EE 331 Devices and Circuits I

Chapter 2

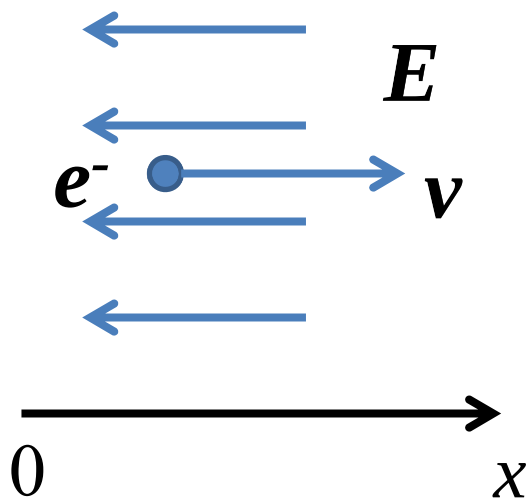
Conduction in Semiconductors

Announcements

- HW 0 Posted on Monday. Due in class on Friday 04/04/2014.
- Lab 0 starts next week. Be read lab handbook and Description for Lab 0 before your lab sessions.
- Office Hours:
  – Monday, Wednesday 2:00-3:00 pm @ EE 218

Electrons in Motion

Constant electric field in vacuum



Force on the electron:

$$F = -qE$$

Newton's 2nd Law:

$$a = \frac{F}{m} = -\frac{qE}{m}$$

q = 1.6 x 10^{-19} C
m = 9.11 x 10^{-31} kg

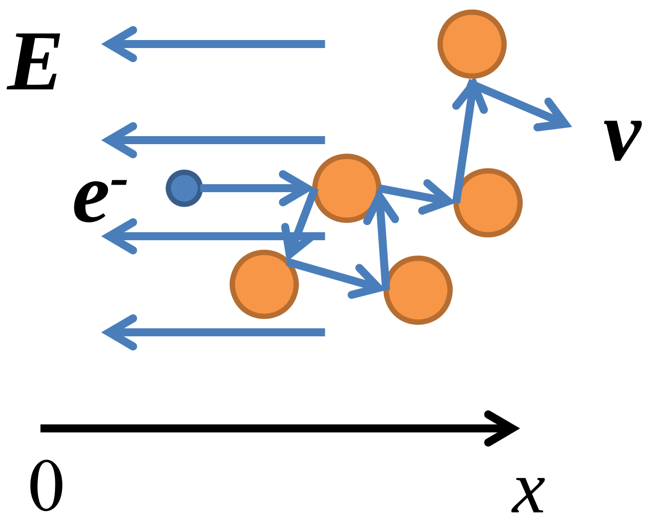
Velocity:

$$v = at \propto t$$

In vacuum, constant E field causes electrons to accelerate at a linearly increasing velocity

Electrons in Motion

Constant electric field in a solid

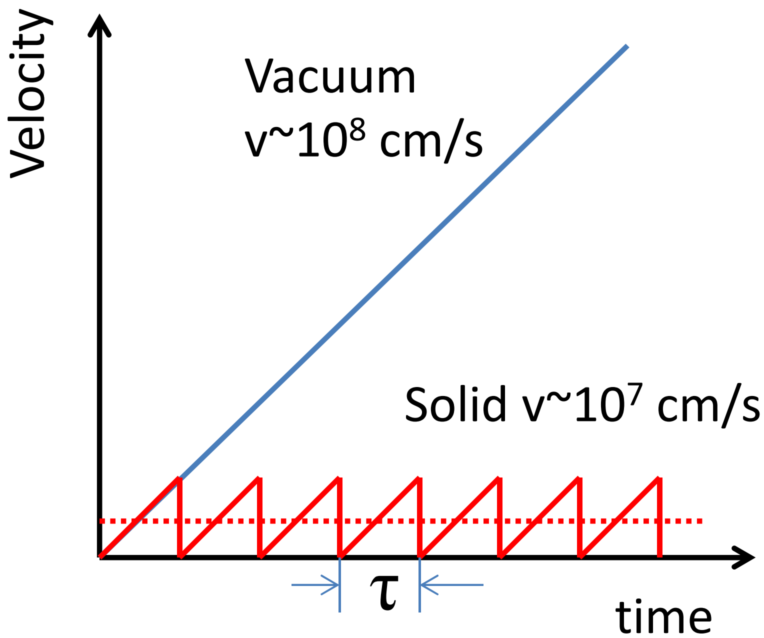


Electron flies for short intervals (~ps) before bumping into scattering objects

Result: Electron's average velocity proportional to field

$$v \propto E$$

Electron in Motion



Electron's average velocity proportional to field

$$v = -\mu E$$

μ: Mobility

$$[\mu] = \frac{[v]}{[E]} = \frac{a\tau}{[E]} = \frac{q\tau}{m}$$

$$[\mu] \sim \frac{cm/s}{V/cm} = \frac{cm^2}{V \cdot s}$$

Example:

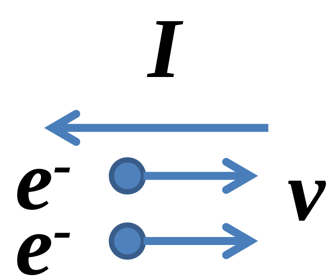
$|E| = 10^4$ V/cm, $\mu = 200$ cm^2/(V·s)

$|v| = \mu\,|E| = 2\times10^6$ cm/s

Current and Current density

- Current: flow of electrons in a medium
- Direction convention: opposite to electron flow
- Current = charge / time

$$I = \frac{Q}{t} \quad [\mathrm{A}]$$



  - Ampere (A) = Coulomb (C) / second (s)
- Current density: current per unit area

$$j = \frac{I}{S} \quad [\mathrm{A/cm^2}]$$

Current density

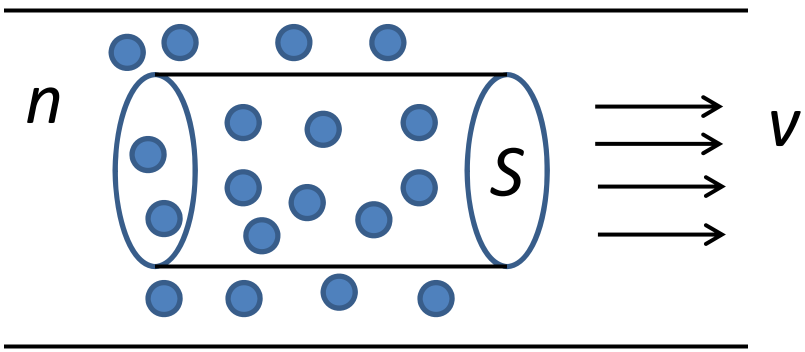


Image a group of electrons are passing through a wire with speed *v*. Pick a small area S perpendicular to the flow direction.

During a short time period *t*:

- Which electrons can pass through area *S*? All the electrons in the cylinder with area *S* and length of *vt*
- How many of them are there? $N_e = n \cdot V = n \cdot vt \ \cdot S$
- How many charges do they carry? $Q = (-q)N_e = -qnvtS$
- What is the current? $I = Q/t = -qnvS$
- What is the current density? $j = I/S = -qnv$

Current Density & Conductivity

Current density = product of carrier charge, carrier density, and velocity
(= product of charge density and velocity)

$$j = -q\ n\ v$$

v → Electron velocity [cm/s]

q → Charge on each Electron [C]

n → Electron density [cm^{-3}]

Intrinsic Ohm's Law: (Drift current density in an electric field)

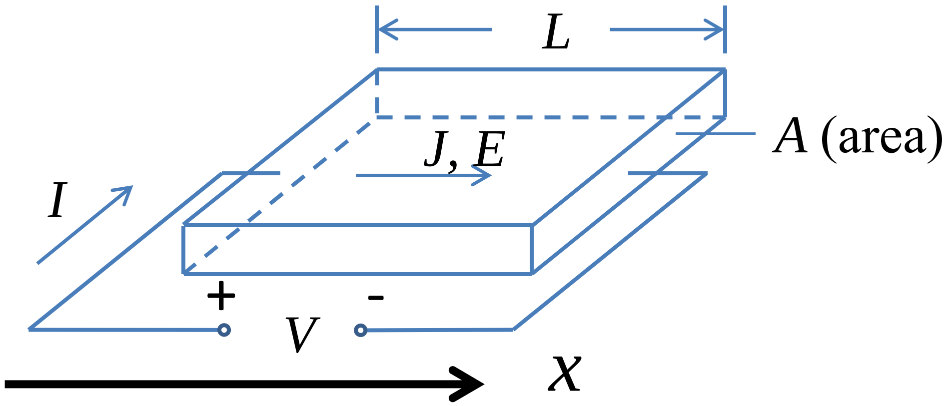
$$j = -qnv = -qn(-\mu E) = qn\mu E = \sigma E$$

where $\sigma = qn\mu$ is the conductivity.

$$[\sigma] = \frac{[j]}{[E]} = \frac{\mathrm{A/cm^2}}{\mathrm{V/cm}} = \frac{1}{\Omega \cdot \mathrm{cm}}$$

Resistivity: $\rho = \frac{1}{\sigma}\ [\Omega \cdot \mathrm{cm}]$

Resistance & Conductance



$$E = \frac{V}{L}$$

$$j = \frac{I}{A}$$

$$j = \sigma E \rightarrow \frac{I}{A} = \frac{1}{\rho}\frac{V}{L}$$

Extrinsic Ohm's Law

$$V = \rho \frac{L}{A} I = RI$$

where $R = \rho \frac{L}{A}$ is the resistance $[\Omega]$.

Conductance: $G = \frac{1}{R} = \sigma \frac{A}{L}$ $[\Omega^{-1}]$.

Electronic Materials

- Electrical characterization of materials
  - Insulators $\rho > 10^5 \Omega \cdot \mathrm{cm}$

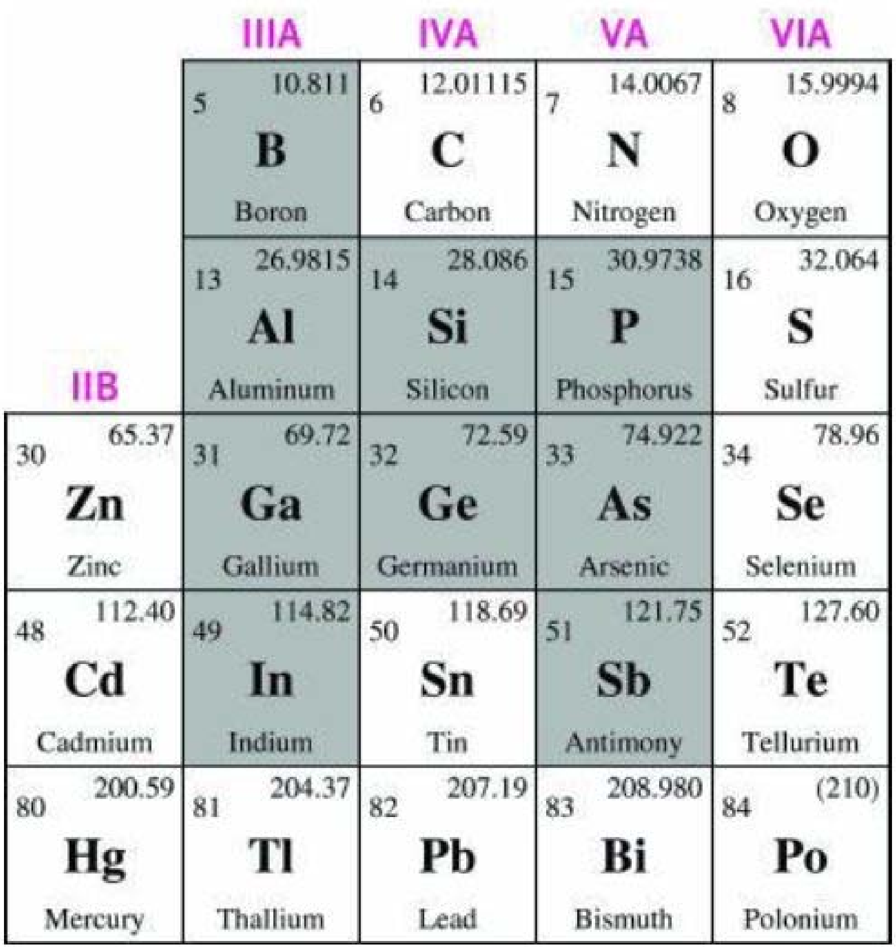
    e.g. Diamond $\rho = 10^{16} \Omega \cdot \mathrm{cm}$

  - Conductors $\rho < 10^{-3} \Omega \cdot \mathrm{cm}$

    e.g. Copper $\rho = 3 \times 10^{-6} \Omega \cdot \mathrm{cm}$

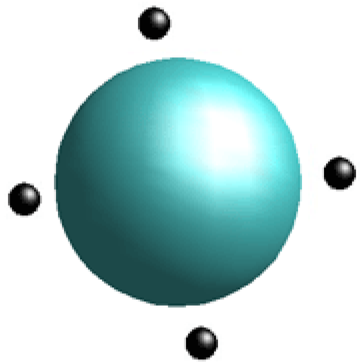
  - Semiconductors ρ in between
    - Elemental semiconductors (e.g. Si)
    - Compound semiconductors (e.g. GaAs)

Semiconductor Materials



Semiconductor	Bandgap
C (diamond)	5.47
Si	1.12
Ge	0.66
Sn	0.082
GaAs	1.42
GaN	3.49
InP	1.35
BN	7.50
SiC	3.26
CdSe	1.70

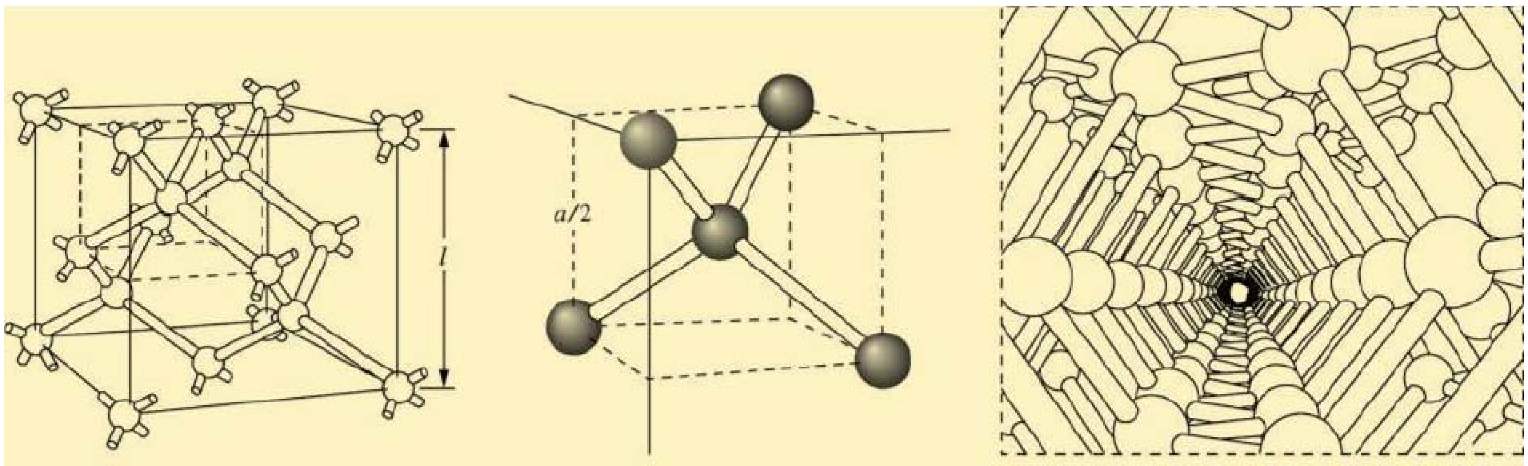
Silicon



^{14}Si: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$

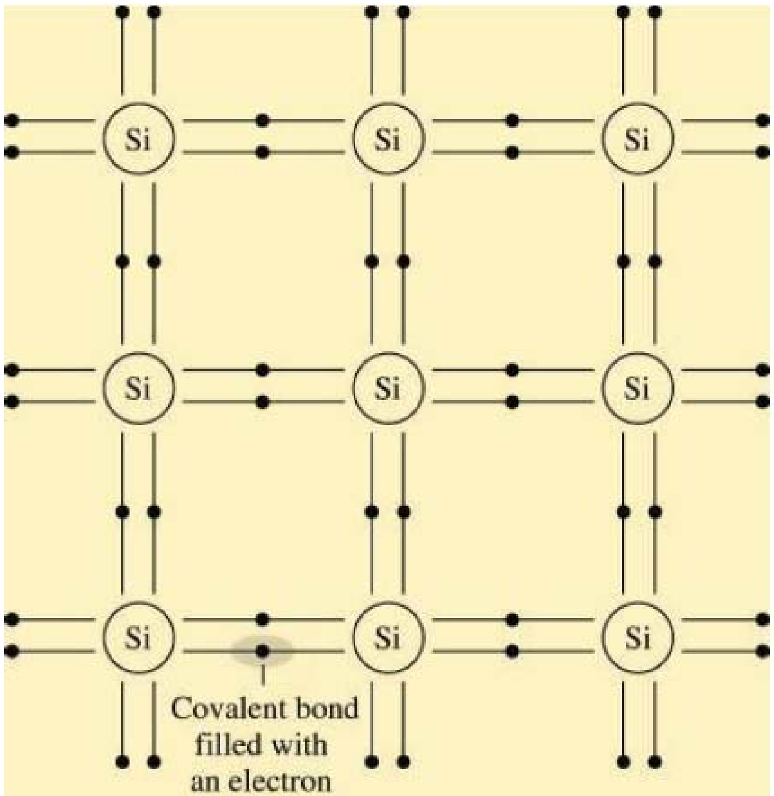
4 outer electrons (sp^3 hybridization)

=> tetrahedral bonding network



Carrier Concentration - Silicon

2d representation of Si crystal structure (T = 0 K)

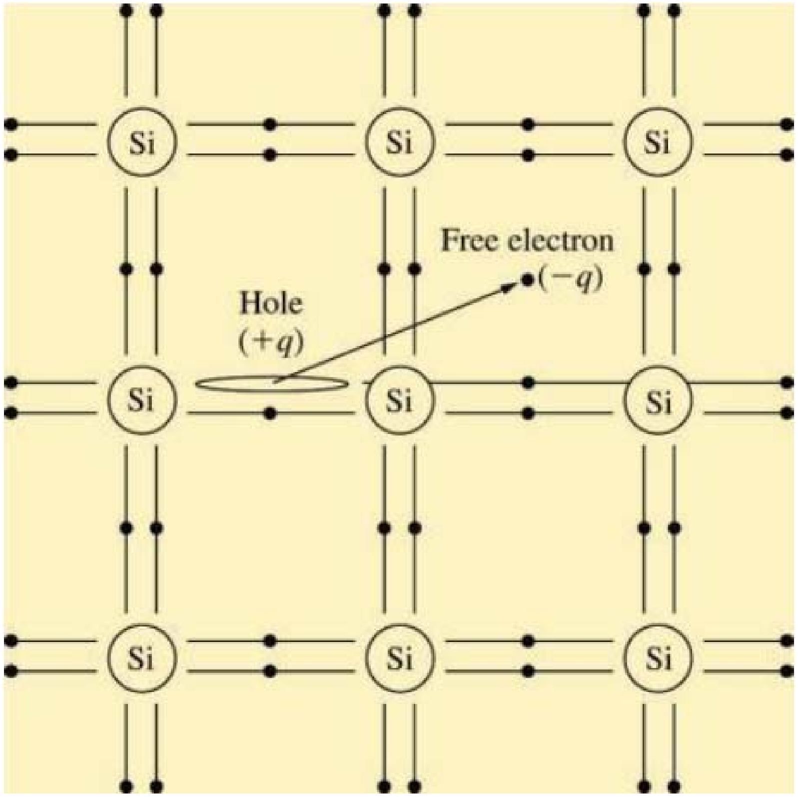


- Si forms 4 symmetric bonds
- Each bond has 2 electrons
- At 0 K, all electrons are bound by the Si atoms and are immobile => No free charge carriers for conduction => perfect insulator ($\sigma = 0, \rho = \infty$)

$$\sigma = q\mu n, n = 0$$

Carrier Concentration - Silicon

2d representation of Si crystal structure (T > 0 K)



- At T > 0 K, thermal energy inside the crystal can excite small amount of bound electrons into free electrons, leaving a hole in the bond
- Density of these free electrons (and also holes) is called the intrinsic carrier concentration