PHYSICS REVISION NOTES

Chapter 14: Semiconductor Electronics

Class 12 - CBSE / JEE / NEET

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Chapter 1

Semiconductor Electronics: Materials, Devices and Simple Circuits

1.1. 1. The Evolution of Solid-State Electronics

Modern technology owes its existence to our ability to manipulate the flow of electrons. Before the advent of solid-state devices in the late 1940s, engineers achieved this control using vacuum tubes, which required a heated cathode to emit electrons into a completely evacuated glass envelope. These early devices were not only physically massive and power-hungry but also required high operating voltages and suffered from notoriously low reliability.

The paradigm shifted entirely when scientists realized that certain solid materials—specifically semiconductors—could natively regulate charge carriers within their own internal atomic structure. This is crucial because it eliminated the need for fragile glass tubes, vacuums, or external heating elements. Consequently, solid-state devices proved to be incredibly small, highly reliable, and exceptionally energy-efficient, paving the way for the miniaturization of modern computers.

1.2. 2. Classification of Solids

When analyzing materials for electrical applications, we rely on their native ability to conduct current. Solids are broadly segregated into three major classes based on their relative electrical conductivity (σ) and electrical resistivity (ρ).

Conductivity-Based Classification

- **Metals (Conductors):** These materials permit current to flow with virtually no opposition. They exhibit incredibly low resistivity, typically ranging between 10^{-2} and 10^{-8} Ω m.
- **Insulators:** At the opposite end of the spectrum, insulators obstruct electron flow entirely, boasting massive resistivity values that span from 10^{11} to 10^{19} Ω m.
- **Semiconductors:** Occupying the critical middle ground, semiconductors possess an intermediate resistivity ranging from 10^{-5} to 10^{6} Ω m. Their ability to conduct can be dramatically altered by external factors like temperature or chemical impurities.

1.3. 3. Understanding Energy Band Theory

To truly understand why a semiconductor behaves differently from a block of wood or a copper wire, we must look at the quantum level using Energy Band Theory. In a single, isolated atom, electrons reside in strict, discrete energy orbits. Notice that when billions of these atoms pack tightly together to form a solid crystal lattice, their outermost electron orbits begin to physically overlap.

Because of this intense atomic proximity, the formerly sharp, discrete energy levels smear out into continuous ranges of allowed energy, which physicists call **energy bands**.

- **Valence Band:** The energy band containing the atom's outermost valence electrons. At absolute zero temperature, this band is completely saturated.
- **Conduction Band:** The energy band located immediately above the valence band. Electrons that manage to reach this band are liberated from their parent atoms and are entirely free to conduct electricity.
- **Energy Band Gap (E_g):** The strictly forbidden energy void separating the highest level of the valence band from the lowest level of the conduction band. Electrons cannot possess energies that fall within this gap.

1.3.1 Distinguishing Solids via Energy Bands

1. **Metals:** The conduction and valence bands either physically overlap ($E_g \approx 0$), or the conduction band is partially filled. This abundance of accessible energy states allows electrons to move effortlessly, granting metals their signature high conductivity.
2. **Insulators:** Characterized by a massive energy gap ($E_g > 3$ eV). Thermal energy at standard room temperature is entirely insufficient to kick electrons across this vast chasm, leaving the conduction band completely empty.
3. **Semiconductors:** These feature a remarkably narrow energy gap ($E_g < 3$ eV). At room temperature, a small but vital fraction of valence electrons naturally acquires enough thermal energy to vault across the gap and enter the conduction band, allowing limited conduction.

1.4. 4. Intrinsic Semiconductors

An intrinsic semiconductor is an absolutely pure crystal of a semiconducting element, most commonly Silicon (Si) or Germanium (Ge). Both elements possess four valence electrons and form a highly stable, three-dimensional diamond-like crystal lattice by sharing electrons to create four strong covalent bonds with their nearest neighbors.

At absolute zero ($T = 0$ K), every single covalent bond remains perfectly intact. The valence band is completely full, and the conduction band is entirely void of electrons, causing the pure semiconductor to act as a flawless insulator.

1.4.1 Thermal Generation and Recombination

As the ambient temperature increases, thermal agitation vibrates the lattice violently enough to literally snap a few of these delicate covalent bonds.

- **Electron Generation:** A ruptured bond liberates an electron, allowing it to transition into the conduction band as a highly mobile charge carrier.
- **Hole Creation:** The sudden departure of this electron leaves behind a localized, positively charged vacancy within the covalent bond. We formally treat this empty space as an independent, mobile positive particle known as a **hole**.
- **Recombination:** This is a dynamic, ongoing system. As new bonds break, other free electrons simultaneously collide with and fall back into empty holes, an opposing process known as recombination.

Intrinsic Carrier Concentration

In a perfectly pure semiconductor operating under thermal equilibrium, the number of free electrons (n_e) is exactly balanced by the number of created holes (n_h).

$$n_e = n_h = n_i \tag{1.1}$$

Where n_i represents the intrinsic carrier concentration.

1.5. 5. Extrinsic Semiconductors

Relying solely on ambient thermal generation yields an electrical conductivity that is far too feeble for practical electronic applications. To forcefully manipulate and drastically amplify this conductivity, we intentionally inject microscopic amounts (a few parts per million) of specific foreign atoms directly into the pure crystal lattice. This deliberate, precision contamination is called **doping**, and the resulting enhanced material is known as an extrinsic semiconductor.

1.5.1 n-type Semiconductors

When a tetravalent pure semiconductor (like Si or Ge) is doped with a pentavalent impurity (an element boasting 5 valence electrons, such as Arsenic, Antimony, or Phosphorus), an n-type material is created. Four of the dopant's electrons securely lock into covalent bonds with neighboring silicon atoms. The fifth, orphaned electron remains very weakly bound to its parent atom. It requires a trivial 0.01 eV (for Ge) or 0.05 eV (for Si) of thermal energy to break entirely free and flood into the conduction band. Because these pentavalent atoms readily donate free electrons to the lattice without simultaneously creating corresponding holes, they are termed **donor impurities**.

Charge Carriers in n-type

In an n-type semiconductor, the immense influx of donated electrons causes them to aggressively outnumber the native holes. Thus, electrons become the **majority carriers**, and holes are relegated to **minority carriers** ($n_e \gg n_h$).

1.5.2 p-type Semiconductors

Conversely, if we dope the crystal lattice with a trivalent impurity (having only 3 valence electrons, like Boron, Aluminum, or Indium), we construct a p-type semiconductor. The dopant atom successfully forms covalent bonds with three neighbors but critically lacks an electron to satisfy the fourth bond. This inherent missing electron establishes a permanent vacancy, or hole, right from the start. An electron from a nearby silicon bond can easily jump over to fill this void, which effectively transfers the hole to a new location. Because these impurities eagerly accept electrons from the surrounding lattice, they are classified as **acceptor impurities**. Here, the injected holes drastically outnumber the thermal electrons, making holes the dominant majority carriers ($n_h \gg n_e$).

Mass Action Law

For any semiconductor (whether intrinsic or extrinsic) residing in thermal equilibrium, the mathematical product of the electron and hole concentrations is a constant.

$$n_e n_h = n_i^2 \tag{1.2}$$

1.6. 6. The p-n Junction: The Heart of Electronics

The p-n junction is the fundamental architectural building block of nearly all modern semiconductor devices, from basic light-emitting diodes to the most complex microprocessors. It is manufactured by precisely treating a single, continuous semiconductor wafer so that one distinct region becomes p-type while the directly adjacent region is converted to n-type.

1.6.1 Formation Dynamics: Diffusion and Drift

The very instant the metallurgical junction is established, two massive concentration gradients exist. The p-side is densely populated with holes, while the n-side is saturated with electrons.

- **Diffusion Current:** Driven strictly by this sheer concentration difference, electrons naturally diffuse across the boundary from the n-side into the p-side, while holes diffuse from the p-side into the n-side. This migration creates an initial diffusion current.
- **Depletion Region Formulation:** As an electron diffuses away from the n-side, it exposes a positively charged, immobile donor ion that is rigidly anchored within the crystal lattice. Similarly, holes abandoning the p-side leave behind immobile, negatively charged acceptor ions. This continuous charge migration rapidly establishes a microscopic border zone on either side of the junction that is entirely swept clean of all mobile charge carriers. This highly resistive, uncompensated zone is aptly named the **depletion region**.

- **Barrier Potential and Drift:** The exposed wall of positive ions on the n-side and negative ions on the p-side generates an intense, internal electric field aimed directly from the n-side toward the p-side. This field aggressively opposes any further diffusion, yet it violently sweeps any stray minority carriers straight across the junction, generating a **drift current**. Eventually, the system achieves a state of dynamic equilibrium where the drift current perfectly cancels the diffusion current. The built-in voltage drop that successfully halts further net charge movement is formally known as the **barrier potential** (V_0).

1.7. 7. Semiconductor Diode Biasing

A standard semiconductor diode is practically a solitary p-n junction outfitted with external metallic contacts to permit connection to electrical circuits. The conductive behavior of this junction alters dramatically depending entirely on the polarity of the external voltage applied across it, a process known as biasing.

1.7.1 Forward Bias Mechanics

When the positive terminal of an external battery is deliberately wired to the p-side and the negative terminal to the n-side, the diode enters a state of forward bias. This applied external voltage (V) inherently pushes in direct opposition to the internal barrier potential (V_0). As a direct result, the effective barrier height is significantly squashed to $(V_0 - V)$, and the physical width of the depletion layer dramatically narrows. With the electrostatic wall substantially lowered, huge numbers of majority carriers suddenly possess the thermal energy required to surmount the junction. Electrons flood from the n-side into the p-side, and holes rush from the p-side into the n-side. This sustained injection of carriers produces a large, exponential forward current, typically measured in practical milliamperes (mA).

1.7.2 Reverse Bias Mechanics

If we intentionally flip the battery connections—attaching the n-side to the positive terminal and the p-side to the negative terminal—the diode is heavily reverse biased. In this specific configuration, the applied voltage aligns perfectly with the internal barrier field. This constructive interference physically thickens the depletion region and erects a towering effective barrier of height $(V_0 + V)$. This massive electrostatic wall effectively terminates all majority carrier diffusion. However, the strong field acts as a high-speed slide for minority carriers (the thermally generated electrons on the p-side and holes on the n-side), sweeping them effortlessly across the junction. This produces a minuscule, almost constant drift current, usually on the scale of microamperes (μA), which remains largely independent of the applied voltage.

The Danger of Diode Breakdown

If the reverse bias voltage is aggressively dialed up beyond a critical safety threshold known as the **breakdown voltage** (V_{br}), the reverse current will skyrocket uncontrollably. Without protective series resistance in the circuit, this explosive surge will rapidly overheat and permanently destroy the delicate p-n junction.

1.8. 8. Application: The Junction Diode as a Rectifier

Because a p-n junction diode offers remarkably low resistance during forward bias and massive, blocking resistance during reverse bias, it essentially functions as an electronic one-way valve. This highly asymmetric property makes diodes incredibly useful for **rectification**—the vital engineering process of converting an alternating current (AC) into a direct current (DC).

1.8.1 Half-Wave Rectifier

By placing a single diode in series with an AC power source and a load resistor, we create a basic half-wave rectifier. The diode will only conduct current during the specific positive half-cycles of the AC input when it is naturally forward biased. During the subsequent negative half-cycles, it enters reverse bias and completely blocks the flow of current. The resulting output is a unidirectional, pulsating voltage that successfully captures only half of the original alternating wave's energy.

1.8.2 Full-Wave Rectifier

To harness the total energy of the AC cycle, a full-wave rectifier employs a center-tapped transformer alongside two strategically placed diodes. During the positive half of the cycle, the first diode is forward biased and conducts current straight through the load, while the second diode remains reverse biased and idle. During the negative half-cycle, the polarities seamlessly flip: the first diode switches off, and the second diode becomes forward biased, pushing current through the load in the exact same direction. This elegant push-pull setup ensures a continuous, unidirectional output voltage across the entire AC cycle.

To iron out the pulsating, bumpy ripples of this rectified voltage into a smooth, steady DC supply comparable to a battery, engineers connect large **filter capacitors** in parallel across the output terminals. These capacitors charge up rapidly to the peak voltage during the pulse and slowly discharge through the load when the voltage dips, maintaining a remarkably steady output.

Quick Revision Summary

Key Conceptual Checklist

- ✓ **Energy Gap (E_g):** The foundational property determining if a solid is a metal, insulator, or semiconductor.
- ✓ **Intrinsic Semiconductor:** A pure semiconductor crystal where thermally generated electrons equal holes ($n_e = n_h = n_i$).
- ✓ **n-type Doping:** Achieved via a pentavalent impurity; features electrons as the dominant majority carriers.
- ✓ **p-type Doping:** Achieved via a trivalent impurity; features holes as the dominant majority carriers.
- ✓ **Depletion Region:** The critical boundary area completely devoid of mobile charges at the metallurgical junction.
- ✓ **Forward Bias:** Actively lowers the barrier potential, shrinks the depletion zone, and enables a massive forward current.
- ✓ **Reverse Bias:** Actively increases the barrier, widens the depletion zone, and allows only a minute drift current to flow.
- ✓ **Rectification:** The application of converting AC to DC by utilizing the strict unidirectional nature of diodes.

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