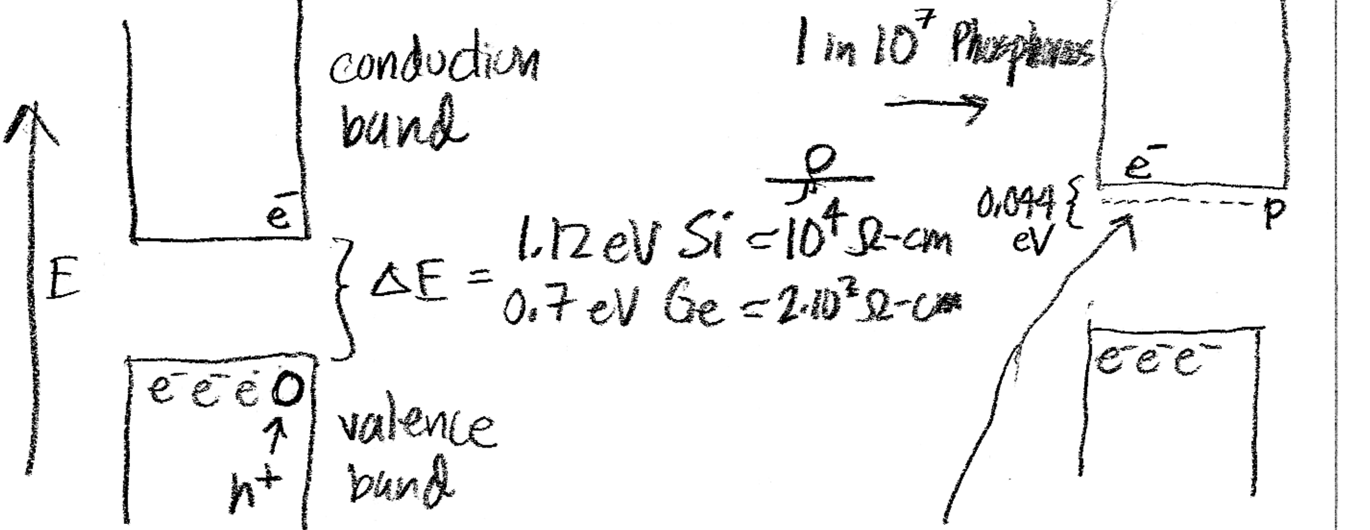
→ picture from p. 144.

→ the hole contributes to current, but the $\langle \Delta t \rangle_+ \neq \langle \Delta t \rangle_-$, $m_* = M_+ \neq M_-$

"Doping"

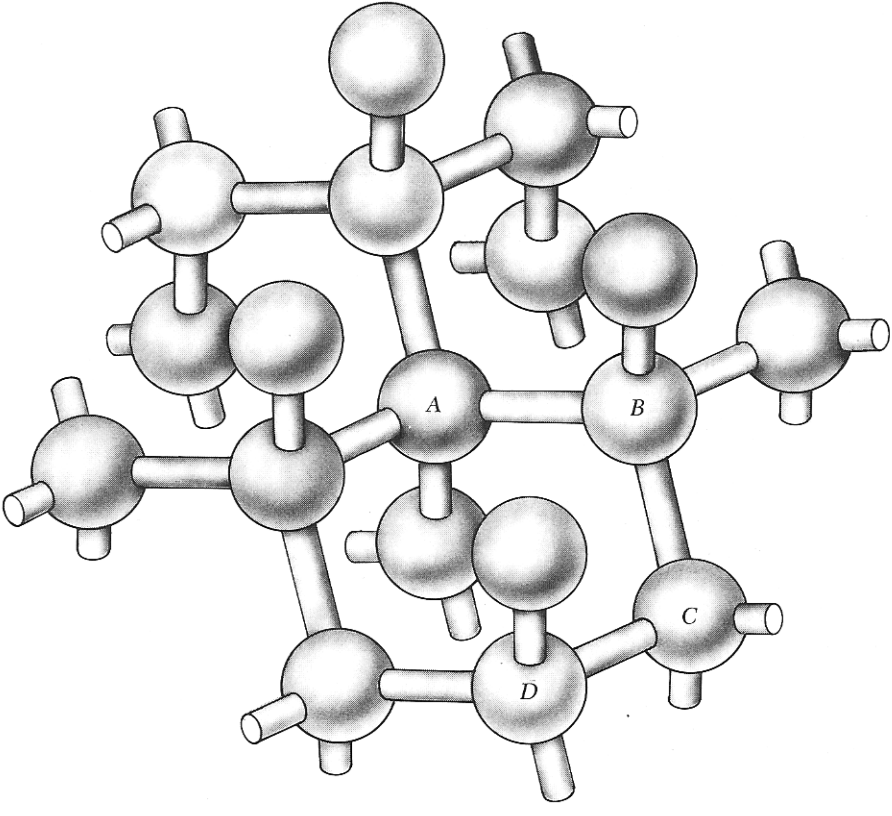
Replacing a small fraction of silicon or germanium can have a big influence on conductivity....

no doping — "n-type"



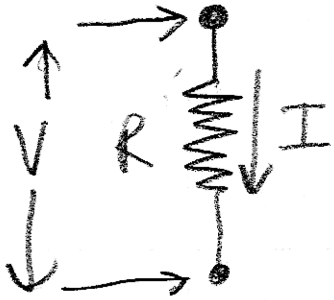
P^+ stays put!

dope with aluminum → "p-type" → Al^- stays put


A
B
C
D

Circuit Elements

When Ohm's law applies, the resistor is depicted as a zig-zag line:



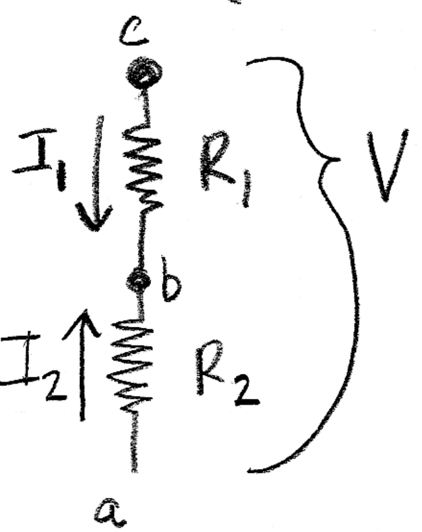
$$V = IR$$

Combined Resistor Elements

→ Current entering a node must sum up to zero, when steady state reached $\left(\frac{\partial \rho}{\partial t} = 0\right)$ (#1)

→ Potential Drop around a loop must sum up to zero (#2

(Kirchoff's Laws, Watch Out for Sign!)



$$I_1 + I_2 = 0 \quad (\#1)$$

$$-V + I_1 R_1 - I_2 R_2 = 0 \quad (\#2)$$

$$I_2 = -I_1$$

$$-V + I_1(R_1 + R_2) = 0$$

$$V = I_1(R_1 + R_2) = I_1 R$$

Series: $R = R_1 + R_2$