# ECE 421

## Electronics Circuits: Devices and Analysis

# INTRODUCTION TO SEMICONDUCTORS

# Topic Outcomes

- Describe the structure of an atom
- Discuss insulators, conductors, and semiconductors and how they differ
- Describe how current is produced in a semiconductor
- Describe the properties of n-type and p-type semiconductors
- Describe how a pn junction is formed

# Introduction to Semiconductors

# Introduction

- System nowadays are getting incredibly smaller, current speeds of operation are very significant and new gadgets are released everyday.
- In almost all areas of technology, fundamental principles change little over time.
- The first device that will be introduced here is the simplest of all electronics devices, nevertheless has a range of applications that seem endless.

# Introduction

- Electronics devices such as **diodes**, **transistors**, and **integrated circuits (IC)** are made of a **semiconductive material**.
- An important concept presented in this module is a **PN junction** that is formed when two different types of semiconductive material are joined.
- This is also fundamental to the operation of devices such as the solar cell, the diode and certain types of transistors.
- This module will present the construction, characteristics and models of semiconductor diodes.

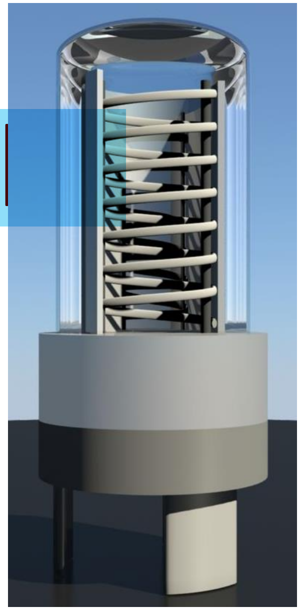
# Electronics

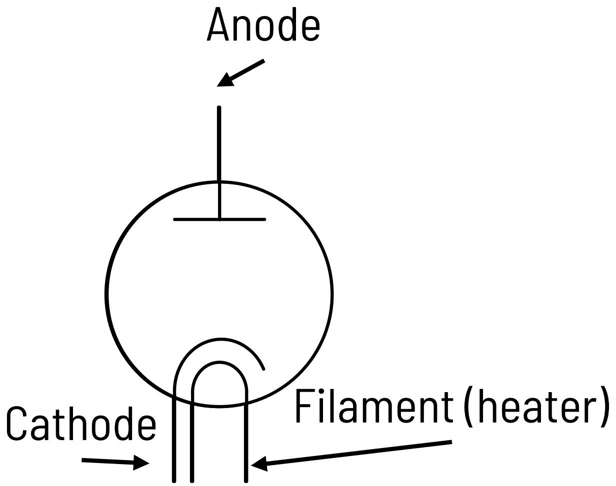
- **RA 5734, Sec. 21 C**
  - The science that deals with the development and application of devices and systems involving the flow of electrons in vacuum, in gaseous media, plasma and in semiconductors.
- **RA 9292, Sec. 3 H**
  - The science dealing with the development and application of devices and systems involving the flow of electrons or other carriers of electric charge, in a vacuum, in gaseous media, in plasma, in semiconductors, in solid-state and/or in similar devices, including, but not limited to, applications involving optical, electromagnetic and other energy forms when transduced or converted into electronic signals.

# Development of Semiconductors

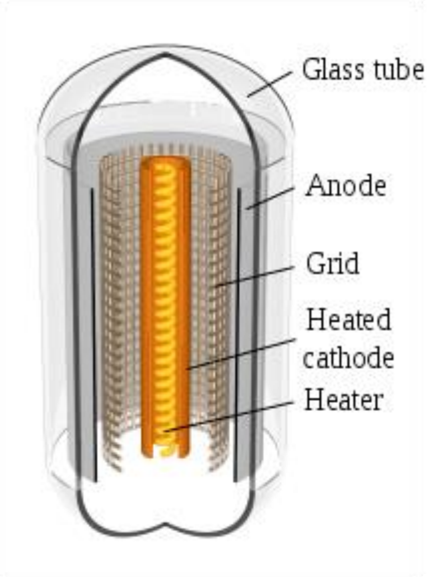
# Two-electrode vacuum tu

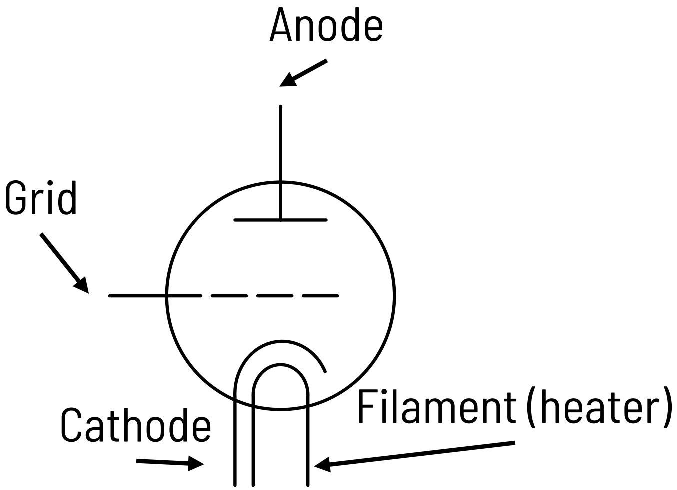
- Introduced by **Thomas Edison** and **John Ambrose Fleming** in **1904**
- Thomas Alva Edison, the inventor of the first practical incandescent light bulb, had also noticed that the direct electric current flowed from a heated metal filament in the bulb to the other electrode only when the latter had a positive voltage. John Ambrose Fleming used this effect (known as the Edison effect) to invent the two-electrode vacuum tube rectifier, which was soon to play an important role in the electrical circuits.






**Vacuum Tube Diode**



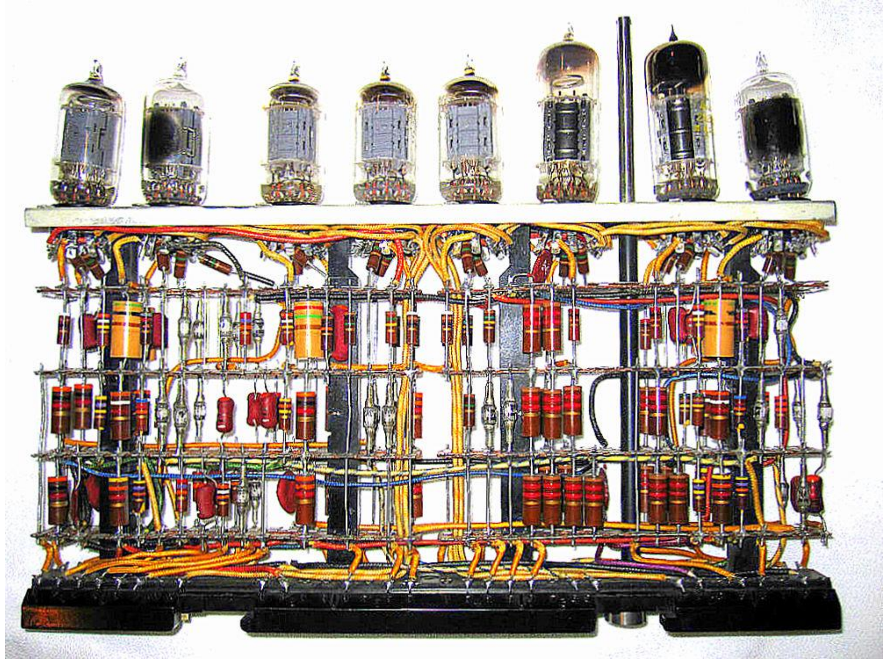




**Vacuum Tube Triode**

# Vacuum Tube

- Commercial TV began around **1946**.
- First vacuum tube computer was built in **1943** at the University of Pennsylvania.


**Old TV Set**

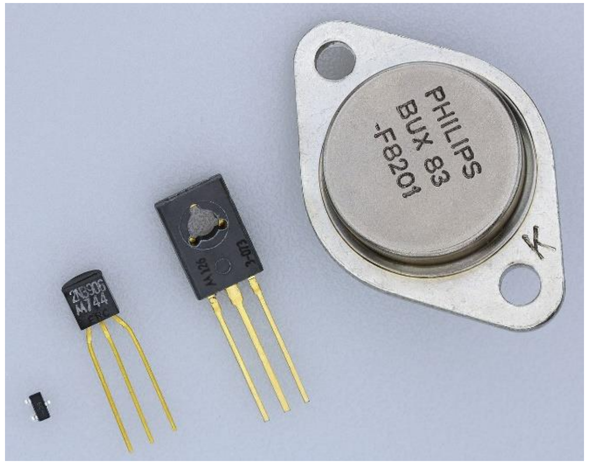


**Vacuum Tube Computer**

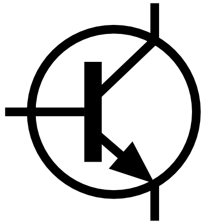
# Transistor

- Introduced the point-contact transistor on **December 23, 1947** by **Walter H. Brattain**, and **John Bardeen** at **Bell Telephone Laboratories**.
- **William Shockley** introduced the bipolar junction transistor in **1948**.


**First Transistor**



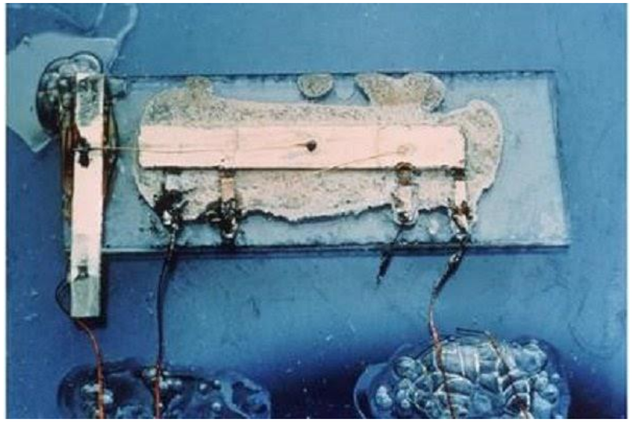

**Transistors today**



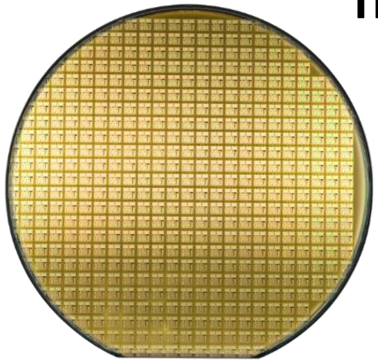
**Schematic Symbol**

# Integrated Circuit

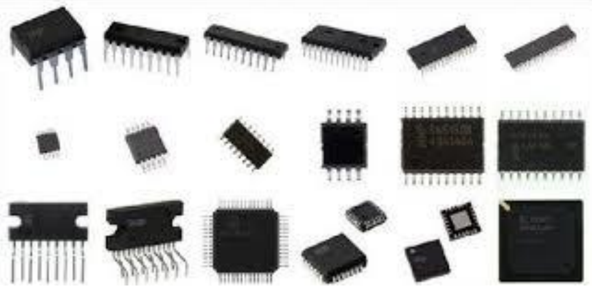
- **Jack Kilby** of **Texas Instruments** invented the integrated circuit (IC), paving the way for the miniaturization of early microdevices.
- ICs are a complex combination of several kinds of devices on a common base, called substrate, or in any piece of silicon.



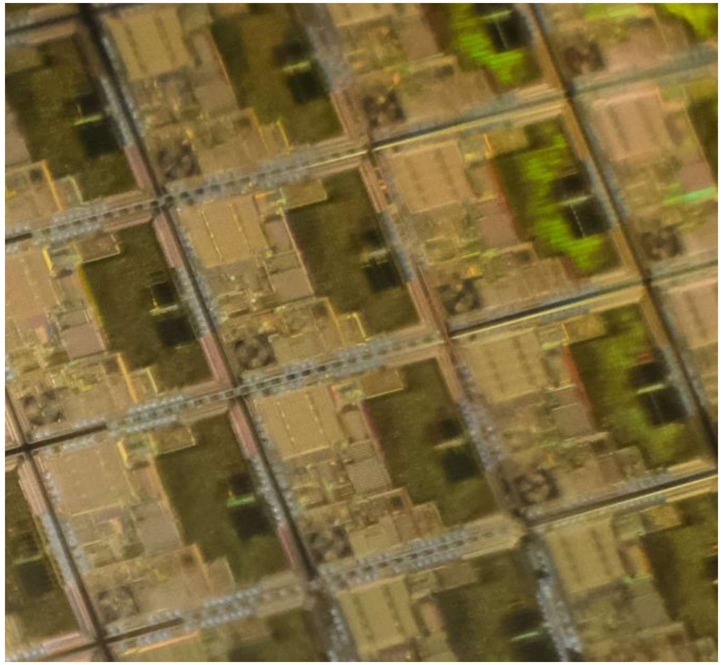
The 1st IC



Silicon Wafer



ICs today



Close-up of Dice in Wafer

# Applications of Electronics

- **Communication Electronics** – this includes AM and FM radio, television and satellite communication.
- **Electric Power** – electronics play an important role in the control and monitoring of electrical systems as in power plants, refineries, etc.
- **Digital Electronics** – the circuits for digital applications operate with pulse of voltage or current. Example of digital electronics includes calculators, computers, data processing and data communication.
- **Automotive Electronics** - applied to cars for changing battery, measuring gauges and monitoring of engine performances. Important of all is electronic ignition for better timing of the ignition spark.
- **Industrial Electronics** – includes control of heating and welding processes, the use of elevator's control, operating of copying machines, automatic door openers and burglar alarms.
- **Medical Electronics** – combines electronics with biology, medical research, diagnosis and treatment, all use electronic equipment. Examples are the electronic microscope and electro-cardiograph (ECG) Machine. In hospitals, oscilloscope are commonly used as display to monitor the heartbeat of patients in the ICU.

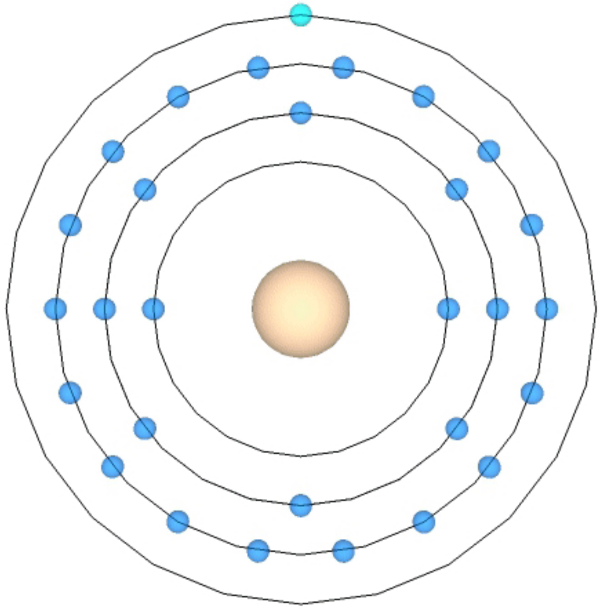
# The Atom

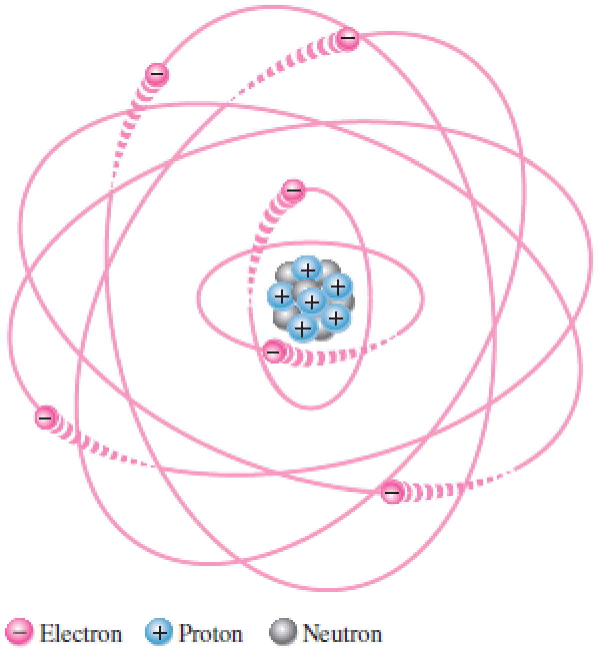
# Atom

- The smallest particle of an element that possesses the unique characteristics of that element.
- All matter is composed of atoms; all atoms consist of electrons, protons, and neutrons except normal hydrogen, which does not have a neutron.
- Each element in the periodic table has a unique atomic structure, and all atoms for a given element have the same number of protons.
- Niels Bohr proposed that the electrons in an atom circle the nucleus in different obits, similar to the way planets orbit the sun in our solar system. The Bohr model is often referred to as the planetary model.

# The Bohr Model

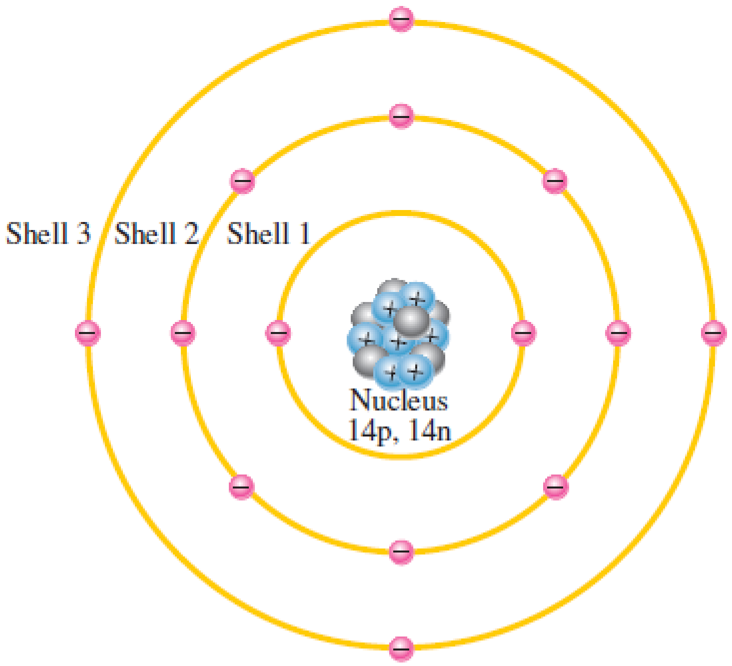
- According to the classical **Bohr model**, atoms have a planetary type of structure that consists of a central nucleus surrounded by orbiting electrons.
- The **nucleus** consists of positively charged particles called **protons** and uncharged particles called **neutrons**. The basic particles of negative charge are called **electrons**.
- Each type of atom has a certain number of electrons and protons that distinguishes it from the atoms of all other elements.
- The **atomic number** equals the number of protons in the nucleus, which is the same as the number of electrons in an electrically balanced (neutral) atom.





# Electrons and Shells

- **Energy Levels**. Electrons orbit the nucleus of an atom at certain distances from the nucleus. Electrons near the nucleus have less energy than those in more distant orbits.
- Each discrete distance (orbit) from the nucleus corresponds to a certain energy level.In an atom, the orbits are grouped into energy levels known as shells. A given atom has a fixed number of shells. Each shell has a fixed maximum number of electrons. The Maximum Number of Electrons in Each Shell $N_e = 2n^2$



# Valence Electrons

- Electrons that are in orbits farther from the nucleus have higher energy and are less tightly bound to the atom than those closer to the nucleus. This is because the force of attraction between the positively charged nucleus and the negatively charged electron decreases with increasing distance from the nucleus.
- This outermost shell is known as the **valence shell**, and electrons in this shell are called **valence electrons**.

# Free Electrons

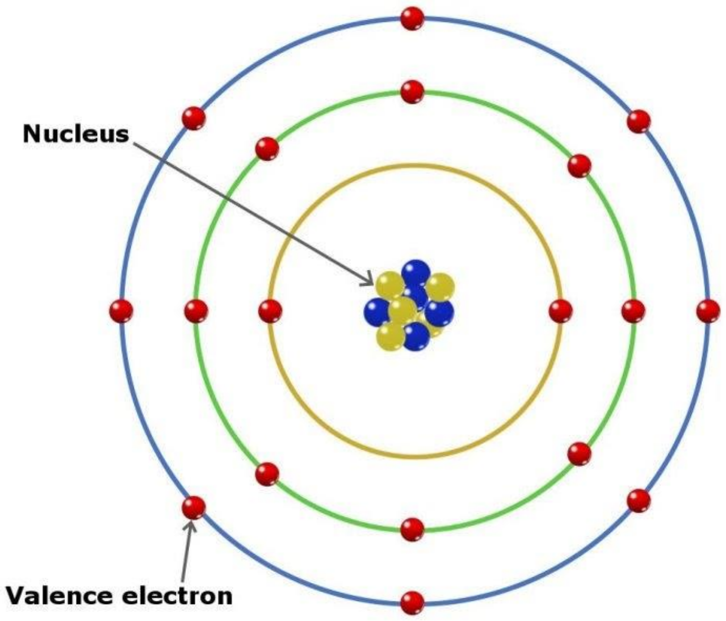
knock or force out of position:

- They are electrons **dislodged** from the **outer shell** of an atom.
- Free electrons **may exist by themselves** such as electrons moving from one plate to another.
- Free electrons constitute the **electric current** in a conductor.
- Materials capable of having **many free electrons** and which **could carry electric current** are called **conductors**.
- Materials capable of having **very few free electrons** are called **insulators**.
- Materials capable of having **not so many free electrons** are called **semiconductors**.
  - They are **also capable** of carrying electric current.
- The **more free electrons** there are in a material, the **better it will conduct**.

# Materials Used in Electronic Devices

# Insulators

- Possess no free charge carriers and thus are non-conductive.
- The atomic bond is based on shared electron pairs of nonmetals. The elements which behave like nonmetals have the desire to catch electrons, thus there are no free electrons which might serve as charge carriers.
- Electric charges **do not flow freely** in this material
  - Ideal in a sense that they coat or provide a barrier between conductors to keep electric currents under control.
- The most effective electrical insulators are **rubber, glass, pure water, oil, air**.

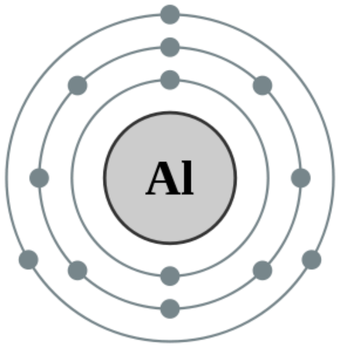



**Atomic structure of an insulator**

# Conductors

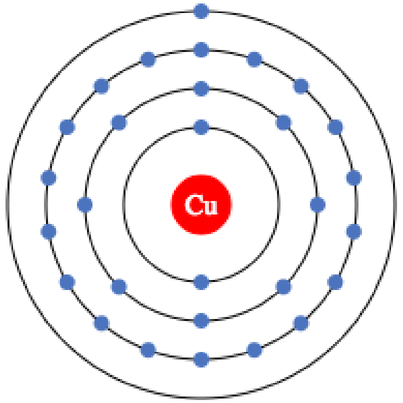
- Materials (e.g. all metallic substances) that permit electrons to flow freely from particle to particle
- Allow for charge transfer through the free movement of electrons
- In any metal element, it contains **less than 4 electrons** in its outer shell (**less than 4 valence electrons**).
  - Aluminum – 3 Valence Electrons
  - Magnesium – 2 Valence Electrons
  - Copper – 1 Valence Electron
- The best conductors are single-element materials, such as copper (Cu), silver (Ag), gold (Au), and aluminum (Al),

13: Aluminium 2,8,3



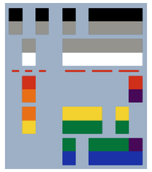

**Al atomic structure**

29: Copper




[Ar] 3d10 4s1 [2, 8, 18, 1]

**Cu atomic structure**



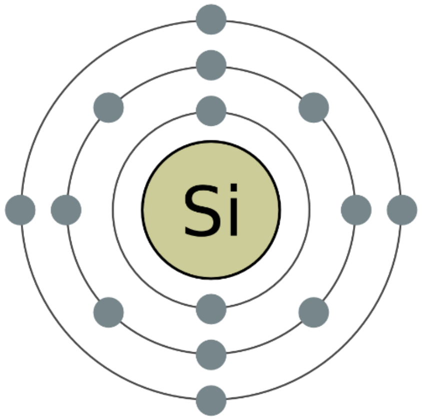
# Semiconductors

14: Silicon 2,8,4

- Semiconductors are solids whose conductivity lies between the conductivity of conductors and insulators. Due to exchange of electrons - to achieve the noble gas configuration - semiconductors arrange as lattice structure. Unlike metals, the **conductivity increases** with increasing temperature.

^ TEMP = ^ CONDUCTIVITY

- Increasing temperatures leads to broken bonds and free electrons are generated. At the location at which the electron was placed, a so-called defect electron ("**hole**") remains.

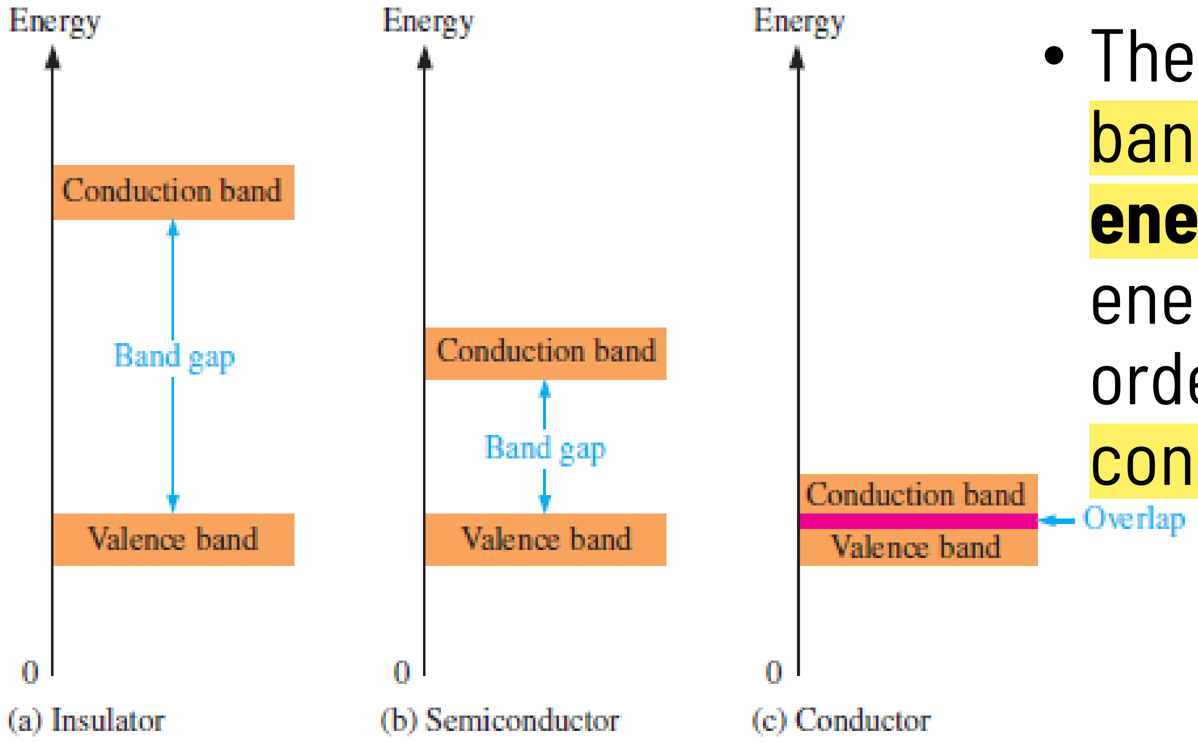



**Si atomic structure**

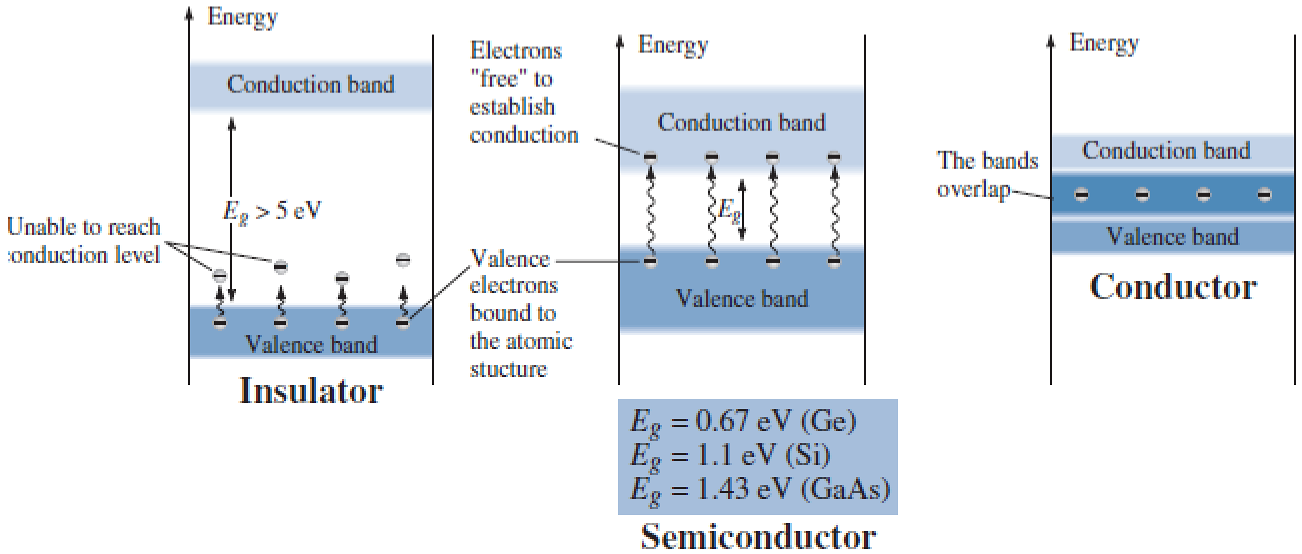
# Semiconductor Materials

- Semiconductor materials can be classified as:
  - **Single Crystal** – has a repetitive crystal structure such as Germanium (Ge), and Silicon (Si). Single-element semiconductors are antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), silicon (Si), and germanium (Ge).
  - **Compound** – constructed of **two or more semiconductor materials** of different atomic structures such as gallium arsenide (GaAs), indium phosphide (InP), gallium nitride (GaN), silicon carbide (SiC), and silicon germanium (SiGe) which are commonly used.
- The three semiconductors **most frequently used** are Ge, Si and GaAs.
- Most commonly used semiconductor is Silicon (Si).

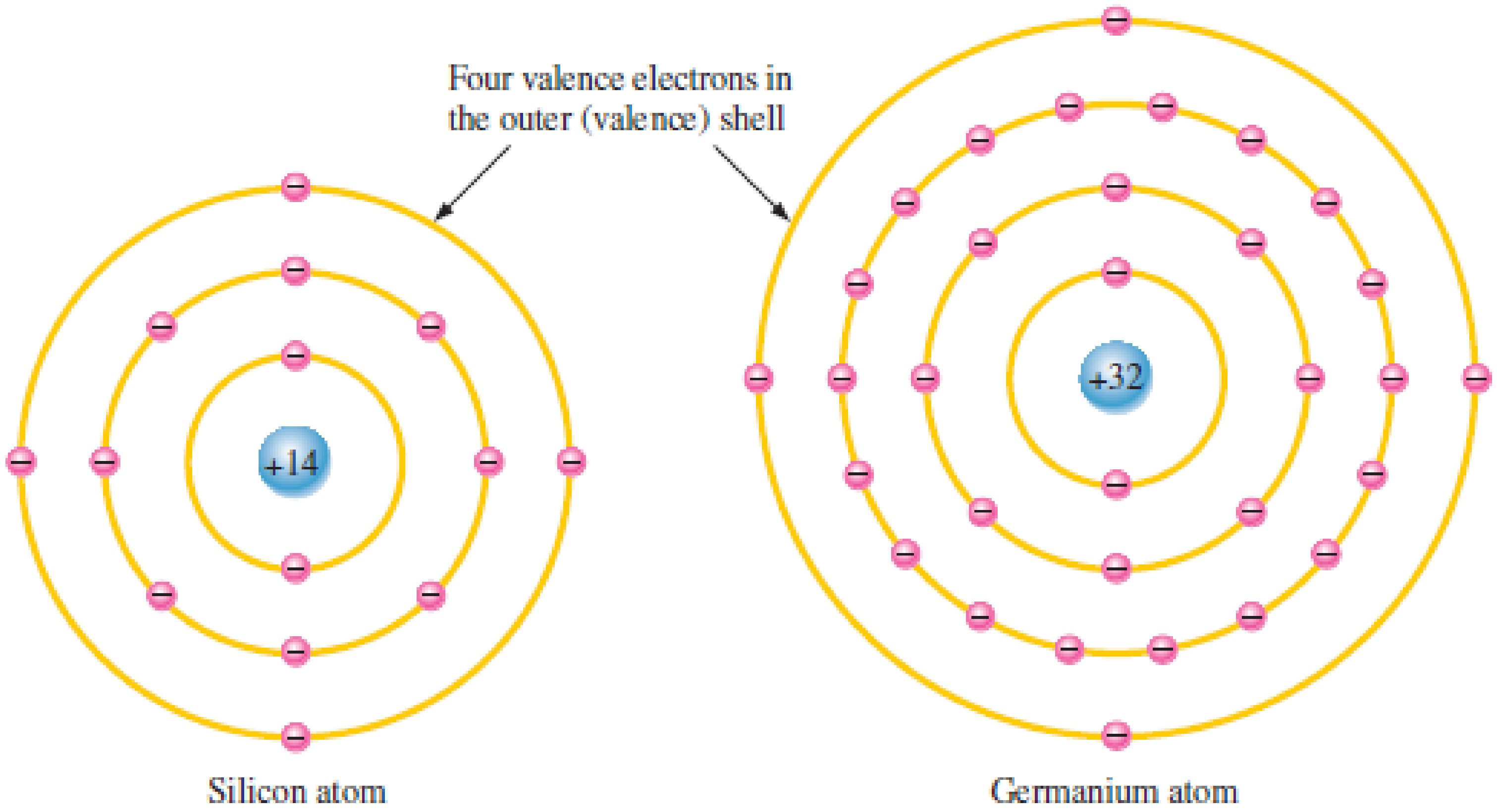
# Band Gap




- The difference in energy between the valence band and the conduction band is called an **energy gap** or **band gap**. This is the amount of energy that a valence electron must have in order to jump from the valence band to the conduction band.



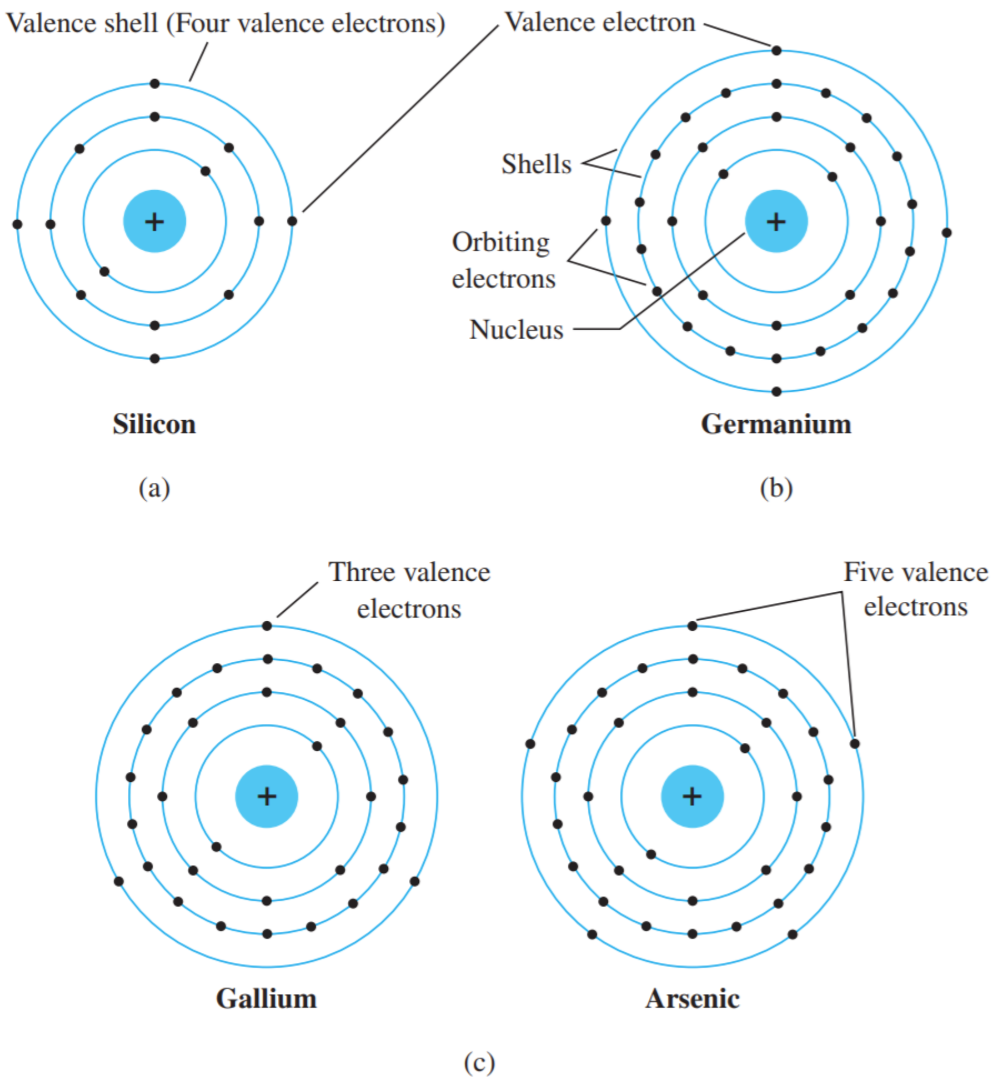
# Silicon and Germanium



# Covalent Bonding

# Covalent Bonding

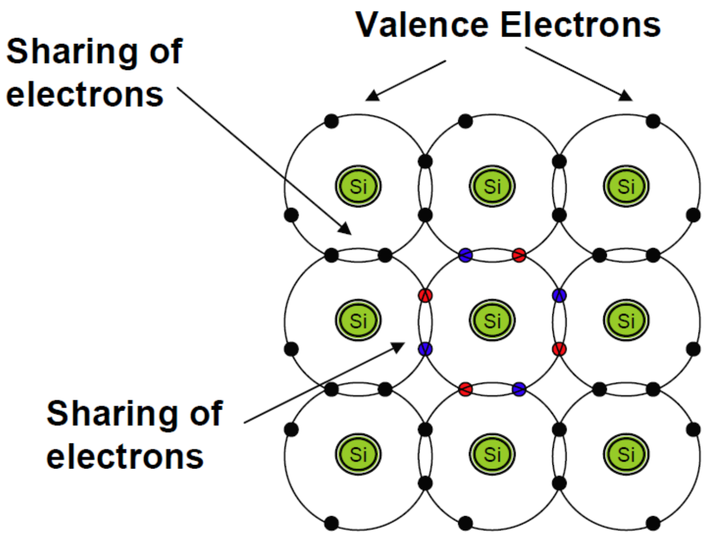
- Germanium
  - Has 32 orbiting electrons
  - Has 4 valence electrons (**tetravalent**)
- Silicon
  - Has 14 orbiting electrons
  - Has 4 valence electrons (**tetravalent**)
- Gallium
  - Has 31 orbiting electrons
  - Has 3 valence electrons (**trivalent**)
- Arsenide
  - Has 33 orbiting electrons
  - Has 5 valence electrons (**pentavalent**)



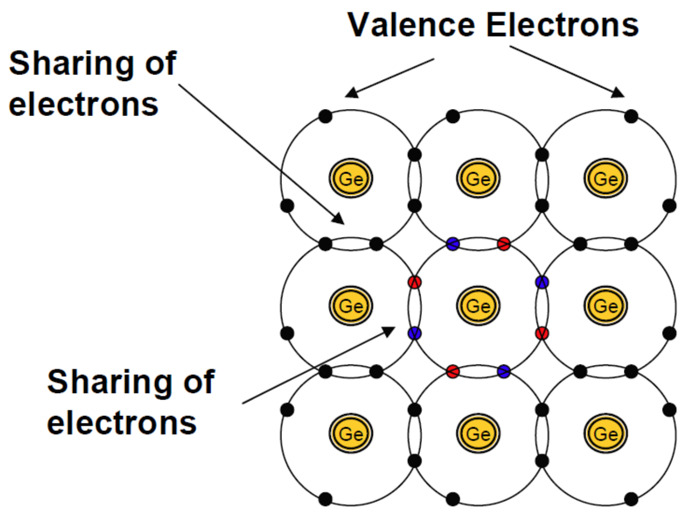

**Atomic Structures of Semiconductor Materials**

# Covalent Bonding

- In a ***pure Silicon*** or ***Germanium*** crystal, the ***four valence electrons*** of one atom form a ***bonding arrangement*** with ***four adjoining atoms***.
- The bonding of atoms, strengthened by the sharing of electrons, is called ***covalent bond.***
- The atoms align to form a pattern called ***crystal.***
- The ***outermost shell*** contains ***not more than 8 electrons***.



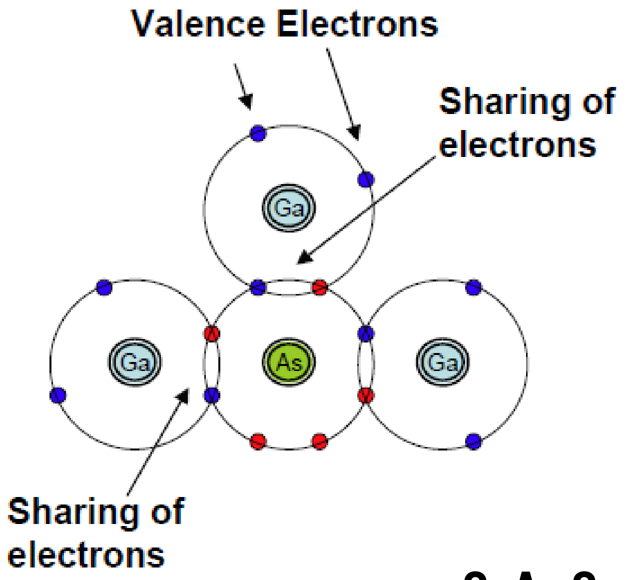

**Si Crystal Structure**

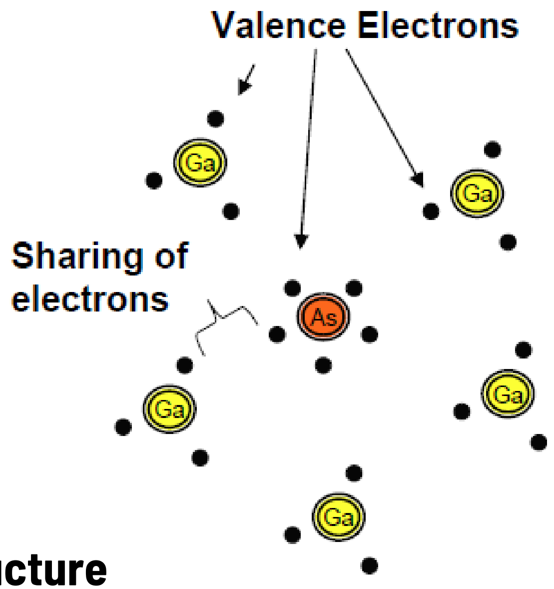



**Ge Crystal Structure**

# Covalent Bonding

- In a ***Gallium Arsenide*** compound, there is sharing of electrons between ***two different atoms***.
- ***Five electrons*** are provided by ***Arsenide*** and ***3 electrons*** are provided by ***Gallium*** to form a covalent bond.
- Even with the presence of covalent bonds, it is ***still possible*** for the valence electrons ***to break*** from its parent atom and assume the ***"free" state.***
    - Natural causes that can break the bond:
        1. Light energy (photons)
        2. Thermal energy from surrounding medium



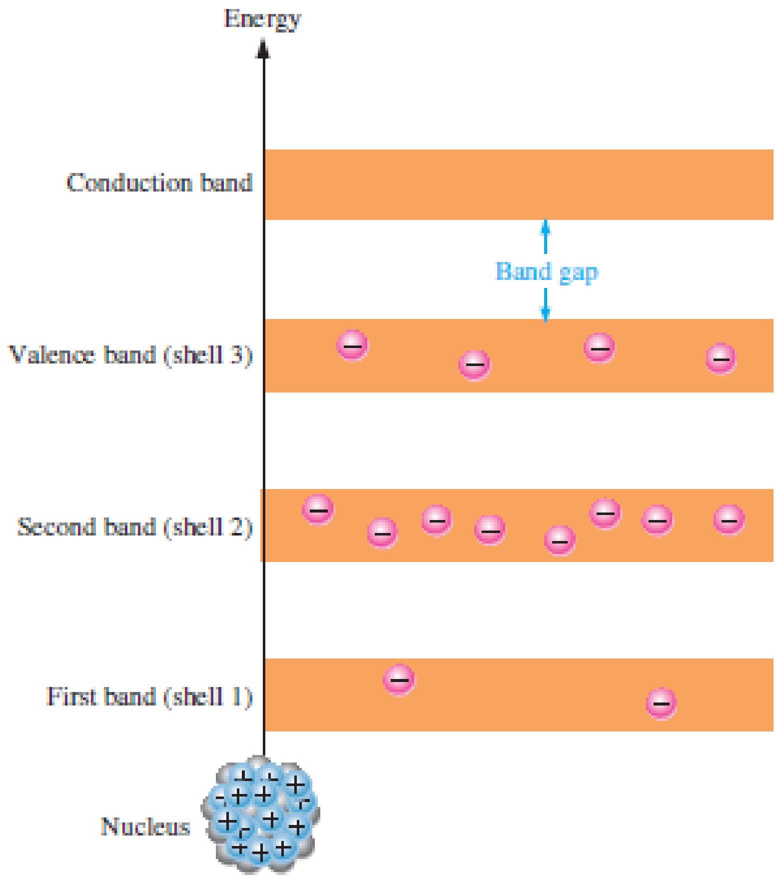




GaAs Crystal Structure

# Current in Semiconductors

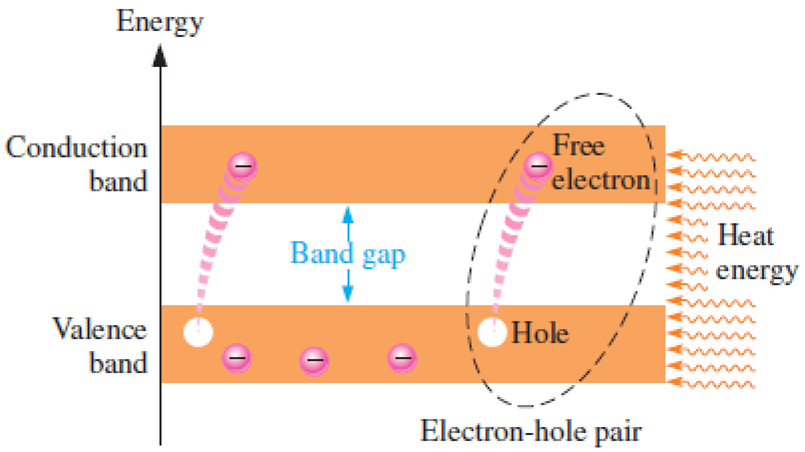
# Current in Semiconductors

- Energy band diagram for an atom in a pure (intrinsic) silicon crystal at it lowest energy state. There are no electrons in the conduction band at a temperature of 0 K

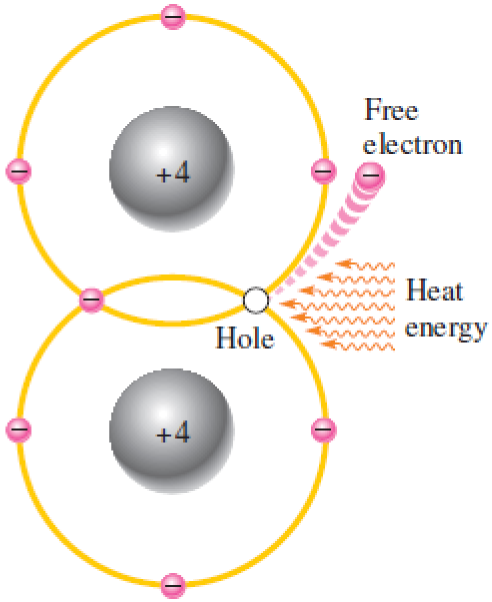


# Conduction Electrons and Holes

- An intrinsic (pure) silicon crystal at room temperature has sufficient heat (thermal) energy for some valence electrons to jump the gap from the valence band into the conduction band, becoming free electrons. Free electrons are also called **conduction electrons.**



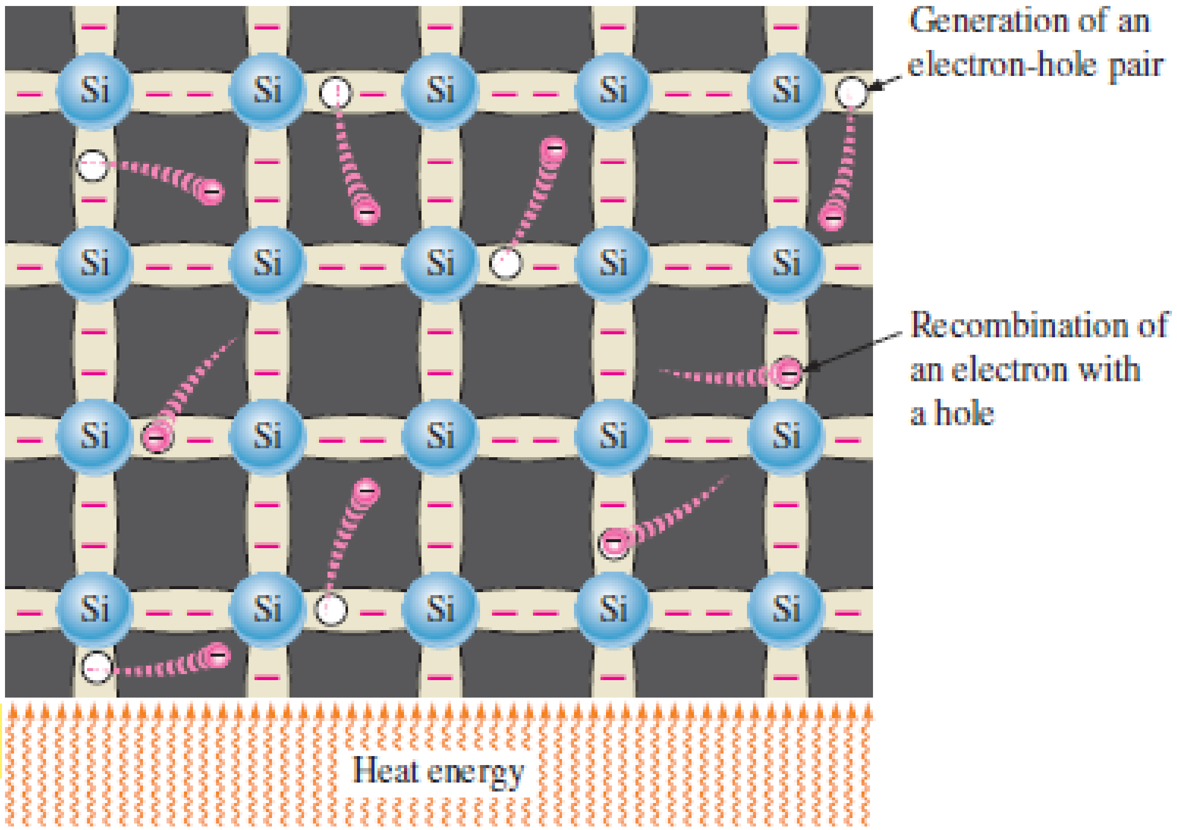

(a) Energy diagram for the outer two bands




(b) Bonding diagram

# Conduction Electrons and Holes

- When an electron jumps to the conduction band, a vacancy is left in the valence band within the crystal. This vacancy is called a **hole**. For every electron raised to the conduction band by external energy, there is one hole left in the valence band, creating what is called an **electron-hole pair**. **Recombination** occurs when a conduction-band electron loses energy and falls back into a hole in the valence band.



# Intrinsic and Extrinsic Semiconductors

# Intrinsic Semiconductors

- **Intrinsic semiconductor** is a semiconductor material that has been carefully refined to reduce the number of impurities to a very low level.
- The **free electrons** in a material due to external causes are referred to as **intrinsic carriers**.
- The **number of intrinsic carriers** vary from one material to another.
- Electric current in a material is dependent on the **number of intrinsic carriers** and **relative mobility** of carriers.
- **Relative mobility** ($\mu_N$ and $\mu_P$) of free carriers in a material is the ability of the free carriers to move throughout the material.

Intrinsic Carriers

| Semiconductor | Intrinsic Carriers (per $cm^3$) |
|---|---|
| GaAs | $1.7 \times 10^6$ |
| Si | $1.5 \times 10^{10}$ |
| Ge | $2.5 \times 10^{13}$ |

Relative Mobility Factor, $\mu_N$

| Semiconductor | $\mu_N$ ($cm^2$/V-s) |
|---|---|
| Si | 1500 |
| Ge | 3900 |
| GaAs | 8500 |

# Intrinsic Semiconductor

- A **change in temperature** of a semiconductor material **can increase** the number of free electrons quite substantially.
- Semiconductor materials such as germanium and silicon shows that the reduction in the resistance with the increase in temperature are said to have **negative temperature coefficient**.
- Conductors have **positive temperature coefficient**.

# Extrinsic Semiconductor

- A semiconductor that has been subjected to the doping process
  - **Doping** is a process of adding impurities to pure semiconductor material to provide positive and negative charges.
    - Extrinsic Materials:
      1. N-type
      2. P-type
- Both n-type and p-type materials are formed by adding impurity atoms into a germanium and silicon base. The elements for doping generally have an electron valence of either 5 or 3. As a result, the doped semiconductor has either an excess or a shortage of electrons in the covalent bond structure.

# Semiconductor Doping

- Doping means the introduction of impurities into a semiconductor crystal to the defined modification of conductivity. Two of the most important materials silicon can be doped with, are boron (trivalent) and phosphorus (pentavalent). Other materials are aluminum, indium (trivalent) and arsenic, antimony (pentavalent).
- The dopant is integrated into the lattice structure of the semiconductor crystal, the number of outer electrons define the type of doping. Elements with **3 valence electrons are used for p-type doping**, **5-valued elements for n-doping**.

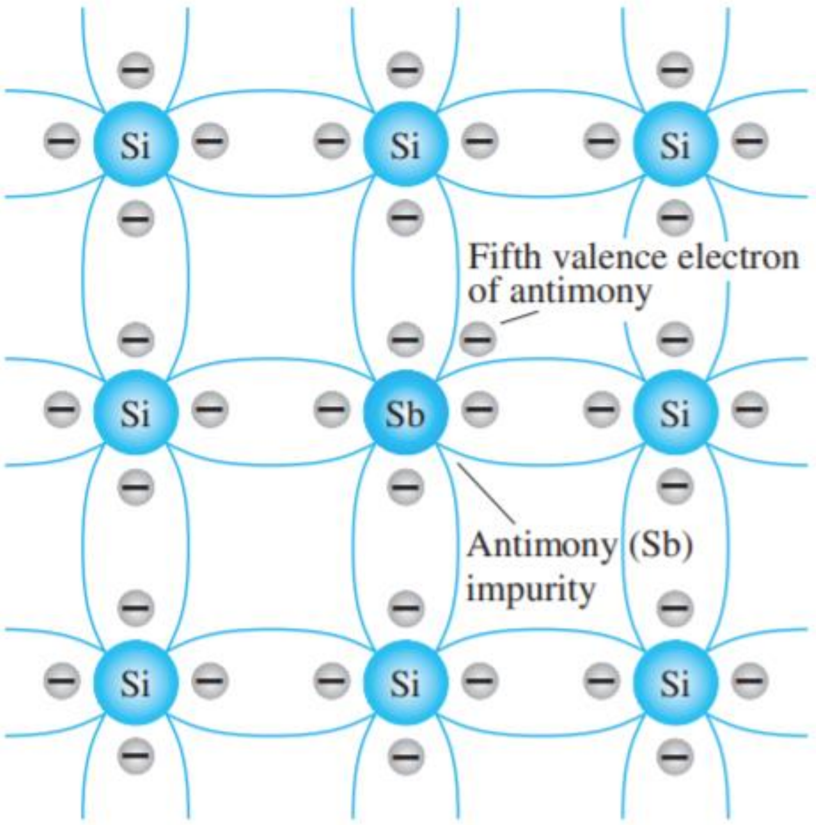
# Semiconductor Doping

| ELEMENT | ATOMIC NUMBER | VALENCE | APPLICATION |
|---|---|---|---|
| Antimony<br>Arsenic<br>Phosphorus | 51<br>33<br>15 | 5<br>5<br>5 | Donor impurity elements. Gives electrons to form N-type semiconductor. As and Sb for Ge; P for Si. |
| Germanium<br>Silicon | 32<br>14 | 4<br>4 | Intrinsic semiconductor used in pure crystal form to be doped with impurity elements. Doped semiconductors are extrinsic. |
| Aluminum<br>Boron<br>Gallium<br>Indium | 13<br>5<br>31<br>49 | 3<br>3<br>3<br>3 | Accept impurity elements. Take electrons to form P-type semiconductor, Ga and In used for Ge; Al and B for Si. |

# N-type and P-type materials

# N-Type Material

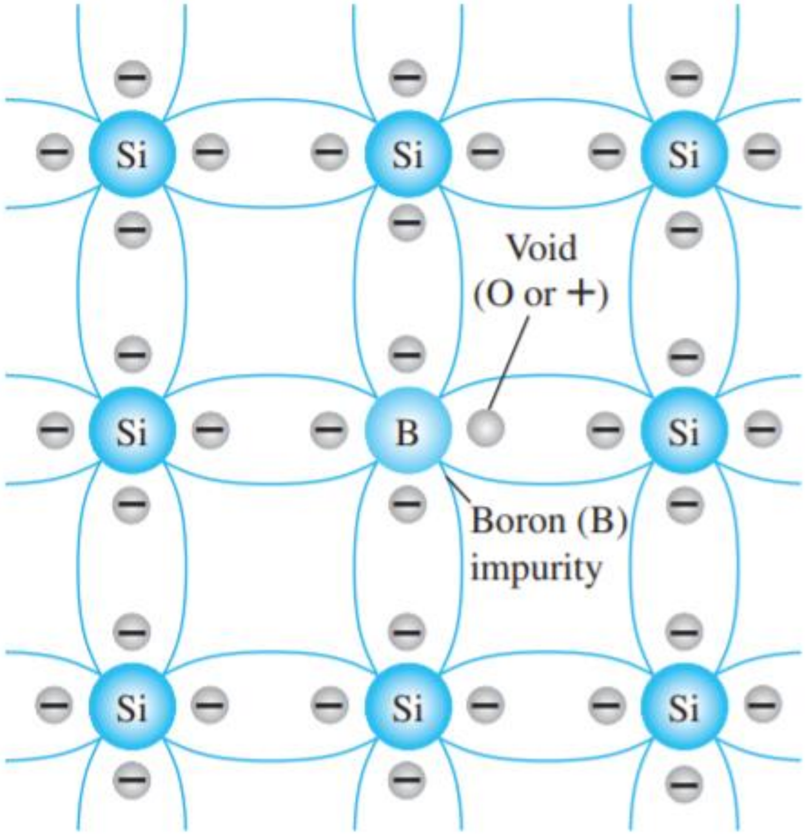
- To increase the number of conduction-band electrons in intrinsic silicon, pentavalent impurity atoms are added. These are atoms with five valence electrons such as **arsenic (As), phosphorus (P), bismuth (Bi),** and **antimony (Sb).**
- Diffused impurities with five valence electrons are called **donor atoms**.
- This extra electron becomes a conduction electron because it is not involved in bonding. Because the pentavalent atom gives up an electron, it is often called a donor atom
  - **Majority Carriers** – Electron
  - **Minority Carriers** – Holes (Thermally generated)




**Antimony Impurity in n-type material**

# P-Type Material

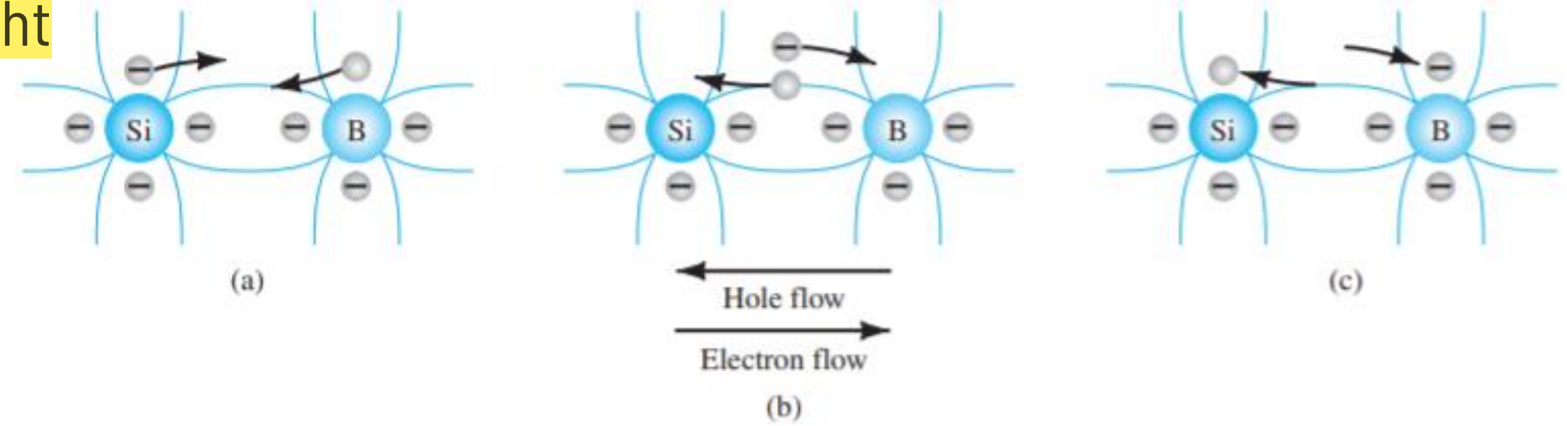
- To increase the number of holes in intrinsic silicon, trivalent impurity atoms are added. These are atoms with three valence electrons such as **boron (B), indium (In),** and **gallium (Ga).**
- Note that there is now an insufficient number of electron to complete the covalent bonds or the newly formed lattice. The resulting vacancy is called a **hole** and is represented by a small circle of positive sign due to absence of negative charge. Since it's resulting vacancy will easily accept a "free" electrons. The impurities added are called **acceptor atoms**.
    - **Majority Carriers** – Holes
    - **Minority Carriers** – Electron (Thermally generated)




**Boron Impurity in p-type material**

# Effect of the Hole Conduction

- If a valence electron **acquires sufficient kinetic energy** to break its covalent bond to fill the void created by a hole, then a hole, will be created in the covalent bond that releases the electron. There is therefore a transfer of holes to the left and electrons to the right




**Electron vs Hole Flow**

- Hole current is the same as that of the conventional current (opposite of electron flow).
- Hole current flows only in p-type semiconductors, likewise, electron flow is the current in n-type semiconductors and all wire conductors.

# Semiconductor Doping

- The resulting p-type material is electrically neutral, for the same reasons as for the n-type material.
- A hole has the same amount of positive charge as proton, equal to that of an electron but opposite polarity. However, **a hole charge is not a proton**.
- A proton is a stable charge in the nucleus that is not free to move. A hole is a positive charge outside the nucleus present only in semiconductors because **of unfilled covalent bonds**.
- Hole charges can be moved by an **applied potential difference**.

# End