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:**
  \[ a = \frac{F}{m} = -\frac{qE}{m} \]

- **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

\[ v = -\mu E \]

**\( \mu \): Mobility**

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

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

Example:

\[ |E| = 10^4 \text{ V/cm}, \mu = 200 \text{ cm}^2/(\text{V} \cdot \text{s}) \]

\[ |v| = \mu |E| = 2 \times 10^6 \text{ cm/s} \]
Current and Current density

- Current: flow of electrons in a medium
- Direction convention: opposite to electron flow
- Current = charge / time
  \[ I = \frac{Q}{t} \text{ [A]} \]
  - Ampere (A) = Coulomb (C) / second (s)
- Current density: current per unit area
  \[ j = \frac{I}{S} \text{ [A/cm}^2\text{]} \]
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?** \( I = Q/t = -qns \)

- **What is the current density?** \( j = I/S = -qsv \)
Current Density & Conductivity

Current density = product of carrier charge, carrier density, and velocity
( = product of charge density and velocity )
\[ j = -q \, n \, v \]

Electron velocity [cm/s]

Charge on each Electron [C] \( \leftrightarrow \) Electron density [cm\(^{-3}\)]

Intrinsic Ohm’s Law: (Drift current density in an electric field)
\[ j = -qn\mu E = qn(-\mu E) = qn\mu E = \sigma E \]

where \( \sigma = qn\mu \) is the conductivity.

\[
[\sigma] = \frac{[j]}{[E]} = \frac{A}{V \cdot cm} = \frac{1}{\Omega \cdot cm}
\]

Resistivity: \( \rho = \frac{1}{\sigma} \) [\( \Omega \cdot cm \)]
Resistance & Conductance

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 $\rho > 10^5 \Omega \cdot \text{cm}$
    e.g. Diamond $\rho = 10^{16} \Omega \cdot \text{cm}$
  – Conductors $\rho < 10^{-3} \Omega \cdot \text{cm}$
    e.g. Copper $\rho = 3 \times 10^{-6} \Omega \cdot \text{cm}$
  – Semiconductors $\rho$ in between
    • Elemental semiconductors (e.g. Si)
    • Compound semiconductors (e.g. GaAs)
Semiconductor Materials

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Bandgap</th>
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<tbody>
<tr>
<td>C (diamond)</td>
<td>5.47</td>
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<tr>
<td>Si</td>
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<tr>
<td>Ge</td>
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<td>Sn</td>
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<tr>
<td>SiC</td>
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<tr>
<td>CdSe</td>
<td>1.70</td>
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</tbody>
</table>
Silicon

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

4 outer electrons (sp$^3$ hybridization)

$\Rightarrow$ 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