Introduction to digital electronics

Electronics and Magnetism

by Sir C. Allan

Introduction

In this topic we are going to discuss the following:

- Conductors, Semiconductors, and Insulators.
- The Band Theory
- Intrinsic and Extrinsic semiconductors.
- Doping semiconductors.
- The P-N junction diode.
- Characteristics of a forward-biased diode.

Conductors, Insulators, and Semiconductors

In terms of electrical conductivity, materials can be grouped into three, namely;

a. **Conductors:** These are materials that **allow** an electric current to pass through them easily. Also called good conductors. Examples of conductors include **copper**, **aluminum**, **gold**, and **zinc**.

b. **Insulators:** These are materials that **do not allow** the electric current to pass (flow) through them. Also called bad conductors. Examples of insulators include **wood**, **plastic**, and **paper**.

c. **Semiconductors:** These are materials whose conductivity is between that of an insulator and a conductor. This means that under certain conditions they act as a conductor and sometimes as an insulator. Examples of semiconductors include **silicon** and **germanium**.

The Band Theory

- This theory suggests that the electrons in materials move collectively in **energy bands** (energy levels).
- These bands are the **valency band**, where electrons are found, and **the conduction band**, where electrons move freely.
- These two bands are **separated by a gap called the forbidden gap**. This forbidden gap determines the conductivity of a material.
- In **conductors** the valency band and the conduction band **overlap**, as such electrons can move easily from the valency band to the conduction band, allowing good electrical conductivity.
- In **insulators** the forbidden gap is large, as such any attempt to make the material conduct electricity, ends up breaking the material.

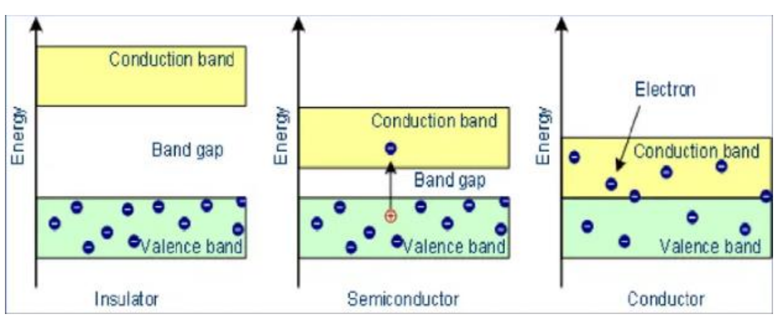
The Band Theory

- In **semiconductors** the gap (forbidden gap) is **small**, as such the material conducts electricity **when the temperature increases** since the electrons in the valency band gain thermal energy and cross the gap into the conduction band.
- But **at low temperatures**, the material **will not** conduct electricity, as the electrons will remain in the valency band.

Note: As the temperature increases, the conductivity of a semiconductor increases as more electrons gain thermal energy and cross the gap into the conduction band. So we say***: the resistance in semiconductors decreases with an increase in temperature***.

- We have **two** types of semiconductors: **Intrinsic** and **Extrinsic** semiconductors.
- The next slide shows an illustration of the band theory in conductors, semiconductors, and insulators.

The Band Theory

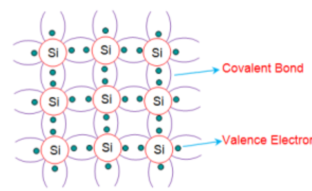


Intrinsic semiconductors

- These are semiconductors **without any impurities** added to them.
- The electrical conductivity of these semiconductors is purely based on their intrinsic properties.
- They are also called **pure** semiconductors.
- The common examples of pure semiconductors are **Silicon (Si)** and **Germanium (Ge)**.
- Let's look at Silicon(SI) as an intrinsic semiconductor.

Silicon as a pure semiconductor

- A silicon has 4 valence electrons, and it undergoes **covalent bonding** with other four silicon atoms to form a **crystal lattice**.
- Below is a crystal lattice of silicon



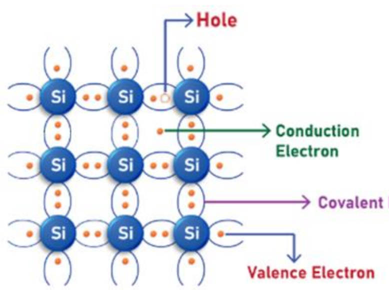
Intrinsic semiconductors

- In the lattice, **at low temperatures**, all the valance electrons are **locked** in the covalent bonds.
- But at **higher temperatures**, some electrons gain thermal energy and move into the conduction band by **breaking the covalent bond**.
- The electrons that break free from the covalent bond are called **thermal electrons**, and they leave behind a **positive vacancy** on their atom called a **hole**.
- If the process continues, ***a hole seem to drift in the lattice***, hence the material conducting electricity.
- If this material is in a circuit, we have **two types of charge** that will contribute to the conduction of current, thus; the **negatively charged electron** and the **positively charged hole**.
- In this circuit, the electron and the hole will move **in the opposite direction** to each other in the conduction band.

Note that in an intrinsic semiconductor, we have **same number** of electrons and holes.

Intrinsic semiconductors

- Below is an illustration of a thermal electron and a positive hole in a Silicon lattice.



Mid-lesson Quiz

a. Define a thermal electron. **(1)**

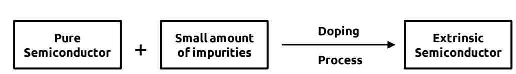
b. What type of bonding exists between atoms in an intrinsic semiconductor? **(1)**

c. Explain how an intrinsic semiconductor conducts electricity. **(4)**

Extrinsic semiconductors

- These are pure semiconductors with some **small amount of impurities** added to improve their conductivity.
- The process of adding these impurities to a pure semiconductor is called **doping**.
- **Doping** is the process of adding very small amount of impurities into a pure semiconductor.
- So, we can also define an extrinsic semiconductor as **an externally doped pure semiconductor**.

- Below is a **block diagram** of the doping process:



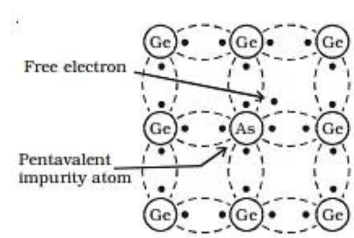
Extrinsic semiconductors

- Extrinsic semiconductors can be grouped into **Negatively charged (N-type)** and **Positively charged (P-type)** semiconductors depending on the type of impurities used during the doping process.
- The impurities during the doping process can either be **trivalent** atoms or **pentavalent** atoms.
- A **trivalent** atom is an atom with **three valence electrons**.
- A **pentavalent** atom is an atom with **five valence electrons**.
- If a pure semiconductor is doped using a **trivalent** atom, a **P-type** extrinsic semiconductor is formed.
- If a pure semiconductor is doped using a **pentavalent** atom, an **N-type** extrinsic semiconductor is formed.
- Below is a table showing examples of trivalent and pentavalent elements.

Trivalent	Pentavalent
Boron, Aluminum, Gallium, and Indium	Arsenic, Bismuth, Antimony, and Phosphorous

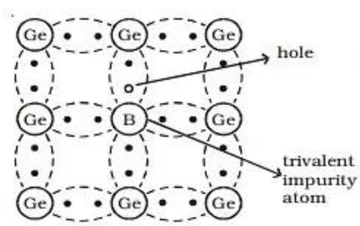
Doped Semiconductors: N-type

- N-type semiconductors are pure semiconductors doped using a pentavalent atom.
- Imagine Germanium (Ge) doped using Arsenic (As). The four valence electrons of germanium will be used in the covalent bonding process with the four valence electrons of arsenic **except** for one electron which will be left free and ready for conduction.
- In this case, the arsenic atom is said to be a **donor impurity** – has donated an electron.
- The resulting semiconductor from this bonding process is called an N-type semiconductor because of the **negatively charged electron**.
- In this type of semiconductor, the **electrons** are the **majority charge carriers**.
- Below is an illustration of a germanium–arsenic lattice.



Doped Semiconductors: P-type

- P-type semiconductors are pure semiconductors doped using a trivalent atom.
- Imagine Germanium (Ge) doped using Boron (B). Only three valence electrons of germanium will be used in the covalent bonding process with all the three valence electrons of boron and this **creates** one vacancy **hole**.
- In this case, the boron atom is said to be an **acceptor impurity** – has a hole to accept an electron.
- The resulting semiconductor from this bonding process is called a P-type semiconductor because of the **positively charged hole**.
- In this type of semiconductor, the **holes** are the **majority charge carriers**.
- Below is an illustration of a germanium–boron lattice.

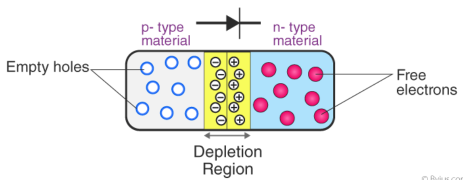


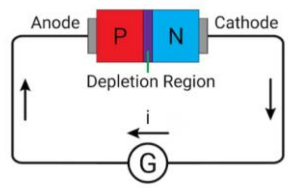
The P-N Junction diode

- One application of the P-type and N-type semiconductors is the formation of the P-N junction diode.
- A **diode** is a two-terminal device that conducts current in **one direction only**.
- A P-N junction diode is formed by merging the P-type semiconductor material and the N-type semiconductor material.
- When the junction is formed, there is movement of charge **only** around the area of contact (Junction) until an **equilibrium** point is reached.
- This equilibrium point is reached when all the free holes and electrons have **combined** resulting in a **net positive charge at the N-type** and a **net negative charge at the P-type**.
- These net charges prevent further movement of the holes and electrons by creating a region with **no** holes and electrons, called the **depletion region**.
- This depletion region leads to the development of a **barrier potential difference** between P-type and N-type material, as such a wire connected to the N-type is considered a **cathode**, and to the P-type an **anode**.

The P-N Junction diode

- Below are illustrations of the P-N Junction diode.





Operation of P-N Junction diode

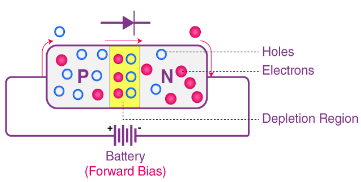
- A P-N junction diode is an electronic component that conducts electricity in **only one** direction.
- For a P-N junction diode **to conduct** electricity in a circuit, it is set in a conducting state called the **Forward Bias**.
- When connected in a **Reverse Bias** also called the Non-conducting state, the diode **will not** conduct electricity.

Forward Bias

- In this state the **positive terminal** of the power supply is **connected to the P-type** side of the diode, and the **negative terminal** is **connected to the N-type** of the diode.
- This **reduces the built-in potential** between the P-type and the N-type, and as the **applied voltage exceeds the built-in potential, it allows current to flow across the junction**.
- As such the diode conducts electricity.

Operation of P-N Junction diode

- **Note:** In forward bias the electrons move from the N-type to the P-type, and the holes move in the opposite direction.
- Below is an illustration of a P-N junction diode set in a **Forward Bias**.



Reverse Bias

- In this state the **positive terminal** of the power supply is **connected to the N-type** side of the diode, and the **negative terminal** is **connected to the P-type** of the diode.
- This **increases the built-in potential** between the P-type and the N-type, and as the **applied voltage becomes larger than the built-in potential, the depletion region becomes thicker and more resistive**.
- As such the diode **does not** conducts electricity

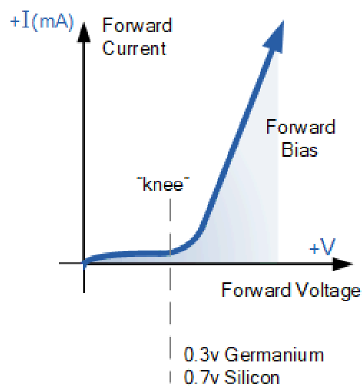
Voltage - Current Characteristics for a forward biased diode

- In a forward bias, the current through the diode varies with the applied voltage in the following stages:

1. **Very low forward voltage:** at very low voltage, the current is minimal because the diode is **not fully turned on**, as such the we have an exponential relationship of current and voltage.
2. **At threshold voltage:** as the voltage increases it reaches a certain point called the **cut-in, knee** or the **threshold** voltage (0.7v for silicon and 0.3v for germanium) at this point current also start to increase rapidly as such the diode start conducting current easily.
3. **Above the threshold voltage:** above the threshold voltage the current increases exponentially with a small voltage and this is the operating region of the diode.

- Below is a sketch of the PN junction diode in forward bias.

Voltage - Current Characteristics for a forward biased diode



4. **Very high voltage:** at very high forward voltages the current increases very rapidly, and this current may end up damaging the diode.

In summary we can say that the graph of a PN junction diode in forward bias shows that the diode conduct electricity significantly only after the applied voltage excessed a certain threshold.

Quiz

1. What is a diode?
2. Describe the **two** types of semiconductors.
3. Explain the operation of a PN junction diode in forward bias.
4. In terms of the band theory, explain how a semiconductors conducts electricity.
5. Give **three** uses of a diode.