Engineering Physics (2025)
Course code 25PY101
Unit 1: Metals and Semiconductors

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Unit 1 Plan

1. Condensed matter
2. Metals
3. Classical free electron theory
4. Expression of electrical conductivity
5. Introduction to Semiconductors
6. Electrical conductivity of semiconductors
7. Hall effect
8. Concept of Panchabhuta

Unit 1 Plan

Lecture 3 plan

Learning Objectives

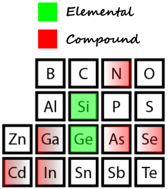
- Classification of semiconductors
- Nature of bonding in semiconductor
- Doping of semiconductor

Semiconductors: Classification

Definition

Semiconductor is a class of condensed matter having electrical conductivity ($10^{-4}\,\mathrm{S\,m^{-1}}$ to $1\,\mathrm{S\,m^{-1}}$) greater than that of insulator ($<10^{-10}\,\mathrm{S\,m^{-1}}$) but lower than that of conductor ($10^{7}\,\mathrm{S\,m^{-1}}$).

- In the periodic table, there are 11 elements that are semiconductors. These are called **elemental semiconductors**. Si and Ge from Group IV are widely used elemental semiconductors.
- Certain combinations of elements of Groups III and V or Groups II and VI also are semiconductors. These are called **compound semiconductors**. GaAs, InP are some of the well known examples.
- The unique feature of semiconductor is that two charge carriers, namely **electrons** and **holes**, transport current.



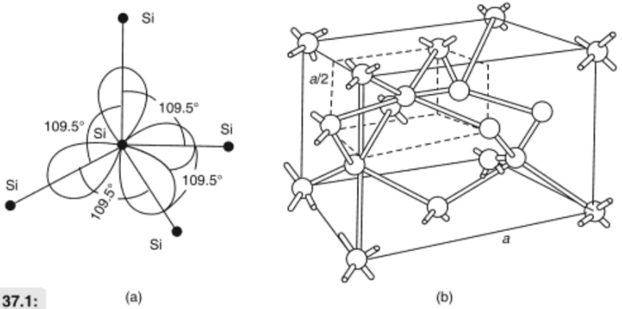


Fig. 37.1:

(a) Tetrahedral arrangement (b) Diamond crystal structure. Taken from Avadhanulu, Chapter 37.

- ^{18}Si atom has electronic configuration $1\,s^2\,2\,s^2\,2\,p^6\,3\,s^2\,3\,p^2$.
- In Si crystal, the four valence electrons undergo **hybridization** to form four sp^3 molecular orbitals. These orbitals form covalent bonds with neighbouring atoms arranged in tetrahedral arrangement. The resulting structure is the **diamond cubic crystal structure**.

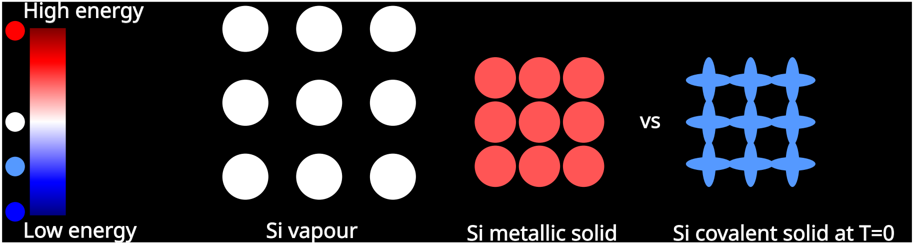
Intrinsic Semiconductor

- Chemically pure semiconductor is called intrinsic semiconductor.
- Practically, a semiconductor is considered pure if there is less than one impurity atom per billion host atoms i.e. < 1 ppb (part per billion).
- It has five properties
  1. Perfect insulator at absolute zero temperature
  2. Generation of charge carriers by thermalization
  3. Existence of energy band gap (M2U3)
  4. Conductivity is **highly** influenced by temperature
  5. Recombination of charge carriers
- For Si, the valence electron density is of the order of $10^{29}\,\mathrm{m}^{-3}$. However, at room temperature the conduction electron density is only of the order of $10^{18}\,\mathrm{m}^{-3}$.

Estimate: Valence electron density of Si

The lattice constant of Si crystal is $5.43\,\mathrm{Å}$.

Nature of intrinsic semiconductor at $T = 0$ (property 1)

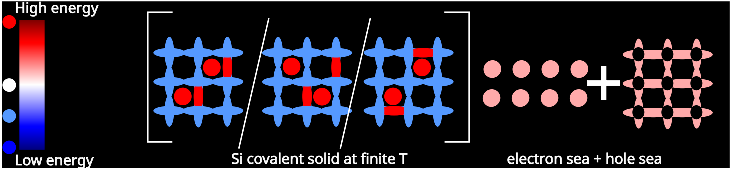


- Valence electrons are strongly attracted to the nucleus. This prevents the formation of free electron gas.
- Instead the valence electrons are shared between neighbouring atoms resulting in **covalent bond**.
- As all the valence electrons are involved in bonding,
  there are no "free" electrons at absolute zero temperature.

Key Insight

Intrinsic semiconductor is a perfect insulator at absolute zero!

Nature of intrinsic semiconductor at $T \neq 0$ (property 2)

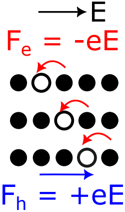


- However, at finite temperature, due to thermalization, few bonds are broken, releasing the electrons to the **free electron sea**.
- In the process of bond breaking, the crystal lattice deficient with one electron can be considered as a new type of charge carrier. This is defined as the **hole**.
- The holes are released into the **free hole sea**.
- Every free electron is associated with a free hole. Hence they are called **electron-hole pair**.

Definition

An intrinsic semiconductor is a semiconductor crystal in which the electrical conduction arises due to **thermally excited** electrons- hole pairs.

Nature of hole: Drift motion (property 2)



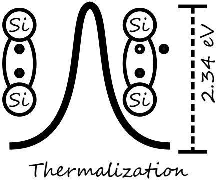
(a) Analogy for a hole: Bubbles (b) Drift motion of holes

- A hole is a **quantum vacancy** that is described as an absence of electron.
- Analogy is the bubbles appearing in carbonated water. The bubbles are absence of water.
- Under application of electric field, the bonded electrons move in the opposite direction. The hole appears to move along the electric field.

Key Insight

The motion of hole is along the electric field.

Energy band gap: Chemistry view (property 3)

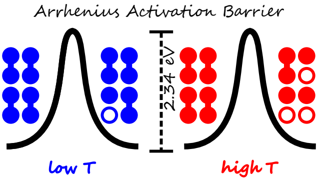


- The electron of the covalent bond needs to overcome bonding strength to become free.
- If all the bonds are broken, then the crystal vapourizes. The energy needed to vapourize a crystal is called **cohesive energy**.
- The actual energy to free electron is $1.12\,\mathrm{eV}$ and is called the **energy band gap** (M2U3).

Estimate: Bonding strength

The cohesive energy of Si crystal is $450\,\mathrm{kJ\,mol^{-1}}$. Estimate the Si−Si bond strength.

Charge carriers vs temperature (property 4)



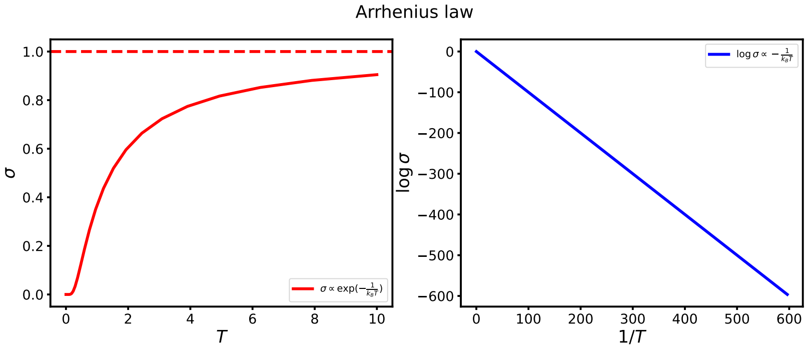
- The scale of thermal energy is given by $k_B T$. At room temperature, the thermal energy of electron is of the order of 26 meV. [Estimate]
- The bond strength can be considered an **activation barrier** for the generation of electron-hole pair. This is analogous to rate of chemical reaction

$$\text{covalent bond} + \text{thermal energy} \rightarrow \text{electron} + \text{hole}$$

- Electron-hole pair density increases exponentially with temperature. This follows the **Arrhenius law**.

$$n \propto \exp\left(-\frac{1}{k_B T}\right) \quad p \propto \exp\left(-\frac{1}{k_B T}\right)$$

Conductivity vs temperature (property 4)



- Since conductivity is proportional to number density, conductivity also follows Arrhenius law.

$$\sigma \propto n \quad \sigma \propto p$$

Key Insight

Conductivity exponentially depends on temperature.

Recombination of carriers (property 5)

- We have seen thermal energy to generate electron-hole pairs. This is an example of **equilibrium** generation
- Light can also be used to generate electron-hole pairs.

  $$\text{covalent bond} + \text{light} \rightarrow \text{electron} + \text{hole}$$

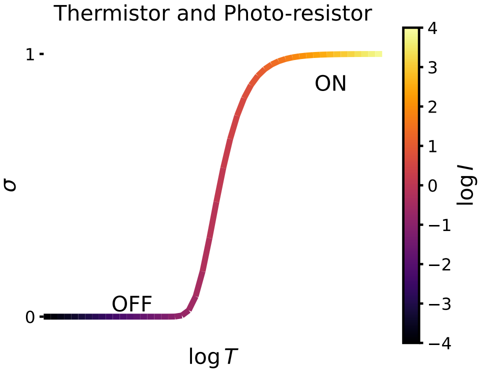
  However, this is a **non-equilibrium** generation process.
- The reverse process where the electron-hole pairs combine to become part of the covalent lattice is called **recombination**.

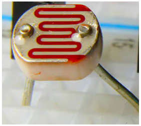
  $$\text{electron} + \text{hole} \rightarrow \text{covalent bond} + \text{light/lattice vibration}$$

  The additional energy is released either as light (**photon**) or lattice vibration (**phonon**).
- The generation-recombination of charge carriers is a **dynamic** two way process.

Key Insight

For analysis, a semiconductor is a collection of electron, holes, photons and phonons and the interaction between them.





- Thermistor (Temperature dependent resistor). Generation of carriers by temperature.
- Photo-resistor: (Light Dependent Resistor (LDR)). Generation of carriers by light.

App	Material
Thermistor	Fe_3O_4
Photoresistor	CdSe

Extrinsic semiconductor

- The electrical properties of intrinsic semiconductor can be altered by adding impurities.
- The technique of adding controlled impurity is called **doping** and the impurity added is called **dopant**.
- Doped semiconductor is called **extrinsic** semiconductor.
- Dopant atom substitutes the position of parent atom. The dopants are of two types – donor and acceptor.
- For Si, donors are P, As, etc and acceptors are B, Al, etc.
- For P as a donor dopant, four valence electrons contribute to covalent bonding. The fifth electron is loosely bound to the phosphorus atom
- For B as an acceptor dopant, three valence electrons contribute to covalent bonding.

Estimate: Dopant concentration

P doping is 1 ppm. $n_{valence} \sim 2 \times 10^{23}\,\mathrm{cm}^{-3}$

Ionization energy of dopants

Definition

The energy required to ionize a dopant atom is called ionization energy.

- Lattice vibrations (phonons) supply the ionization energy (I.E.)
- For P as donor dopant,

$$\mathrm{P} + \mathrm{I \cdot E \cdot} \longrightarrow \mathrm{P}^{+} + \mathrm{e}$$

- Similarly, for B as acceptor dopant,

$$\mathrm{B} + \mathrm{I \cdot E \cdot} \longrightarrow \mathrm{B}^{-} + \mathrm{h}$$

- If thermal energy (E_{th}) is greater than I.E. E_{ion}, then ions are completely ionized. This is called **complete** ionization.
- For $E_{th} \ll E_{ion}$, there is no ionization. This is called **freeze out**.
- **Partial** ionization occurs when $E_{th} \lesssim E_{ion}$
- In Si, $E_{ion} \sim 25\,\mathrm{meV}$ and $E_{th} \sim 25\,\mathrm{meV}$ at room temperature. Thus, the ions are **completely ionized**.