Chapter 26

Introduction to Semiconductors

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Semiconductor Basics

- Atoms
  - Protons
  - Neutrons
  - Electrons

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Semiconductor Basics

- Electron shells: K, L, M, N, etc.
  - Conductor
    - 1 electron in outer shell (valence shell)
  - Insulator
    - 8 in valence shell (outer shell full)
  - Semiconductor
    - 4 in valence shell

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Semiconductor Basics

- Most common semiconductors
  - Silicon (Si)
  - Germanium (Ge)

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Semiconductor Basics

- Valence electrons have greatest energy
- Electrons have discrete energy levels that correspond to orbits

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Semiconductor Basics

- Valence electrons have two energy levels
  - Valence Band
    - Lower energy level
  - Conduction Band
    - Higher energy level

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Semiconductor Basics

- Differences in energy levels provide
  - Insulators
  - Semiconductors
  - Conductors

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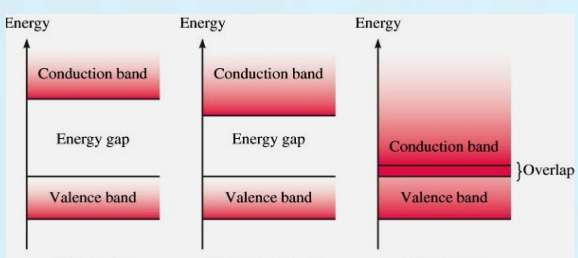
Semiconductor Basics

- Energy gap between Valence and Conduction Bands



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Semiconductor Basics

- Conductor has many “free” electrons
- These are called “conduction” electrons
- Energy Gap is between valence and conduction band

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Semiconductor Basics

- Atomic Physics
  - Energy expressed in electron volts (eV)
  - 1 eV = 1.602×10^{-19} joules
- Energy gap
  - Small for conductors
  - Large for insulators

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Semiconductor Basics

- Silicon has 4 electrons in its valence shell
- 8 electrons fill the valence shell
- Silicon forms a lattice structure and adjacent atoms "share" valence electrons

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Semiconductor Basics

- Electrons are shared so each valence shell is filled (8 electrons)
- Valence shells full
  - No "free" electrons at 0 K

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Conduction in Semiconductors

- At temperatures > ° K
  - Some electrons move into conduction band
- Electron-Hole pairs are formed
  - Hole is vacancy left in lattice by an electron that moves into conduction band
  - Continuous recombination occurs

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Conduction in Semiconductors

- Electrons available for conduction
  - Copper ≈ 10^{23}
  - Silicon ≈ 10^{10} (poor conductor)
  - Germanium ≈ 10^{12} (poor conductor)

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Conduction in Semiconductors

- Hole: absence of an electron in the lattice structure
  - Electrons move from – to +
  - Holes (absence of electrons) move from + to –
  - Recombination
    - When an electron fills a hole

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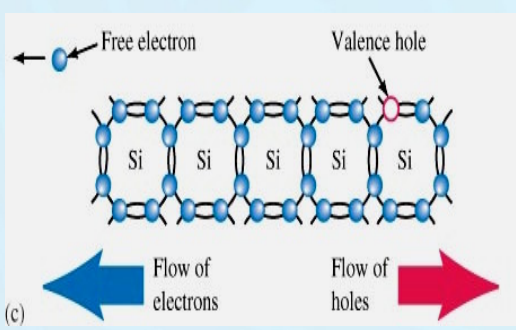
Conduction in Semiconductors



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Conduction in Semiconductors

- As electrons move toward + terminal
  - Recombine with holes from other electrons
  - Electron current is mass movement of electrons
  - Hole current is mass movement of holes created by displaced electrons

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Conduction in Semiconductors

- Effect of temperature
  - Higher energy to electrons in valence band
  - Creates more electrons in conduction band
  - Increases conductivity and reduces resistance
  - Semiconductors have a negative temperature coefficient (NTC)

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Doping

- Adding impurities to semiconductor
  - Creates more free electron/hole pairs
  - Greatly increased conductivity
  - Known as “doping”

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Doping

- Terminology
  - Pure semiconductor known as intrinsic
  - Doped semiconductor known as extrinsic

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Doping

- Creates *n*-type or *p*-type semiconductors
  - Add a few ppm (parts per million) of doping material
  - *n*-type
    - More free electrons than holes
  - *p*-type
    - More holes than free electrons

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Doping

- Creating *n*-type semiconductors
  - Add (dope with) atoms with 5 valence electrons
  - Pentavalent atoms
    - Phosphorous (P)
    - Arsenic (As)
    - Antimony (Sb) – Group V on periodic table

Doping

- Creating *n*-type semiconductors
  - New, donor atoms become part of lattice structure
  - Extra electron available for conduction

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Doping

- Intrinsic semiconductors
  - Equal number of holes and electrons
  - Conduction equally by holes and electrons
  - Very poor conductors (insulators)

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Doping

- *n*-type extrinsic semiconductor
  - Free electrons greatly outnumber free holes
  - Conduction primarily by electrons
  - Electrons are the “majority” carriers

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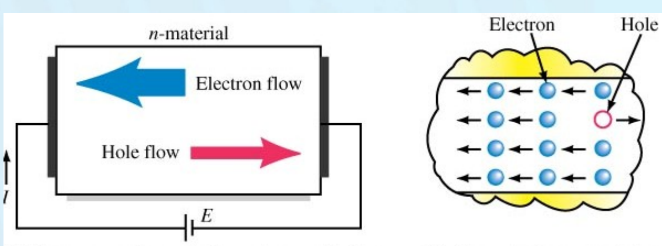
Doping

- Conduction in an *n*-type semiconductor



(a) Electrons are the majority carriers, and holes are the minority carriers

(b) Conceptual representation. Note that most of the carriers are electrons

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Doping

- Creating *p*-type semiconductors
  - Add (dope with) atoms with 3 valence electrons
  - Trivalent atoms
    - Boron (B)
    - Aluminum (Al)
    - Gallium (Ga) – Group III on periodic table

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Doping

- Creating *p*-type semiconductors
  - New, acceptor atoms become part of lattice structure
  - Extra hole available for conduction

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Doping

- *p*-type extrinsic semiconductor
  - Free holes greatly outnumber free electrons
  - Conduction primarily by holes
  - Holes are the “majority” carriers
  - Electrons are the “minority” carriers

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The *p*-*n* Junction

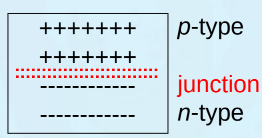
- Abrupt transition from *p*-type to *n*-type material
- Creation
  - Must maintain lattice structure
  - Use molten or diffusion process

The *p-n* Junction

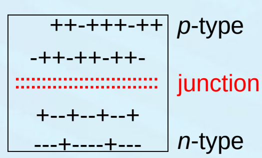
- Example
  - Heat *n*-type material to high temperature
  - Boron gas diffuses into material
  - Only upper layer becomes *p*-type
  - *p-n* junction created without disturbing lattice structure

The *p-n* Junction

- Joined *p*-type and *n*-type semiconductors

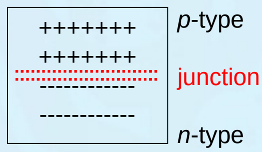


- Diffusion across junction creates barrier potential

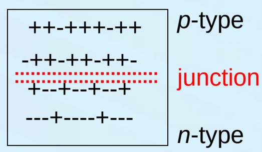


The *p*-*n* Junction

- Joined *p*-type and *n*-type semiconductors



- Diffusion across junction creates barrier potential



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The *p*-*n* Junction

- Depletion region
- Barrier voltage, V_B
- Silicon
  - $V_B \approx 0.7$ volts at 25°C

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The *p-n* Junction

- Germanium
  - $V_B \approx$ 0.3 volts at 25°C
- V_B must be overcome for conduction
- External source must be used

The Biased *p-n* Junction

- Basis of semiconductor devices
- Diode
  - Unidirectional current
  - Forward bias (overcome V_B) – conducts easily
  - Reverse bias – virtually no current
  - *p*-type end is anode (A)

The Biased *p-n* Junction

- Diode
  - *n*-type end is cathode (K)
  - Anode and cathode are from vacuum tube terminology

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The Biased *p-n* Junction

- Diode symbol
  - Arrow indicates direction of conventional current for condition of forward bias (A +, K -)
  - External voltage source required
  - External resistance required to limit current

Anode (A)  Cathode (K)

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The Biased *p*-*n* Junction

- Holes are majority carriers in *p*-type
- Electrons are majority carriers in *n*-type

The Biased *p*-*n* Junction

- Reverse biased junction
  - Positive (+) terminal draws *n*-type majority carriers away from junction
  - Negative (–) terminal draws *p*-type majority carriers away from junction
  - No majority carriers attracted toward junction
  - Depletion region widens

The Biased *p*-*n* Junction

- Electrons are minority carriers in *p*-type
- Holes are minority carriers in *n*-type
- Reverse biased junction
  - Minority carriers drawn across junction
  - Very few minority carriers

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The Biased *p*-*n* Junction

- Reverse biased current
  - Saturation current, I_S
  - Nanoamp-to-microamp range for signal diodes

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The Biased *p-n* Junction

- Reverse biased junction
  - Positive terminal of source connected to cathode (*n*-type material)

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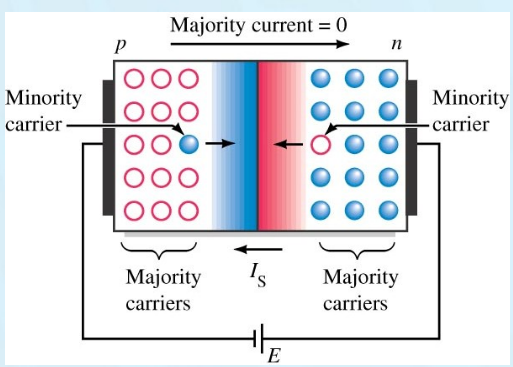
The Biased *p-n* Junction



The Biased *p*-*n* Junction

- *p*-type
  - Holes are majority carriers
- *n*-type
  - Electrons are majority carriers

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The Biased *p*-*n* Junction

- Forward biased junction
  - + terminal draws *n*-type majority carriers toward junction
  - – terminal draws *p*-type majority carriers toward junction
  - Minority carriers attracted away from junction
  - Depletion region narrows

The Biased *p-n* Junction

- Forward biased junction
  - Majority carriers drawn across junction
  - Current in *n*-type material is electron current
  - Current in *p*-type material is hole current
  - Current is referred to as $I_{majority}$ or I_F (for forward current)

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The Biased *p-n* Junction

- Voltage across Forward biased diode ≈ V_B
  - Often referred to as V_F (for forward voltage)
  - $V_B \approx 0.7$ for Silicon and 0.3 for Germanium
- Forward biased current
  - Majority and Minority current
  - Minority current negligible

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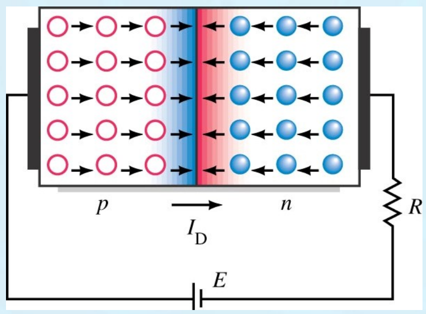
The Biased *p-n* Junction

- Forward biased junction
  - Positive terminal of source connected to Anode (*p*-type material)



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The Biased *p-n* Junction

- Forward biased junction
  - Conducts when E exceeds V_B
  - For $E < V_B$ very little current flows
  - Total current = majority + minority current
  - Diode current, $I_F \approx$ majority current
  - $V_F \approx$ 0.7 volts for a silicon diode

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Other Considerations

- Junction Breakdown
  - Caused by large reverse voltage
  - Result is high reverse current
  - Possible damage to diode
- Two mechanisms
  - Avalanche Breakdown
  - Zener Breakdown

Other Considerations

- Avalanche Breakdown
  - Minority carriers reach high velocity
  - Knock electrons free
  - Create additional electron-hole pairs
  - Created pairs accelerated
    - Creates more electrons
  - “Avalanche” effect can damage diode

Other Considerations

- Peak Inverse Voltage (PIV) or Peak Reverse Voltage (PRV) rating of diode

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Other Considerations

- Zener Breakdown
  - Heavily doped *n*-type and *p*-type materials in diode
  - Narrows depletion region
  - Increases electric field at junction
  - Electrons torn from orbit
  - Occurs at the Zener Voltage, V_Z

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Other Considerations

- Zener Diodes
  - Designed to use this effect
  - An important type of diode

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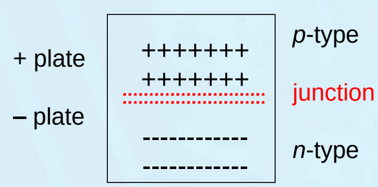
Other Considerations

- Diode junction



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Other Considerations

- Like a capacitor
  - Thickness of depletion region changes with applied voltage
  - Capacitance dependent on distance between plates