Frequently, two species, 

\[ q_1 = e, \quad M_+ \quad q_2 = -e, \quad M_- \]

density same, \( n = \frac{\text{mass}}{\text{volume}} \)

then \[ \mathbf{j} = \mathbf{j}_+ + \mathbf{j}_- \]

\[ = e n \mathbf{v}_+ - e n \mathbf{v}_- \]

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

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

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

\[ \langle \Delta t \rangle \text{ called } \tau \text{ in book.} \]

\[ \langle \Delta t \rangle = \text{time between collisions} \]

\[ M = \text{mass} \]

\[ \text{may be different for} \]

\[ + \rightarrow \text{ions, usually} \]

\[ - \rightarrow \text{electrons, usually} \]
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 \( T \rightarrow 0 \), motion of atoms (not electrons) vanishes
   - due to quantum mechanics, electrons can pass through a
     stationary forest of atoms almost unimpeded!
   - \( \langle \Delta T \rangle \rightarrow 0 \) as \( T \rightarrow 0 \)
     motion of atoms messes this
     up as \( T \) increases
   - \( \sigma \) decreases as \( T \) increases!

3. Semi-conductors: electrons cannot easily get free,
   - there is a minimum energy
     necessary to free an electron
Dominant feature in semiconductors is \( \sigma \) the density of "carriers".

**Influences on \( \sigma \):**

- **A** Temperature \( \to \) Boltzmann \( \to \)
  \[
  \frac{n(\text{above gap})}{n(\text{below})} \propto e^{\frac{-\Delta E}{kT}} 
  \]
  \( \sim \frac{1}{40} \) eV, at 300 K

- **B** Presence of impurities.
  Phosphorous or aluminum in Silicon
  - frees extra \( e^- \)
  - 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 (1.1)

- picture from p. 144.

- the hole contributes to current, but the $\langle \Delta^+ \rangle + \langle \Delta^- \rangle$, $m^* = M^+ + M^-$

"Doping"

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

no doping

\[ \text{conduction band} \]

\[ \text{valence band} \]

\[ \Delta E = 1.12 \text{ eV} \quad \text{Si} \quad 10^3 \text{ cm} \]

\[ 0.7 \text{ eV} \quad \text{Ge} \quad 2 \times 10^2 \text{ cm} \]

1 in $10^7$ Phosphorus

\[ e^- \quad p \]

\[ \text{P}^+ \text{ stays pot,} \]

dope with aluminum $\rightarrow$ "p-type" Ai stays pot
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 (\( \sum I = 0 \)) (#1)

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

(Kirchhoff'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: \( R = R_1 + R_2 \)