# Chapter One: Basic Semiconductor Theory


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# Outlines

# Introduction. . . .

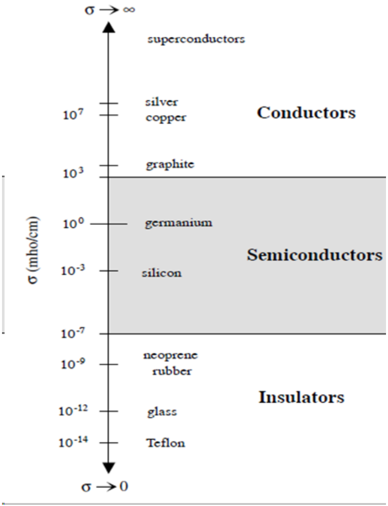
- Word "electronics" stands for '*electron-mechanics*'

  Thus electronics is that field of science and engineering which deals with the motion of electrons under the influence of applied electric and/or magnetic field
- Electron device means the device in which conduction takes place by the movement of electrons through a vacuum, a gas or a semiconductor and capable of performing various functions:
  - Rectification (conversion of ac into dc)
  - Amplification (strengthening of a weak signal)
  - Control
  - Generation (conversion of dc power into ac power of any frequency)
  - Conversion of light into clectricity and vice versa, . . .

# Introduction. . . .

- The vital concern of electronic field is predicting and controlling the flow of the atomic charge
  - Conductor is a material that will support a **generous** flow of charge when a voltage source is applied across its terminals.
  - An insulator is a material that offers a **very low level of conductivity** for an applied voltage source.
  - A semiconductor is a material that has a **conductivity level** somewhere between the **extremes** of **an insulator** and a **conductor**.
  - The study of electronic devices is now almost synonymous with the study of *semiconductor devices*

## Introduction



## Cont. . . .

- Resistivity ($\rho$): Inversely related to the conductivity of a material is its resistance to the flow of charge, or current

$$\rho = \frac{RA}{l} = \frac{\Omega cm^2}{cm} \implies \Omega - cm \tag{1}$$

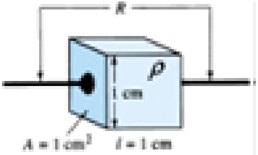



**Figure:** defining the metric units of resistivity

| TABLE 1.1 Typical Resistivity Values | | |
|---|---|---|
| *Conductor* | *Semiconductor* | *Insulator* |
| $\rho \cong 10^{-6}$ Ω-cm (copper) | $\rho \cong 50$ Ω-cm (germanium)<br>$\rho \cong 50 \times 10^3$ Ω-cm (silicon) | $\rho \cong 10^{12}$ Ω-cm (mica) |

# Cont. . . .

- Ge and Si have received the attention they have for a number of reasons
  - They can be manufactured to a very high purity level
    - The ability to change the characteristics of the material significantly through adding impurity levels process, known as “**doping**”
  - Their characteristics can be altered significantly through the application of heat or light
    - Important consideration in the in the development of heat- and light-sensitive devices
  - The atoms of both materials form a very definite pattern that is periodic in nature

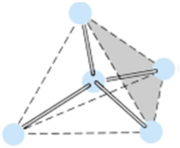
# Atomic Theory

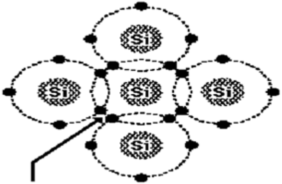
- Some of the unique qualities of *Ge* and *Si* are due to their atomic structure
  - The atoms of both materials form a very definite pattern

A crystal : One complete pattern

A lattice : The periodic arrangement of the atoms

A single-crystal : Any material composed solely of repeating crystal structures of the same kind





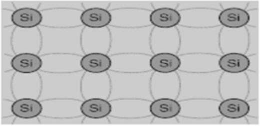
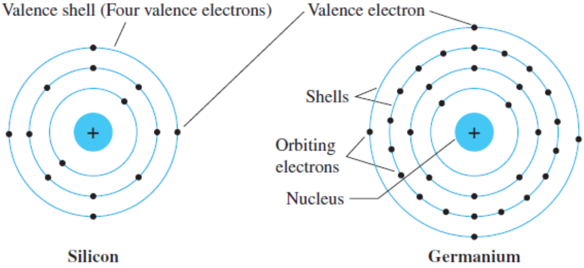




**Figure:** Ge and Si (Single-crystal structure Silicon Lattice)

# Cont. . . .

- The Bohr models of the two most commonly used semiconductors; Germanium and silicon




- The potential (ionization potential) required to remove any one of valence electrons is lower than that required for any other electron in the structure
- In a pure germanium or silicon crystal 4 valence electrons are bonded to 4 adjoining atoms

- A bonding of atoms, strengthened by the sharing of valence electrons, is called covalent bonding

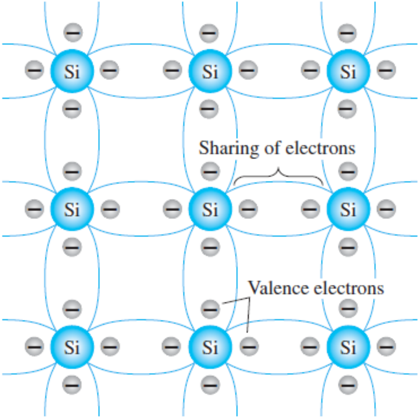
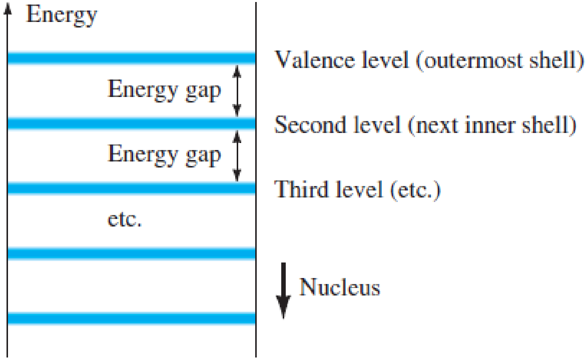



**Figure:** Covalent bonding of the silicon atom

# Energy Levels

- In the isolated atomic structure there are discrete (individual) energy levels associated with each orbiting electron




- Each material have its own set of permissible energy levels for the electrons in its atomic structure

*The more distant the electron from the nucleus, the higher the energy state, and any electron that has left its parent atom has a higher energy state than any electron in the atomic structure*

- The energy associated with each electron is measured in electron volts (eV)

$$W = QV \tag{2}$$

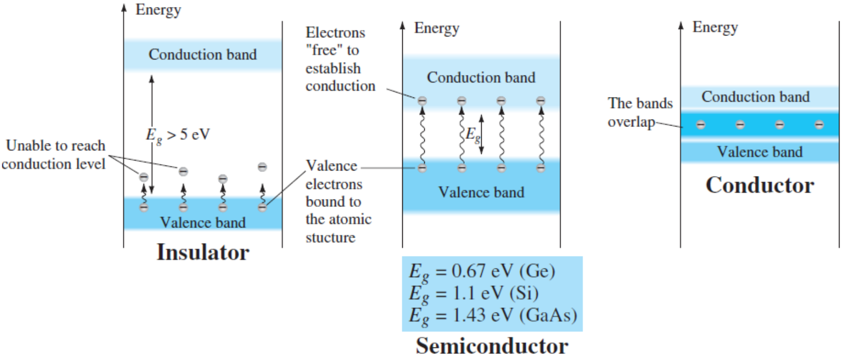
$$\boxed{1eV = 1.6 \times 10^{-19} J}$$

**Example**

1. How much energy in joules is required to move a charge of $6C$ through a difference in potential of $3V$?
2. If $48eV$ of energy is required to move a charge through a potential difference of $12V$, determine the charge involved.

# Energy Band Model

- One method of characterizing an electrical material is based up on a diagram that represents electron energy in that material
- Electronic energy is divided among three bands
  1. Valence band: bonding electrons with lowest energy
     - The electrons are tightly bound to the atoms of the material
  2. Forbidden gap or band : electrons do not occupy energy states
     - Is not a physical void, but rather an energy gap
     - Absent in metallic conductors, very large in insulators, and in semiconductors it is relatively small.
  3. Conduction band : conduction electrons with highest energy.
- Electrons occupy specific energy states, or levels, in the conduction and valence bands, but they may not occupy energy states located in the band gap




- To achieve electrical conduction, electrons must transfer from energy states in the valence band to energy states in the conduction band
- The valence band represents low energy states of the electrons, in which the electrons are tightly bound to the atoms of the material

# Cont. . . .

- To cross the band gap, an electron must attain energy equal to or greater than the lowest allowed energy state in the conduction band
  - In metals, electrons acquire sufficient thermal energy to transfer from the valence band to the conduction band, thus making electrical conduction possible
  - In semiconductors, Atoms are ionized(electrons are torn loose), and free (conduction) electrons are released to establish an electric current.
- The forbidden gap regions associated with insulators and semiconductors represent energy levels that electrons may not assume
  - The only way that an electron can move from the valence to conduction band is by acquiring sufficient energy to cross the gap, the material is usually damaged or destroyed
  - In the pure (intrinsic) state, semiconducting materials manifest a forbidden gap that is less than that found in insulators
    - By the addition of certain impurities, new (allowed) valence electrons states are created high in the forbidden gap, so that electrons can jump relatively easily into the conduction band

## Semiconductor Materials

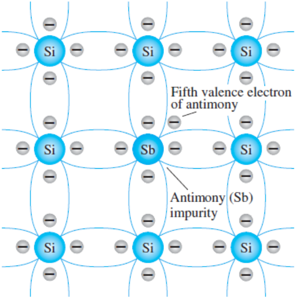
- Semiconductor materials are basically
  1. Intrinsic semiconductor
     - Impurities *do not* appreciably affect its electrical behaviour
     - All carriers are created due to thermally or optically excited electrons from the full valence band into the empty conduction band
     - Equal numbers of electrons and holes are present
     - Electrons and holes flow in opposite directions in an electric field, though they contribute to current in the same direction since they are oppositely charged
     - Hole and electron current are not necessarily equal, however, because electrons and holes have different effective masses (crystalline analogues to free inertial masses).
     - The concentration of carriers is strongly dependent on the temperature.
     - At low temperatures, the valence band is completely full making the material an insulator.
     - Increasing the temperature leads to an increase in the number of carriers and increase in conductivity.
  2. Extrinsic semiconductor
     - Material that has been subjected to the doping process

# Types of Extrinsic Semiconductor Materials

- There are two extrinsic materials of immeasurable importance to semiconductor device fabrication:
  - n-type and
  - p-type
- Both the n- and p-type materials are formed by adding a predetermined number of impurity atoms into a germanium or silicon base

N-Type Material

- Created by introducing those impurity elements that have five valence electrons (pentavalent), such as antimony, arsenic, and phosphorus.



# Cont. . . .

- There is an additional fifth electron due to the impurity atom, which is not associated with any particular covalent bond, free to move within the newly formed n-type material
- Diffused impurities with five valence electrons are donor atoms.
- A large number of “free” carriers have been established in the n-type material, it is still electrically **neutral**
- A **discrete energy** level (called the donor level) appears in the forbidden band with an $E_g$ significantly less than that of the intrinsic material.
- “free” electrons due to the added impurity have less difficulty absorbing a sufficient measure of thermal energy to move into the conduction band at room temperature

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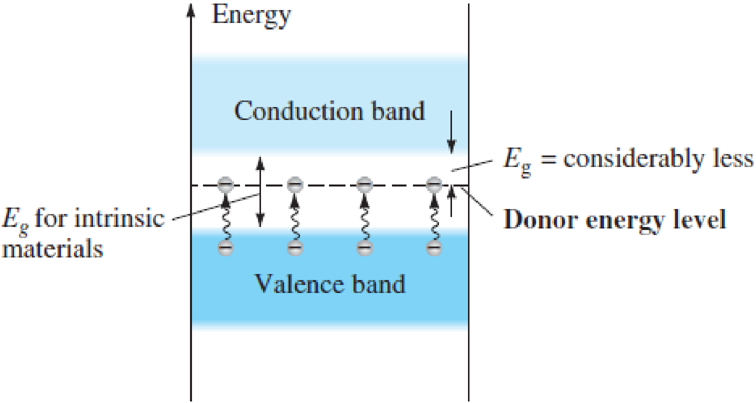
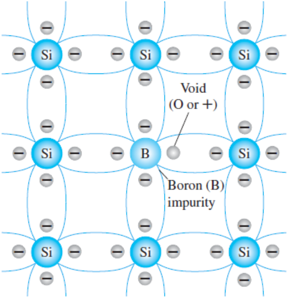
- At room temperature, there are a large number of carriers (electrons) in the conduction level and the conductivity of the material increases significantly.



### P-Type Material

- Formed by doping a pure Ge or Si crystal with impurity atoms having three valence electrons, such as boron, gallium, and indium

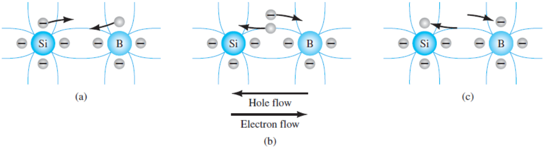



- There is an insufficient number of electrons to complete the covalent bonds of the newly formed lattice.
- The resulting vacancy is called a hole and is represented by a small circle or positive sign due to the absence of a negative charge.

- Since the resulting vacancy will readily accept a "free" electron: The diffused impurities with three valence electrons are called acceptor atoms
- The resulting p-type material is electrically neutral

Electron versus Hole Flow

- If a valence electron acquires sufficient kinetic energy to break its covalent bond and fills the void created by a hole, then a vacancy, or hole, will be created in the covalent bond that released the electron




(a) (b) (c)

- A transfer of holes to the left and electrons to the right

# Cont. . . .

## Diffusion and drift current

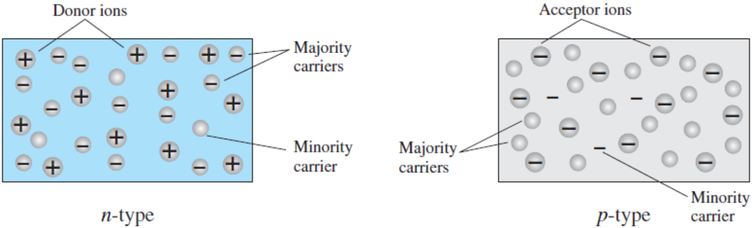
- The diffusion is a flow of charge carriers from a region of high density to a region of low density due to non uniform distribution of it. Diffusion current is the transport of charge carriers in a semiconductor.
- Drift is charged particle motion in response to an applied electric field.
- When an electric field is applied across a semiconductor, the carriers start moving, producing a current.
- The positively charged holes move with the electric field, whereas the negatively charged electrons move against the electric field.

## Majority and Minority Carriers

- In the intrinsic state, the number of free electrons in Ge or Si is due only to those few electrons in the valence band that has acquired sufficient energy from thermal or light sources to break the covalent bond or to the few impurities that could not be removed

# Cont. . . .

- In an n-type material the electron is called the majority carrier and the hole the minority carrier
- In a p-type material the hole is the majority carrier and the electron is the minority carrier.

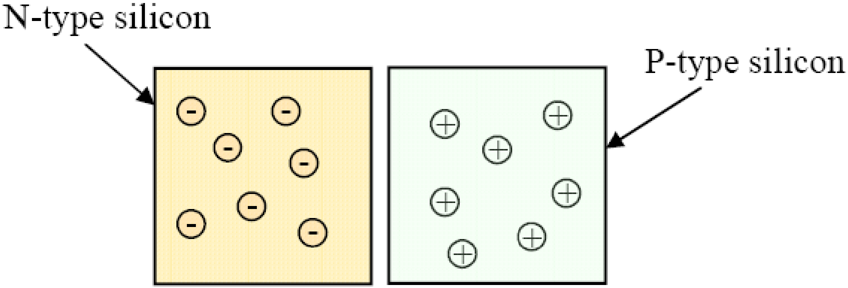



- The n- and p-type materials represent the basic building blocks of semiconductor devices

- Regeneration and Recombination of Electron-Hole Pair
  - Free electrons and holes are generated by thermal energy, which causes covalent bonds to break at a rate depending strongly on temperature
    - The higher the temperature, the higher will be the rate of regeneration
  - The process of recombination and generation of electron-hole pairs establishes equilibrium at a particular temperature.
  - For every 'liberated' electron a 'hole' remains in valence band
    - The liberated electrons to the conduction band give up energy and drop into a hole in the valence band which does not contribute to the current; rather it is cancellation of charge carriers and recombination has occurred
  - At any particular temperature there exists a certain number of electron-hole pairs that will govern the conductivity and the resistance of the material
  - Semiconductors have a negative Temperature Coefficient of Resistance

# PN- Junction Theory

- Pure silicon can be turned into a relatively good electrical conductor when contains both p-type and n-type regions.




- In the real world, two such crystals cannot be joined together usefully.
- A practical pn junction can only be created by inserting different impurities into different parts of a single crystal.

# Cont. . . .

- Unbiased PN-Junction
    - When we join the n- and p-type crystals together, the extra electrons in the n region will seek to lose energy by filling the holes in the p region which leaves an empty zone, or depletion region, around the junction, also leaves a small electrical imbalance inside the crystal.
    - The n region is missing some electrons so it has a positive charge.
    - Those electrons have migrated to fill holes in the p region, which therefore has a negative charge.
    - Electrical imbalance amounts to about 0.3 volt in a germanium crystal, and about 0.65 to 0.7 volt in a silicon crystal, known as a barrier potential.

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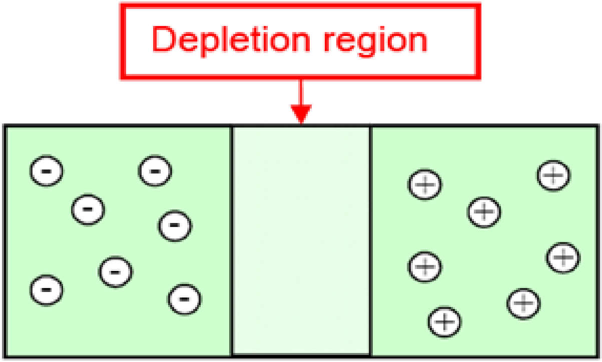

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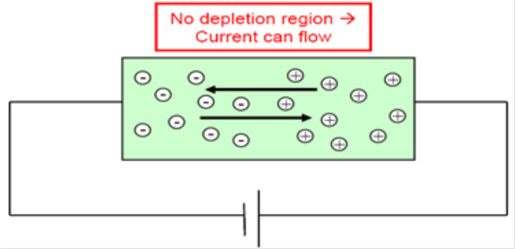
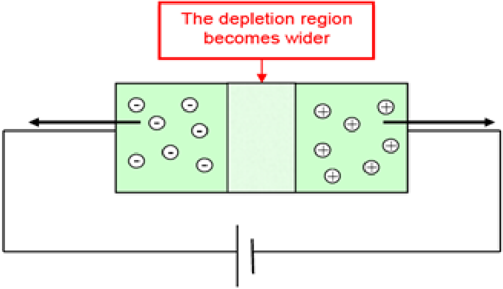
- PN – Junction Biasing
  - Forward Biasing
    - The negative terminal of the supply voltage is connected to the N-type end and the positive terminal is connected to the P-type material




    - Due to the decrease of depletion region resistance, an electrical current can flow through the junction in the forward direction, but not in the reverse direction.
    - **diode acting as a closed switch**

# Cont. . . .

- Reverse Biasing
  - The positive terminal of the external voltage is applied to the n-type material and the negative terminal of the supply voltage is connected to the p-type end.




  - all available current carriers are attracted away from the junction, and the depletion region grows correspondingly larger and its resistance increases
  - No current flow through the crystal
  - **diode acting as an open switch**

Thank You