AIM: to describe the current-voltage characteristics of materials.
## QUIZ 5

1. Electrical properties of materials are directly related to the ________.
   a) Behavior of atoms in vacuum
   b) Behavior of electrons in crystal lattice
   c) Behavior of Nihat Doğan
   d) Behavior of the molecules in liquid

2. The best formulation to describe the behavior (motion) of electrons is ________.
   a) Quantum mechanics called wave mechanics
   b) Classical physics
   c) Fick’s 1st law
   d) Nihat Doğan Model

3. Schrödinger is ________
   a) The person who described the diffusion in solids
   b) The person who described the motion of electrons by wave equation
   c) The neighbor of Pascal Nouma
   d) The person who gave the plum pudding atomic model.

- Electrical properties of materials are directly related to the behavior of electrons in crystal lattice.
- The best formulation to describe the behavior (motion) of electrons is Quantum mechanics called wave mechanics.
- Schrödinger is the person who described the motion of electrons by wave equation
A. Energy-Band Theory

✓ Discussed: Single atom
  ✤ The energy of the bound electron is quantized
  ✤ The radial probability density for the electron
    ➢ Probability of finding electron at a particular distance from the nucleus
    ➢ Electron is not localized at a given radius

✓ Now: Extrapolate these single atom results to a CRYSTAL!

We will find that the energy states for electrons occur in bands of allowed states and are separated by forbidden energy bands

1. Formation of Energy Bands

• When two atoms get closer → their valence electrons will interact → splitting of energy levels into a band of energies.
2. The Energy Band and the Bond Model

- **Valence band** – filled – highest occupied energy levels
- **Conduction band** – empty – lowest unoccupied energy levels

Breaking of a covalent bond
Generation of a negative and positive charge with the breaking of a covalent bond
3. Charge Carriers

- Interested in the I-V characteristics
- Current is a result of the flow of charge
- Charges that can move when forces are applied
- Charges → CARRIERS
  - ELECTRONS
  - HOLES
  - IONS

ELECTRONS

- Negatively charged particle
- We are interested in number of electrons in CB.
- Net drift of electrons in CB → DRIFT CURRENT

If a force is applied to a particle and particle moves, it must gain energy: $dE = F \cdot dx = F \cdot v \cdot dt$

- Due to the external force, electrons can gain energy and a net momentum → Drift current density due to the motion of electrons:

$$j = -e \sum_{i=1}^{N} n_i v_i$$

- $e$: electronic charge
- $N$: # of electrons per unit volume in CB
- $v$: electron velocity

CURRENT → related to HOW WELL THE ELECTRON MOVE IN THE CRYSTAL

CB: Conduction Band
4. Effective Mass

• The movement of an electron in a lattice will be different from free space.
• In addition to an externally applied force, there are internal forces in crystal due to:
  • positively and negatively charged ions
  • Protons
  • Other electrons

\[ F_{\text{total}} = F_{\text{ext}} + F_{\text{int}} = m \cdot a \]
\[ F_{\text{ext}} = m^* \cdot a \]

\( m^* \): effective mass
(particle mass and effect of internal forces)

Motion of an electron in vacuum
Motion of an electron in a solid
5. Metals, Insulators and Semiconductors

- Each crystal has its own energy band structure
- Variations in band structures \(\rightarrow\) wide range of electrical characteristics in various materials
6. Electrons traveling in different directions

Electrons traveling in different directions encounter different potential patterns.

Homework

- Read Chapter 19: Electrical Properties
- Do the Example problems: 1, 2, 3
About the presentations
Some examples...

- 15min ppt
- There will be a question related in final
- How does a «...» work?

1. Metal-Oxide-Semiconductor Field-Effect Transistor
2. Bipolar Transistor
3. Junction Field-Effect Transistor
4. Solar Cells
5. Photodetectors
6. Light Emitting Diodes
7. Laser Diodes

Metals, Insulators and Semiconductors
Excitation

- Photo-excitation
- Thermal-excitation
- Chemo-excitation

The pure semiconductor is called INTRINSIC SEMICONDUCTOR. Adding controlled amounts of dopant atoms result in EXTRINSIC SEMICONDUCTOR.

Chemo-excitation

- Dopant Atoms and Energy Levels
- Qualitative Description

N-type semiconductor ➔
N-type semiconductor

- Impurity donates an electron to the conduction band → so is called DONOR IMPURITY ATOM.

P-type semiconductor
P-type semiconductor

- Addition of donor or acceptor impurity atoms will change the distribution of electrons and holes in the material.
- Density of electrons > density of holes $\rightarrow$ n-type
  - Majority carriers: electrons
- Density of electrons < density of holes $\rightarrow$ p-type
  - Majority carriers: holes
Carrier Transport

- Net flow of electrons and holes will generate currents
- The process by which these charged particles move is called TRANSPORT.

Two transport mechanisms:

- Drift
  - Apply an electric field to semiconductor \(\rightarrow\) produce force on electrons and holes \(\rightarrow\) a net acceleration and net movement (if there are available energy states in CB and VB)
  - Net movement of charge due to and electric field: DRIFT \(\rightarrow\) DRIFT CURRENT

- Diffusion
  - Due to density gradient
  - DIFFUSION CURRENT

Carrier Drift

- \(J=\) charge density \(\times\) drift velocity
- \(F=m^*a=e.E\)
- Average drift velocity \(\rightarrow v = \mu \cdot E\)
- \(\mu\), mobility: how well a particle will move in lattice due to an electric field.

Collisions with
- \(\text{Ionized impurity atoms}\)
- \(\text{Thermally vibrating lattice atoms}\)
Semiconductor Conductivity and Resistivity

Drift current density: \( J_{drf} = e \cdot (\mu_n \cdot n + \mu_p \cdot p) \cdot E = \sigma \cdot E \)

\( \sigma \): conductivity \((\Omega \cdot \text{cm})^{-1}\)

Resistivity: \( \rho = \frac{1}{\sigma} \)

\( J = \frac{I}{A} \quad E = \frac{V}{L} \quad J_{drf} = \sigma \cdot E \quad R = \frac{\rho \cdot L}{A} \)

Ohm's law \( \Rightarrow \) resistance = f(resistivity, geometry)

A bar of semiconductor material

Intrinsic Conductivity

\[ \sigma = n|e|\mu_n + p|e|\mu_p \]

for intrinsic semiconductor

\( n = p \quad \Rightarrow \quad \sigma = n|e|\mu_n + \mu_n \)
Semiconductor Conductivity and Resistivity of an Extrinsic Semiconductor

- Assume complete ionization
- $F$ (concentration and mobility of the majority carrier)
- Ex. For N-type: $n >> p \Rightarrow \sigma \approx e \mu_n n_e$

Effect of Temperature
Metals: Resistivity vs T, Impurities

- Imperfections increase resistivity
  -- grain boundaries
  -- dislocations
  -- impurity atoms
  -- vacancies

These act to scatter electrons so that they take a less direct path.

- Resistivity increases with:
  -- temperature
  -- wt% impurity
  -- %CW

\[ \rho = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{deformation}} \]

Adapted from Fig. 18.8, Callister 7e. (Fig. 18.8 adapted from J.O. Linde, Ann. Physik 5, p. 219 (1932); and C.A. Wert and R.M. Thomson, Physics of Solids, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

Pure Semiconductors: Conductivity vs T

- Data for Pure Silicon:
  -- \( \sigma \) increases with \( T \)
  -- opposite to metals

\[ \sigma \propto e^{-E_{\text{gap}}/kT} \]

Adapted from Fig. 19.15, Callister 5e. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, Phys. Rev. 75, p. 865, 1949.)
Doped Semiconductor: Conductivity vs. T

• Data for Doped Silicon:
  -- \( \sigma \) increases doping
  -- reason: imperfection sites lower the activation energy to produce mobile electrons.

Adapted from Fig. 19.15, Callister 5e. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, Phys. Rev. 75, p. 865, 1949.)

• Comparison: intrinsic vs extrinsic conduction...
  -- extrinsic doping level:
    \( 10^{21}/m^3 \) of a \( n \)-type donor impurity (such as P).
  -- for \( T < 100 \) K: "freeze-out", thermal energy insufficient to excite electrons.
  -- for \( 150 \) K < \( T < 450 \) K: "extrinsic"
  -- for \( T >> 450 \) K: "intrinsic"

Adapted from Fig. 18.17, Callister 7e. (Fig. 18.17 from S.M. Sze, Semiconductor Devices, Physics, and Technology, Bell Telephone Laboratories, Inc., 1985.)

Example

Consider a bar of Silicon uniformly doped with acceptor impurities and having the geometry given below. For an applied voltage of 5V, a current of 2mA is required. The current density is to be no larger than 100A/cm². Find the required cross-sectional area, length and doping concentration.

A bar of semiconductor material

\[ A \quad L \quad V \quad I \]
Example

• The room temperature electrical conductivity of a semiconductor specimen is $2.8 \times 10^4 \, (\Omega \text{-m})^{-1}$. The electron concentration is known to be $2.9 \times 10^{22} \, \text{m}^{-3}$. Given that the electron and hole mobilities are 0.14 and 0.023 m$^2$/V-s, respectively, calculate the hole concentration (in m$^{-3}$).

• Is this an n or p-type semiconductor?

Example

Si is doped with Phosphorus atoms with a concentration of $3 \times 10^{18} \, \text{m}^{-3}$. If the electron drift velocity is 100 m/s in an electric field of 600 V/m, calculate the conductivity of this material.
Report

- properties of semiconductor materials
  - Conductivity
  - Electron and hole concentration
  - Mobility

Now consider a situation in which one region of a semiconductor is doped p type and the region near is doped with n type.

\[
\mu_e = \frac{v_e}{E}
\]

\[
= \frac{100 \text{ m/s}}{600 \text{ V/m}} = 0.17 \text{ m}^2/\text{V} \cdot \text{s}
\]

Thus, from Equation 18.16, the conductivity is

\[
\sigma = n_0 e |\mu_e|
\]

\[
= \left(3 \times 10^{18} \text{ m}^{-3}\right) \left(1.602 \times 10^{-19} \text{ C}\right) \left(0.17 \text{ m}^2/\text{V} \cdot \text{s}\right)
\]

\[
= 0.082 \left(\Omega \cdot \text{m}\right)^{-1}
\]
The pn Junction

- Most semiconductor devices contain at least one pn junction

Generation and Recombination

- Carrier Generation: the process whereby electrons and holes (carriers) created
- Carrier Recombination: the process whereby electrons and holes are (carriers) annihilated
  \[ e + h \rightarrow \text{energy} \]
How does a «p-n Rectifying Junction»?

- Allows flow of electrons in one direction only (e.g., useful to convert alternating current to direct current.

Results:

--No applied potential: no net current flow.
--Forward bias: carrier flow through $p$-type and $n$-type regions; holes and electrons recombine at $p$-$n$ junction; current flows.
--Reverse bias: carrier flow away from $p$-$n$ junction; carrier conc. greatly reduced at junction; little current flow.

Properties of Rectifying Junction

Fig. 18.22, Callister 7e. Fig. 18.23, Callister 7e.
Summary

Semiconductor Devices for PPTs

1. Metal-Oxide-Semiconductor Field-Effect Transistor
2. Bipolar Transistor
3. Junction Field-Effect Transistor
4. Solar Cells
5. Photodetectors
6. Light Emitting Diodes
7. Laser Diodes

- PPTs: 10-15 min
- Send me you power points by email. Deadline: Jan 1, 2012
- There will be question(s) in the final, so listen all the ppts carefully!
B. Determination of number of electrons and holes in conduction process

- AIM: to describe the current-voltage characteristics of materials.
- Current: result of charge flow
- QUESTION: How to determine the number of electrons and holes in the semiconductor that will be available for conduction

1. Pauli Exclusion principle: only one electron may occupy a given quantum state.
2. Determine the density of the available energy / quantum states
3. Probability of an electron occupying a quantum state
DENSITY OF QUANTUM STATES

Objective: To determine the density of the available energy / quantum states

Use an appropriate model
- Infinite potential well model
- Apply Shrödinger’s wave equation
- Allowed electronic energy states in CB and VB

\[
g_c(E) = \frac{4\pi(2m_n^*)^{3/2}\sqrt{E - E_c}}{\hbar^3}
\]

\[
g_v(E) = \frac{4\pi(2m_p^*)^{3/2}\sqrt{E_v - E}}{\hbar^3}
\]

Statistical Mechanics

Objective: To describe the probability of an electron occupying a quantum state

- Large number of particles ⇒ statistical behavior of the group as a whole
- In crystal ⇒ electrical characteristics ⇒ determined by the statistical behavior of large number of electrons
Statistical Laws that Particles Obey

- Three distribution laws determining the distribution of particles among available energy states:
  - Maxwell-Boltzman probability function → behavior of gas molecules in a container
  - Bose-Einstein function → behavior of photons
  - Fermi-Dirac probability function → electrons in a crystal

Fermi-Dirac Distribution Function & Fermi Energy

- Probability that an allowed quantum state at the energy \( E \) is occupied by an electron (ratio of filled to total number of quantum states \( N(E)/g(E) \))

\[
f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}
\]

- \( E_F \): Fermi energy
Fermi Energy

- To understand the meaning of distribution function and Fermi energy → plot distribution function versus energy
- at $T=0$
  - $E<E_F \Rightarrow \exp(-\infty) = 0 \Rightarrow$ distribution function: $f(E) = 1$
  - $E>E_F \Rightarrow \exp(+\infty) = +\infty \Rightarrow f(E) = 0$

\[
f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}
\]

Meaning: at $T=0K$,
  - the probability of a quantum state being occupied for $E<E_F$ is unity (1) and
  - the probability of a quantum state being occupied for $E>E_F$ is zero.

At $T=0K$, all electrons are in their lowest possible energy states.

The Semiconductor in Equilibrium

✓ Last time: general behavior of electrons in single-crystal lattice.
✓ Now: apply the concepts to semiconductor material

❖ Equilibrium: no external forces such as:
❖ Voltages
❖ Electric fields
❖ Magnetic fields
❖ Temperature gradients
acting on the semiconductor material..
Semiconductor device characteristics

- Determined by conductivity
- Can be varied (good conductor $\leftrightarrow$ good insulator) by controlling the concentration of specific impurities in the material.

- Process by which these impurities are introduced into the material: DOPING
  - By diffusion process
  - By ion implantation process

Charge Carriers in Semiconductors

- Current: the rate of charge flow
- Charge carriers: electrons and holes
- Density of charge carriers $\rightarrow$ number of electrons in CB and number of holes in VB.

- The distribution of electrons (wrt energy) in CB: density of allowed quantum states $\times$ the probability that a state is occupied by an electron.
  $$ n(E) = g_c(E) \cdot f(E) $$
  $g(E)$: density of quantum states in CB
  $f(E)$: Fermi-Dirac probability function
Density of electrons and holes

\[ n_0 = N_e \cdot \exp\left(\frac{-\left(E_c - E_F\right)}{kT}\right) \]

\[ p_0 = N_v \cdot \exp\left(\frac{-\left(E_F - E_v\right)}{kT}\right) \]

• \( N_v \): effective density of states

Intrinsic carrier concentration

\[ n^2_i = N_e N_v \cdot \exp\left(\frac{-E_g}{kT}\right) \]

\( E_g \): band gap energy