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Electrical Engineering Materials

Pedagogical Handout

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Chapter 5: Semiconductors

2nd Year Engineering students

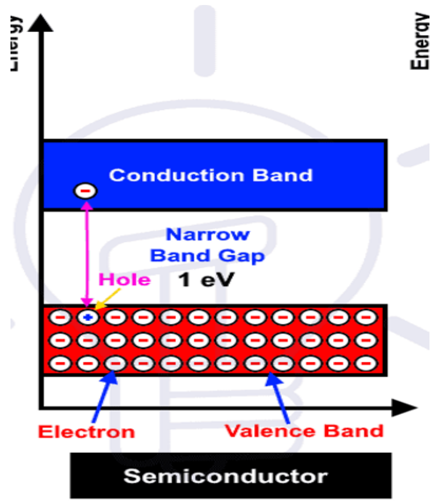
Contents

5.1 Introduction

Semiconductors are a class of materials whose electrical conductivity is between that of conductors and insulators. Their unique property is the ability to control the concentration of charge carriers, making them essential materials for modern electrical and electronic systems [4], [6].

Unlike metals, where a large number of free electrons are available for electrical conduction, and insulating materials, where electrons are strongly bound to atoms, semiconductors have a limited number of charge carriers that can be controlled by temperature and impurity addition (doping).

From the energy band perspective, semiconductors have a relatively small band gap between the valence band and the conduction band. This allows electrons to gain sufficient energy to become free carriers, creating both electrons and holes that contribute to electrical conduction [6].



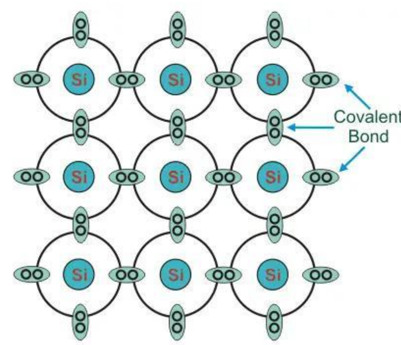
The electrical properties of semiconductors can be modified by introducing controlled impurities, which enables the fabrication of electronic devices such as diodes, transistors, integrated circuits, and power semiconductor components.

5.2 Semiconductor Fundamentals

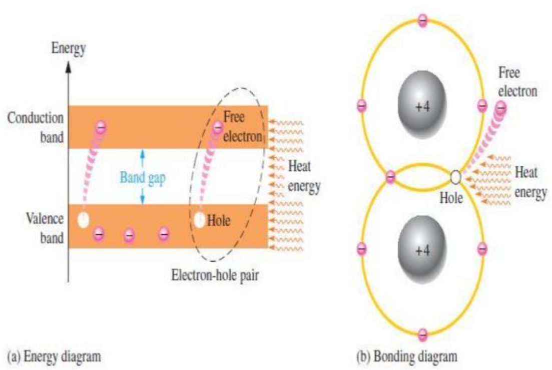
Electrical conduction in semiconductors is based on the movement of **charge carriers** within the crystal lattice. Unlike metals, where electrical conduction results from a large number of free electrons, semiconductors use a dual conduction mechanism involving two types of carriers: **electrons and holes** [4], [6].

A. Charge Carriers: Electrons and Holes

In a pure semiconductor crystal such as silicon, atoms are connected through strong covalent bonds. At low temperatures, these bonds keep electrons strongly bound, limiting electrical conduction. However, at room temperature, thermal energy can provide enough energy to break some covalent bonds [6].



Pure Silicon Crystal Structure



When an electron gains sufficient energy, it moves from the valence band to the conduction band, becoming a **free electron** and acting as a negative charge carrier. The empty position left behind by this electron is called a **hole**. Although a hole is not a real particle, the movement of neighboring electrons to fill this vacancy makes the hole appear to move in the opposite direction; therefore, it behaves as a positive charge carrier [4], [6].

Electrical current in semiconductors is produced by the combined movement of electrons and holes.

For intrinsic silicon at room temperature (300 K), each generated electron creates one corresponding hole, therefore:

$$n = p \approx 1.5 \times 10^{10}\ \text{cm}^{-3}$$

where (n) is the electron concentration and (p) is the hole concentration. This carrier concentration is extremely low compared with metals, which explains the limited conductivity of pure semiconductors [6].

B. Intrinsic and Extrinsic Semiconductors

An **intrinsic semiconductor** is a pure semiconductor material where charge carriers are generated only by thermal energy. In this state, the number of electrons and holes is naturally equal:

$$n = p$$

However, the conductivity of intrinsic semiconductors is relatively low and cannot be easily controlled for practical applications [4].

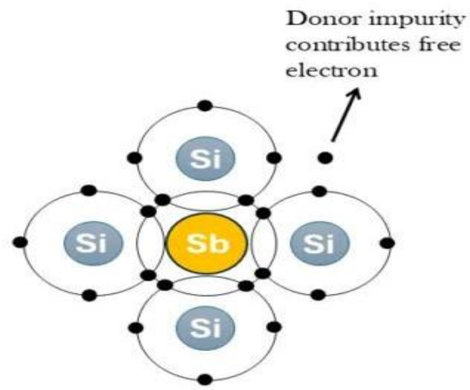
To improve and control electrical conductivity, controlled impurity atoms are intentionally introduced into the crystal lattice. This process is known as **doping**, and the resulting material is called an **extrinsic semiconductor** [4], [6].

C. Doping: N-type and P-type

Doping is the controlled addition of impurity atoms to modify the concentration of charge carriers in a semiconductor [6].

1. N-type Semiconductor

N-type semiconductors are formed by adding donor atoms such as phosphorus (P) or arsenic (As). These atoms contain five valence electrons. Four electrons form covalent bonds with silicon atoms, while the fifth electron remains weakly bound and becomes a free electron [4].



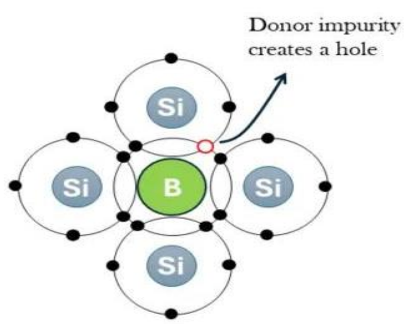
N-Type Semiconductor

As a result:

- Free electron concentration increases.
- Electrons become the **majority carriers**.
- Holes become the **minority carriers**.

2. P-type Semiconductor

P-type semiconductors are formed by adding acceptor atoms such as boron (B), which contain three valence electrons. The missing electron in the fourth covalent bond creates a hole that can move through the crystal structure [6].



P-Type Semiconductor

As a result:

- Hole concentration increases.
- Holes become the **majority carriers**.
- Electrons become the **minority carriers**.

The ability to control carrier concentration through doping is the fundamental principle behind semiconductor devices such as diodes, transistors, and integrated circuits [4], [6].

5.3 Semiconductor Materials

The selection of semiconductor materials depends on their electrical properties, especially band gap energy, carrier mobility, thermal stability, and ability to operate under specific conditions. The most important semiconductor materials used in electrical engineering are Silicon (Si), Gallium Arsenide (GaAs), and Silicon Carbide (SiC) [4], [6].

A. Silicon (Si)

Silicon is the most widely used semiconductor material due to its low cost, availability, and excellent technological maturity.

It has a band gap:

$$E_g \approx 1.12 \text{ eV}$$

Its covalent crystal structure allows controlled electrical conduction through doping. Silicon is mainly used in integrated circuits, diodes, transistors, and power electronic devices [4], [6].

B. Gallium Arsenide (GaAs)

Gallium Arsenide is a compound semiconductor with a direct band gap:

$$E_g \approx 1.42 \text{ eV}$$

It provides higher electron mobility than silicon, making it suitable for high-frequency and optoelectronic applications such as LEDs, laser diodes, and photodetectors [4].

C. Silicon Carbide (SiC)

Silicon Carbide is a wide band gap semiconductor:

$$\boldsymbol{E_g \approx 3.26\ \mathrm{eV}}$$

Its high breakdown voltage, thermal stability, and high operating temperature capability make it suitable for power electronics applications, including electric vehicles, converters, and high-voltage switching systems [6].

The choice of semiconductor material depends on the required balance between electrical performance, thermal behavior, and application constraints [4], [6].

5.4 Electrical Properties of Semiconductors

The electrical properties of semiconductors are mainly determined by the concentration and mobility of charge carriers. Unlike metals, their conductivity can be controlled and varies significantly with temperature and impurity concentration [4], [6].

The electrical conductivity is expressed as:

$$\boldsymbol{\sigma = q(n\mu_n + p\mu_p)}$$

where:

(σ): electrical conductivity

(q): electron charge

(n, p): electron and hole concentrations

(μ_n, μ_p): carrier mobilities

This relationship shows that increasing the number of carriers or improving their mobility increases the conductivity of the material.

– **Temperature Effect**

In semiconductors, increasing temperature increases electrical conductivity because more electrons gain sufficient energy to become conduction carriers.

Therefore:

$$\boldsymbol{T} \uparrow \Rightarrow \boldsymbol{\sigma} \uparrow$$

This behavior is opposite to metals, where conductivity decreases with temperature due to increased atomic vibrations.

– **Comparison with Other Materials :**

- Conductors: high carrier concentration and high conductivity.
- Insulators: very low carrier concentration and negligible conductivity.
- Semiconductors: intermediate conductivity with controllable electrical behavior.

This controllability makes semiconductors suitable for electronic and power applications.

5.5 Applications of Semiconductors

The ability to control electrical conduction in semiconductors makes them essential materials in modern electrical and electronic systems. Their applications cover signal control, energy conversion, and optoelectronic technologies [4], [6].

A. Diodes

A diode is a semiconductor device based on a P–N junction. It allows current flow mainly in one direction and is widely used for:

- AC to DC rectification.
- Protection circuits.
- Signal processing.

B. Transistors

Transistors are semiconductor devices used for switching and amplification. A small input signal can control a larger electrical current, making them fundamental components in:

- Electronic circuits.
- Digital systems.
- Integrated circuits.

C. Power Electronics

Power semiconductor devices such as MOSFETs, IGBTs, and power diodes are designed to control high voltage and current.

They are used in:

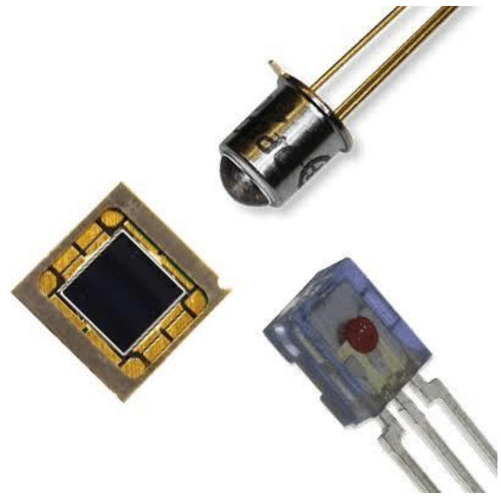
- Motor drives.
- Electric vehicle systems.
- Renewable energy converters.
- Industrial power control.

Advanced materials such as SiC improve efficiency by reducing losses and allowing higher temperature operation [6].

D. Photodetectors and Optoelectronics

Semiconductors can convert light energy into electrical signals through the generation of electron–hole pairs. Applications include:

- Photodetectors.
- Optical communication systems.
- Solar cells.
- Light sensors.



The wide range of semiconductor applications results from their unique ability to control charge transport and interact with electrical and optical signals [4].

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