Parcours Électronique S6 Optoélectronique

Course notes

Eloutassi Omar

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Sommaire :

Chapter 1: Semiconductors

1. Introduction

Semiconductors (for example, Germanium and Silicon) are materials whose electrical characteristics lie between those of conductors and insulators. In terms of energy bands, semiconductors are materials that exhibit a very small energy gap of about 1.0 eV, separating their two energy bands, with a nearly empty conduction band and a nearly filled valence band.

2. Objectives

The objectives of this chapter are to:

- Define semiconductors
- Explain the types of semiconductors
- Define semiconductor alloys
- Explain the formation and recombination of electron-hole pairs
- Explain energy bands in solids

3. Generalities

Semiconductors can be classified as shown in Figure 1:

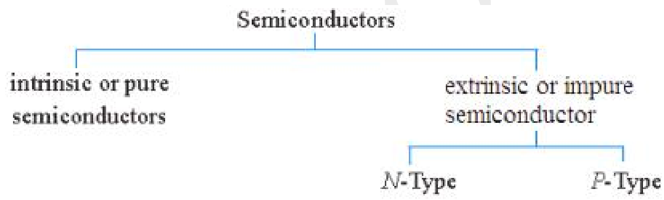


Figure 1: Types of semiconductors

3.1. Intrinsic semiconductors or pure semiconductors:

A semiconductor that is entirely composed of semiconductor material is called an intrinsic or pure semiconductor. Examples include pure Germanium (Ge) and Silicon (Si), which have forbidden energy gaps of 0.72 eV and 1.1 eV, respectively. There are many electrons with enough energy to cross the small energy gap between the valence and conduction bands, even at room temperature, due to the very small energy gap. Pure semiconductors have the same number of holes and conduction electrons. The schematic energy band diagram of an intrinsic semiconductor at room temperature is given in Figure 2.

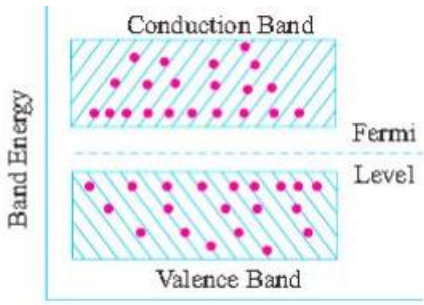


Figure 2: Energy band diagram

3.2. Extrinsic Semiconductors or Impure Semiconductors:

Extrinsic semiconductors, also known as impurity semiconductors, are intrinsic semiconductors to which very small amounts (about 1 part in 10^8) of an impurity, dopant agent, or dopant have been added. Depending on the dopant material used, extrinsic semiconductors can be divided into two categories: see figure 3.

- N-type semiconductors
- P-type semiconductors

3.2.1. N-type semiconductors:

N-type extrinsic semiconductors are made by adding a pentavalent substance such as Antimony (Sb) to pure Germanium or a Silicon crystal. Each Antimony atom uses four of its five electrons to form covalent bonds with the four surrounding Germanium atoms, as shown in Figure 3. The Antimony atom is only weakly connected to the fifth electron, which is not needed. Therefore, by applying an electric field or increasing thermal energy, it can be easily excited from the valence band to the conduction band. As explained above, holes are the minority carriers in N-type semiconductors, while electrons are the majority carriers.

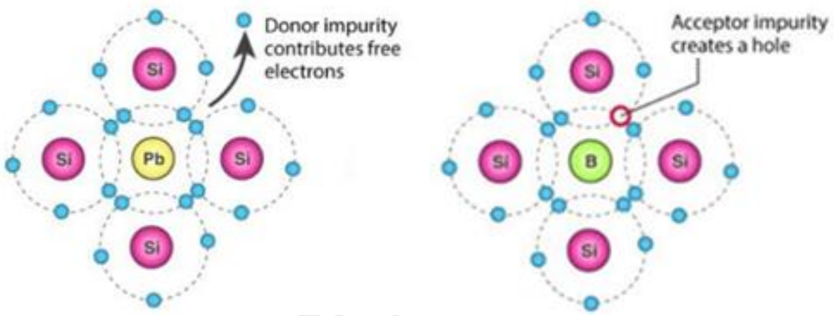


Figure 3: N-type semiconductors and P-type semiconductors

3.2.2. P-type semiconductors:

When atoms of a trivalent element, such as Boron (B), are added to a pure Germanium crystal, a P-type semiconductor is formed. In this case, the three valence electrons of the Boron atom form covalent bonds with four nearby Germanium atoms, leaving only one vacant electron (hole). Consequently, Boron, a so-called acceptor impurity, creates an extrinsic P-type semiconductor (P for positive) in the form of as many positive holes in a Germanium crystal as there are Boron atoms. Conduction in this type of semiconductor results from the movement of holes in the valence band. Figure 4 illustrates the formation of a hole when a bond remains unfulfilled.

3.2.3. Majority and minority carriers:

At 0 K, there are no free charge carriers available in a piece of pure Germanium or Silicon. However, once the temperature reaches room temperature, some covalent bonds are broken by thermal energy, leading to the formation of electron-hole pairs. These are called thermally generated charge carriers. They are also known as intrinsically available charge carriers. They typically do not have many numbers.

3.2.3.1. Majority charge carriers:

Majority charge carriers are the predominant type of charge carriers in a semiconductor material. They are responsible for carrying most of the electric current through the material. The type of majority charge carriers in a semiconductor depends on the doping of the material, which involves the intentional addition of impurities to modify its electrical properties. There are two main types of majority charge carriers:

- In N-type semiconductors, the majority charge carriers are electrons. This is achieved by doping the semiconductor material with elements from Group V of the periodic table, such as Phosphorus or Arsenic. These elements have five valence electrons, one more than required for bonding in the semiconductor crystal structure. The extra electron becomes a mobile charge carrier and is responsible for conducting electric current.
- In P-type semiconductors, the majority charge carriers are holes. This is achieved by doping the semiconductor material with elements from Group III of the periodic table, such as Boron or Gallium. These elements have three valence electrons, one less than required for bonding in the semiconductor crystal structure. The absence of one electron creates a "hole" in the crystal lattice, which behaves as a positively charged mobile carrier and contributes to electric current.

3.2.3.2. Minority charge carriers:

Minority charge carriers are the least abundant type of charge carriers in a semiconductor material. They are present due to thermal excitation processes or generation-recombination but generally contribute less to the overall electric current than majority charge carriers. The type of minority charge carriers is opposite to that of majority charge carriers in the semiconductor:

- In N-type semiconductors, the minority charge carriers are holes. These holes are generated when thermal energy (temperature) excites electrons from the valence band to the conduction band, leaving behind positively charged holes.
- In P-type semiconductors, the minority charge carriers are electrons. These electrons are generated by thermal excitation, causing the breaking of some covalent bonds between dopant atoms and the semiconductor lattice, thus releasing free electrons.

The behavior of minority and majority charge carriers is essential for understanding the operation of semiconductor devices. In devices such as diodes, transistors, and integrated circuits, manipulating minority and majority carriers allows for precise control of electric current flow, leading to desired electronic functionalities.

4. Doping

Doping of semiconductors is a process that involves intentionally introducing impurities into a semiconductor material to modify its electrical properties. The term "doping" refers to the addition of these impurities, which are typically different atoms, to the semiconductor crystal lattice. Doping is a fundamental technique in the fabrication of semiconductor devices and is essential for creating various electronic components such as diodes, transistors, and integrated circuits.

Semiconductors are materials whose electrical conductivity falls between that of conductors (such as metals) and that of insulators (such as ceramics). Pure semiconductors, known as intrinsic semiconductors, possess a crystal lattice composed of atoms of a single element, such as silicon (Si) or germanium (Ge). In their pure form, these semiconductors have a balanced number of electrons and positively charged holes, resulting in an almost equal number of negatively charged electrons and positively charged holes, making them poor conductors of electricity.

To improve electrical conductivity and tailor the properties of semiconductors for specific applications, controlled amounts of impurities are introduced through the doping process.

Dopants are the impurities added to intrinsic semiconductors. Diffusion is the net movement of molecules from a higher concentration to a lower concentration. There are three ways to add dopants to a silicon lattice:

- ➢ Diffusion into empty spaces: In this technique, dopants are used to fill the spaces between the crystal lattices.
- ➢ Diffusion within the lattice: In this technique, the dopant atoms move within the semiconductor material's lattice.
- ➢ Substitution: This technique is applied when the lattice contains impurity atoms. The crystal lattice causes the displacement of these atoms.
- ➢ There are two common types of doping: see Figure 5.

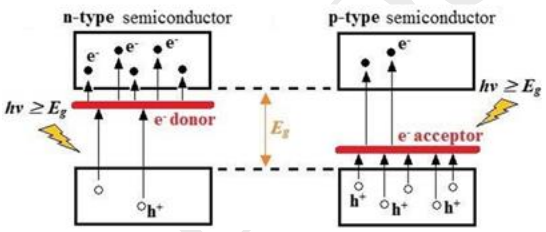


Figure 5: Illustration of N-type and P-type doping in a semiconductor

4.1. N-type doping

In this type of doping, impurities containing more valence electrons than the semiconductor atom are added to the crystal lattice. These impurities are called donor impurities. The most commonly used donor impurities in silicon are phosphorus (P), arsenic (As), and antimony (Sb). When these impurities are added to the semiconductor lattice, they introduce additional electrons into the material, leading to an excess of negatively charged carriers. The added electrons are free to move within the lattice, thereby increasing the conductivity of the material. As a result, the doped semiconductor becomes an N-type semiconductor, where "N" represents the excess of negatively charged carriers.

4.2. P-type doping

In this type of doping, impurities containing fewer valence electrons than the semiconductor atom are added to the crystal lattice. These impurities are called acceptor impurities. The most commonly used acceptor impurities in silicon are boron (B), aluminum (Al), and gallium (Ga). When these impurities are added to the semiconductor lattice, they create "holes" in the electronic structure of the material. These holes act as positively charged carriers. Consequently, the doped semiconductor becomes a P-type semiconductor, where "P" represents the excess of positively charged carriers.

The introduction of these impurities and the resulting excess carriers significantly modifies the electrical behavior of the semiconductor material. By selectively doping different regions of a semiconductor, complex electronic devices such as diodes and transistors can be created. These devices exploit the different electrical properties of N-type and P-type semiconductors to achieve desired functionalities such as rectification, amplification, and switching.

The doping process is generally performed during the fabrication of semiconductor devices. This involves techniques such as diffusion or ion implantation, where impurity atoms are introduced into the crystal lattice at controlled concentrations and depths. The specific concentration and distribution of doping are carefully controlled to achieve the desired electrical characteristics of the final device.

In summary, doping is a crucial process in semiconductor technology that allows for the controlled modification of the electrical properties of semiconductors. By selectively adding impurities to a pure semiconductor material, conductivity and carrier types can be manipulated, enabling the creation of various electronic devices used in modern technology.

5. Semiconductor alloys

Semiconductor alloys are a class of materials that combine two or more elements from different groups of the periodic table to form a compound semiconductor. These materials offer unique properties and advantages compared to single-element semiconductors like silicon or germanium.

In semiconductor alloys, the combination of elements leads to a modification of the electronic band structure, affecting the electrical and optical properties of the material. By adjusting the composition of the alloy, it is possible to tailor the bandgap, carrier mobility, and other key parameters to meet the specific requirements of the device. This versatility makes semiconductor alloys well-suited for a wide range of applications, including optoelectronics, photovoltaics, and high-frequency devices.

The most commonly studied and used semiconductor alloy is that of III-V semiconductor compounds, which combine elements from Group III (such as aluminum, gallium, and indium) and Group V (such as nitrogen, phosphorus, arsenic, and antimony) of the periodic table. Examples of III-V semiconductor alloys include gallium arsenide (GaAs), indium phosphide (InP), and aluminum gallium arsenide (AlGaAs). Alloying in semiconductors can be achieved through several methods, including:

5.1. Molecular beam epitaxy (MBE):

This method involves the growth of thin films of semiconductor alloy on a substrate. Different sources of elements are used in a high-vacuum chamber, and a precisely controlled flux of atoms is directed toward the substrate to form the desired alloy composition.

5.2. Metal-organic chemical vapor deposition (MOCVD):

MOCVD is another common technique for obtaining alloy semiconductors. In this process, metal-organic precursors containing the desired elements are vaporized and then decomposed on the substrate surface to form the alloy compound.

5.3. Alloying by annealing:

In some cases, semiconductor alloys can be formed by annealing a mixture of different elemental layers. The thermal treatment allows the atoms to diffuse and mix, thus forming the desired alloy composition.

The advantages of semiconductor alloys include:

- **Tunable Bandgap:** The bandgap of a semiconductor determines its ability to absorb and emit light. Alloying allows for precise control of the bandgap by adjusting the composition of the alloy. This property is crucial for designing devices that operate in specific regions of the electromagnetic spectrum.
- **Enhanced Carrier Mobility:** Semiconductor alloys can exhibit higher carrier mobility than single-element semiconductors. This characteristic is beneficial for high-frequency and high-speed electronic devices.
- **Compatibility with Existing Technology:** Semiconductor alloys can be integrated with existing semiconductor technologies, such as silicon, to leverage their unique properties. This compatibility enables the development of advanced devices that combine the best features of different materials.
- **Customizable Lattice Constants:** The lattice constant is the distance between atoms in a crystal lattice. Alloying allows for the adjustment of the lattice constant, which is essential for designing hetero-structure devices and minimizing defects at material interfaces.
- **Wide Range of Applications:** Semiconductor alloys find applications in various fields, including light-emitting diodes (LEDs), laser diodes, solar cells, high-speed transistors, and sensors.

Overall, semiconductor alloys provide a versatile platform for the design and fabrication of advanced electronic and optoelectronic devices. By combining different elements in the crystal lattice, the properties of these materials can be finely tuned to meet the requirements of specific applications, paving the way for technological advancements across various industries.

6. Formation and recombination of electron-hole pairs

In semiconductors, the formation and recombination of electron-hole pairs play a crucial role in their electrical behavior. When a semiconductor is subjected to external energy, such as thermal energy or electromagnetic radiation, electron-hole pairs can be generated, leading to changes in the conductivity and optical properties of the material. Let's examine the process of formation and recombination of electron-hole pairs:

6.1. Formation of electron-hole pairs

When sufficient energy is provided to a semiconductor, it can promote an electron from the valence band to the conduction band, leaving behind a vacancy called a hole in the valence band. This process can occur through different mechanisms:

- **Photon absorption:** when a photon with energy equal to or greater than the energy of the semiconductor's bandgap strikes the material, an electron in the valence band, exciting it to the conduction band and creating an electron-hole pair, can absorb it.
- **Thermal excitation:** At finite temperatures, some electrons in the valence band can gain enough thermal energy to overcome the bandgap and move to the conduction band, leaving behind a hole.

Once an electron-hole pair is generated, the electron occupies an energy state in the conduction band, while the hole occupies an energy state in the valence band. These charge carriers are now free to move within the semiconductor lattice.

6.2. Recombination of electron-hole pairs

Electron-hole recombination occurs when an electron from the conduction band recombines with a hole from the valence band, resulting in the annihilation of both the electron and the hole. This process can occur through different mechanisms, as shown in Figure 6:

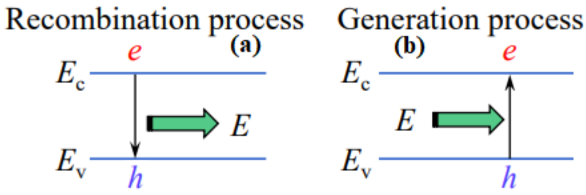


Figure 6: Direct Generation/Recombination Process.

- **Radiative recombination:** In radiative recombination, the electron and hole recombine, releasing energy in the form of a photon. This energy is typically emitted as visible or infrared light, depending on the bandgap energy of the semiconductor. Radiative recombination is a desirable process for electroluminescent devices such as LEDs and lasers.
- **Non-Radiative recombination:** Non-radiative recombination involves the annihilation of electronic holes without photon emission. Instead, the excess energy is transferred to lattice vibrations (phonons), defects, or impurities present in the material. Non-radiative recombination reduces the efficiency of devices and contributes to energy loss.
- **Auger recombination:** Auger recombination occurs in highly doped semiconductors or at high carrier densities. In this process, the recombination energy is transferred to another carrier instead of being emitted as a photon. The energy of the recombined electron or hole is transferred to a third carrier, leading to its excitation and subsequent recombination of the original electron-hole pair.

The rate of recombination of electron-hole pairs depends on various factors, including the properties of the material, temperature, doping concentration, and the presence of defects. Minimizing non-radiative recombination and enhancing radiative recombination are important for improving the performance of semiconductor devices.

During photon-assisted recombination, an electron from the conduction band recombines with a hole in the valence band. The excess energy is transferred to a photon. The reverse process obtains its energy from radiation and generates an electron-hole pair.

6.2.1. Carrier lifetimes

The lifetime of charge carriers (electrons and holes) in a semiconductor determines how long they remain free before recombining. Longer carrier lifetimes enhance conductivity and allow carriers to participate in device operations for a longer period.

Carrier lifetimes can be influenced by various factors, such as material purity, doping levels, temperature, and defects. Techniques such as passivation and materials engineering are used to extend carrier lifetimes and reduce recombination rates, thereby improving the overall performance of semiconductor devices.

In summary, the formation of electron-hole pairs occurs when energy is provided to a semiconductor, causing electrons to transition from the valence band to the conduction band and creating holes in the valence band. Recombination, on the other hand, is the annihilation of these pairs.

7. Energy bands in solids

Energy bands in solids play a crucial role in determining the electronic properties and behavior of materials. A solid can be considered as a large number of atoms or ions arranged in a regular and periodic crystal lattice. When these atoms come together to form a solid, the electronic wave functions of the individual atoms interact, leading to the formation of energy bands. Let’s explore the concept of energy bands in solids:

7.1. Atomic energy levels

In an isolated atom, electrons occupy discrete energy levels or orbitals around the atomic nucleus. These energy levels are determined by the electronic configuration of the atom and are characterized by quantized energy values. The lowest energy level is the ground state, while higher energy levels are excited states.

7.2. Crystal lattice and Bloch's Theorem

In a solid, atoms are arranged in a crystal lattice, forming a periodic structure. Bloch's theorem states that in a periodic potential, the electronic wave function can be represented as the product of a plane wave and a periodic function describing the atomic arrangement. This allows us to describe the electronic states in a solid in terms of Bloch functions, which are combinations of plane waves and periodic functions.

- **Formation of energy bands:** When atoms come together to form a solid, the wave functions of electrons overlap, leading to interactions between the electrons. These interactions cause the splitting and broadening of the energy levels of isolated atoms into bands of allowed energy states. The splitting of energy levels occurs due to constructive or destructive interference of electronic wave functions.
- **Valence band and conduction band:** Energy bands in solids are generally classified into two main bands: the valence band and the conduction band.
- **Valence band:** The valence band is the lower energy band in the electronic structure of a solid. It consists of energy levels filled with electrons at absolute zero temperature. Electrons in the valence band are involved in covalent or ionic bonding with neighboring atoms and are not available for electrical conduction under normal conditions.
- **Conduction band:** The conduction band is the highest energy band in the electronic structure of a solid. It consists of energy levels located above the valence band where electrons can move freely within the crystal lattice. Electrons in the conduction band are not strongly bound to specific atoms and can contribute to electrical conduction and mobility within the material.
- **Bandgap:** The energy difference between the valence band and the conduction band is known as the bandgap. It determines the electrical and optical properties of the material.

Semiconductors are characterized by a moderate bandgap, allowing for intermediate conductivity compared to conductors and insulators.

- **Insulators:** Insulators have a large bandgap, and at absolute zero temperature, the valence band is completely filled with electrons, while the conduction band is completely empty. Therefore, insulators have negligible electrical conductivity.
- **Semiconductors:** Semiconductors have a smaller bandgap than insulators, and at absolute zero temperature, the valence band is largely filled, while the conduction band is empty. By applying external energy, such as thermal energy or photon absorption, electrons can be promoted from the valence band to the conduction band, leading to increased conductivity.
- **Conductors:** Conductors have overlapping valence and conduction bands, meaning that electrons can move freely between the two bands. This overlap allows for high electrical conductivity in conductors.
- **Band structure and density of states:** Energy bands in solids are not continuous but rather consist of a large number of closely spaced energy levels. The density of states (DOS) represents the number of energy levels per unit energy range available for electrons at a given energy.

In solids, including semiconductors, the electronic structure is often described in terms of energy bands. Energy bands represent the allowed energy levels for electrons in a crystal lattice. The two main bands in solids are the valence band and the conduction band, and their properties play a crucial role in determining the electrical behavior of semiconductors. Let's explore these groups in detail, as shown in Figure 7:

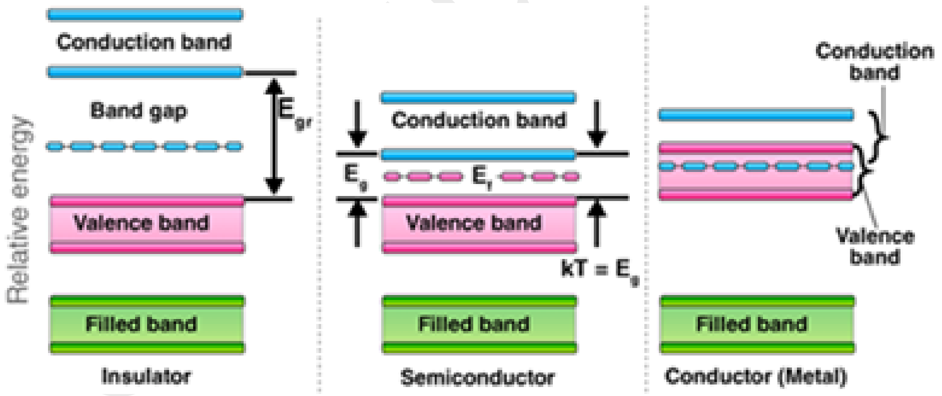


Figure 7: Electronic Band Structure

7.2.1. Valence band

The valence band is the lower energy band in the electronic structure of a solid. It represents the highest energy levels occupied by electrons at absolute zero temperature. Electrons in the valence band are strongly bound to their respective atoms and participate in covalent or ionic bonding with neighboring atoms. The valence band is responsible for the stability of the material and its insulating or conductive properties.

In semiconductors, the valence band is generally filled with electrons, forming a layer of valence electrons around the atomic nuclei. These electrons are tightly bound to the atomic nuclei and are not available for electrical conduction under normal conditions. The valence band plays a crucial role in determining the chemical properties and bonding characteristics of the semiconductor material.

7.2.2. Conduction band

The conduction band is the highest energy band in the electronic structure of a solid. It represents the energy levels above the valence band where electrons can move freely within the crystal lattice. Electrons in the conduction band are not strongly bound to specific atomic nuclei and are relatively free to move under the influence of an electric field.

In semiconductors, the conduction band is generally empty or partially filled with electrons at absolute zero temperature. To promote electrons from the valence band to the conduction band, an external energy source, such as thermal energy or photon absorption, is required. Once in the conduction band, electrons can contribute to electrical conduction and mobility within the material. The energy difference between the valence band and the conduction band is known as the bandgap energy (Eg) and determines the electrical properties of the semiconductor.

7.2.3. Bandgap

The bandgap is the energy difference between the valence band and the conduction band. It determines the conductivity characteristics of a semiconductor material. Semiconductors are classified into two categories based on their bandgap energy:

- **Direct bandgap:** In materials with a direct bandgap, the minimum energy level of the conduction band occurs at the same momentum (k-vector) as the maximum energy level of the valence band. Direct bandgap materials efficiently absorb and emit photons, making them suitable for optoelectronic applications such as LEDs and lasers.
- **Indirect bandgap:** In materials with an indirect bandgap, the minimum energy level of the conduction band occurs at a different momentum than the maximum energy level of the valence band. Indirect bandgap materials have lower efficiency in terms of light emission and absorption compared to direct bandgap materials.

The bandgap energy determines the energy required for electrons to transition from the valence band to the conduction band. Semiconductors with smaller bandgaps (for example, less than 1.5 eV) are considered narrow bandgap materials, while those with larger bandgaps (for example, greater than 1.5 eV) are classified as wide bandgap materials.

In summary, the energy bands in semiconductors include the valence band, where electrons are tightly bound to atoms, and the conduction band, where electrons can move freely within the crystal lattice. The bandgap energy between these two bands determines the electrical conductivity and optical properties of the semiconductor. Understanding the behavior and characteristics of these bands is fundamental to understanding the electronic structure and behavior of semiconductors.

8. Summary

In this chapter, we studied semiconductors and the types of semiconductors. We also discussed the doping of intrinsic semiconductors to create extrinsic semiconductors. Semiconductor alloys were discussed in detail. The formation and recombination of electron-hole pairs were explained. Energy bands in solids were also discussed.

9. Lexicon

Doping**:** Intentionally introducing impurities into an extremely pure semiconductor to modify its electrical properties.

Alloy**:** A substance formed from the combination of two or more metals, sometimes including non-metallic elements.

Extrinsic**:** Referring to a property or factor that comes from outside a system or thing.

Intrinsic**:** Referring to a property that belongs to a thing by its very nature, independent of any external influence.

Hole**:** An absence of an electron in a semiconductor, acting as a positive charge.

10. References

1. S.M. Sze, *Semiconductor Devices - Physics and Technology*, Wiley, New York.
2. J. Singh, *Semiconductor Optoelectronics: Physics and Technology*, McGraw Hill.
3. P. Bhattacharya, *Semiconductor Optoelectronic Devices*, Pearson Education.
4. J. Singh, *Optoelectronics: An Introduction to Materials and Devices*, Tata McGraw Hill.
5. Holger T. Grahn, *Introduction to Semiconductor Physics*, World Scientific Publishing Co Pte Ltd.
6. S.M. Sze and Kwok K. Ng, *Physics of Semiconductor Devices*, John Wiley & Sons.
7. Simon M. Sze and Ming-Kwei Lee, *Semiconductor Devices: Physics and Technology*, Wiley, New York.
8. Otfried Madelung, *Semiconductors: Basic Data*, Springer.
9. Donald A. Neamen, *Semiconductor Physics and Devices: Basic Principles*, McGraw Hill.

11. Recommendations

1. S.M. Sze, *Semiconductor Devices - Physics and Technology*, Wiley, New York.
2. J. Singh, *Semiconductor Optoelectronics: Physics and Technology*, McGraw Hill.
3. P. Bhattacharya, *Semiconductor Optoelectronic Devices*, Pearson Education.
4. J. Singh, *Optoelectronics: An Introduction to Materials and Devices*, Tata McGraw Hill.

Chapter 2: Optical processes in semiconductors

1. Introduction

Optical processes in semiconductors refer to the interaction between semiconductor materials and electromagnetic radiation, particularly in the optical range of the electromagnetic spectrum. These processes involve the absorption, emission, and scattering of photons by the electrons and holes in the semiconductor material. Optical processes are fundamental in many optoelectronic devices and technologies such as light-emitting diodes (LEDs), lasers, photodetectors, and solar cells. Let’s explore the key optical processes in semiconductors: see Figure 1.

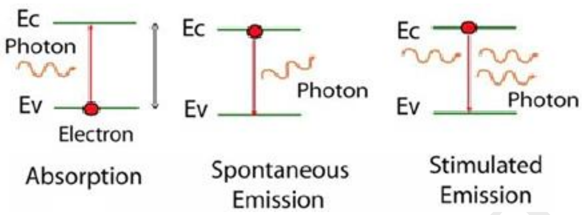


Figure 1: Absorption-Emission

1.1. Absorption

Absorption is the process by which a photon of sufficient energy is absorbed by a semiconductor, causing an electron to transition from the valence band to the conduction band. For absorption to occur, the energy of the incident photon must match or exceed the energy of the bandgap of the semiconductor material. During absorption, the energy of the photon is transferred to the electron, which is then free to participate in electrical conduction or recombination processes.

1.2. Emission

Emission refers to the process by which a semiconductor material releases photons of specific energies when electrons transition from higher energy states to lower energy states. There are two main types of emission processes:

- **Spontaneous emission:** Spontaneous emission occurs when an electron in an excited state in the conduction band recombines with a hole in the valence band, releasing a photon. The energy of the emitted photon corresponds to the energy difference between the involved states. Spontaneous emission is a random process, and the emitted photons are not coherent with one another, resulting in low-intensity light emission.
- **Stimulated emission:** Stimulated emission occurs when an incident photon interacts with an excited electron in the conduction band, causing the electron to transition to a lower energy state. This process releases a photon that is coherent and has the same energy, direction, and phase as the incident photon. Stimulated emission is the fundamental process behind the operation of lasers, where a cascade of stimulated emissions leads to light amplification.

1.3. Photoluminescence

Photoluminescence is a process by which a semiconductor emits light after absorbing photons. This involves the absorption of photons, followed by recombination and subsequent emission of photons. Photoluminescence can occur through two main mechanisms: see Figure 2.

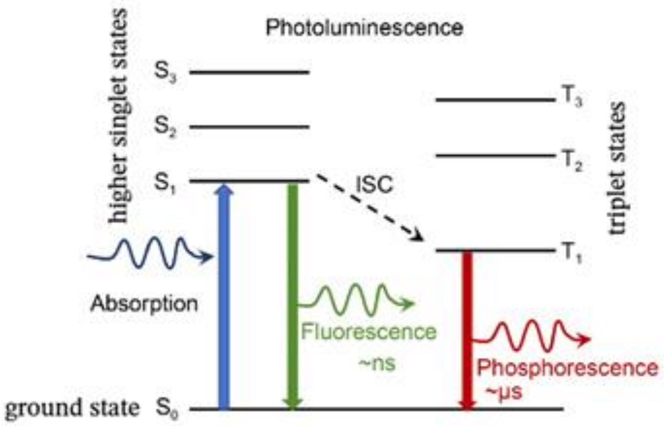


Figure 2: Photoluminescence Process

- **Fluorescence:** Fluorescence is a type of photoluminescence where the emitted light occurs immediately or shortly after the absorption of photons. The absorbed energy is quickly re-emitted as a photon of lower energy. Fluorescence is commonly observed in fluorescent materials and is widely used in biological imaging, detection, and display technologies.
- **Phosphorescence:** Phosphorescence is a type of delayed photoluminescence where the emitted light persists even after the excitation source has been removed. Phosphorescent materials have long-lived excited states, and radiative recombination occurs over a longer timescale. Phosphorescent materials are used in applications such as glow-in-the-dark products and certain types of display technologies.

1.4. Scattering

Scattering refers to the interaction of photons with electrons or other charge carriers in the semiconductor material, resulting in changes in the direction and energy of the photons. There are different types of scattering processes, including Rayleigh scattering, Raman scattering, and Brillouin scattering. Scattering can affect the propagation of light in a material, leading to phenomena such as optical diffraction effects, coloring, and polarization. See Figure 3.

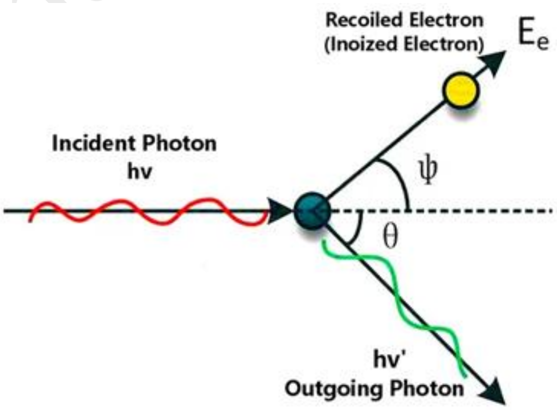


Figure 3: Scattering Principle

These optical processes in semiconductors are essential for the operation of various optoelectronic devices. By manipulating and controlling these processes, researchers and engineers can design and optimize semiconductor materials for applications in lighting, communication, imaging, and energy conversion.

2. Objectives

After studying this unit, you should be able to-

- Understand different optical processes in semiconductors
- Explain absorption in semiconductors and indirect intrinsic transitions
- Explain exciton absorption, donor-acceptor and impurity-band absorption
- Discuss effect of electric field on absorption
- Understand radiation in semiconductors
- Explain relation between absorption and emission spectra
- Discuss near band gap radioactive transitions

3. Absorption in semiconductors

The measurement of absorption and emission spectra in semiconductors constitutes an important aspect of materials characterization.

- They not only provide information on the bandgap, but the measurements also provide information on direct and indirect transitions, the distribution of states, defects and impurities.
- The absorption spectrum spans a wide energy (or wavelength) range, extending from the near bandgap energies to the low energy transitions involving free carriers and lattice vibrations (near bandgap transitions).

Absorption in semiconductors refers to the process by which a semiconductor material absorbs photons of specific energies, leading to the promotion of electrons from the valence band to the conduction band. Here's a detailed explanation of absorption in semiconductors:

3.1. Bandgap energy:

In semiconductors, the valence band is filled with electrons, while the conduction band is mostly empty at absolute zero temperature. The energy difference between these two bands is called the bandgap energy (Eg). The bandgap energy determines the minimum energy required for an electron to transition from the valence band to the conduction band.

3.2. Photon absorption:

When a photon with energy ($h\nu$) interacts with a semiconductor material, the energy of the photon can be transferred to an electron. For absorption to occur, the energy of the incident photon must match or exceed the bandgap energy of the semiconductor. If the photon's energy is greater than the bandgap energy, the excess energy is usually dissipated as heat.

3.3. Energy conservation:

In the absorption process, the energy of the incident photon is transferred to the semiconductor's electron, promoting it from the valence band to the conduction band. The energy conservation principle dictates that the energy of the absorbed photon ($h\nu$) is equal to the sum of the electron's initial energy in the valence band and the energy required to reach the conduction band. Mathematically, this can be expressed as:

$$h\nu = E\_valence + \Delta E$$

Where, $E\_valence$ is the initial energy of the electron in the valence band, and ΔE is the energy required for the electron to transition to the conduction band.

3.4. Electron excitation and pair generation:

When an electron absorbs a photon with energy matching or exceeding the bandgap energy, it gains enough energy to overcome the energy barrier and transition to the conduction band. This promotion of the electron from the valence band to the conduction band creates an electron-hole pair, where the hole (an absence of an electron) is left behind in the valence band.

3.5. Absorption coefficient:

The absorption coefficient (α) quantifies the extent of absorption in a semiconductor material. It represents the fraction of incident photons that are absorbed per unit distance traveled through the material. The absorption coefficient depends on the material properties, photon energy, and other factors. It is typically wavelength-dependent and can vary across different regions of the electromagnetic spectrum.

3.6. Indirect and direct bandgap materials:

The efficiency of absorption in semiconductors depends on the nature of the bandgap. In direct bandgap materials, the minimum energy level of the conduction band aligns with the maximum energy level of the valence band in momentum space. As a result, direct bandgap materials have a higher absorption efficiency and are widely used in optoelectronic devices such as LEDs and lasers.

In contrast, indirect bandgap materials have a mismatch in the momentum space between the conduction and valence bands' energy extrema. Absorption in indirect bandgap materials requires the assistance of phonons or other mechanisms to conserve both energy and momentum, resulting in lower absorption efficiency.

3.7. Absorption spectrum:

The absorption spectrum of a semiconductor material represents its absorption characteristics across a range of photon energies or wavelengths. The absorption spectrum can be experimentally measured using techniques such as optical absorption spectroscopy. It provides valuable information about the material's band structure, bandgap energy, and optical properties.

Understanding absorption in semiconductors is crucial for designing and optimizing semiconductor-based devices that rely on photon absorption, such as solar cells, photodetectors, and optical sensors. By tailoring the bandgap energy and material properties, researchers can optimize the absorption efficiency and spectral response of semiconductor

4. Indirect intrinsic transitions

In optoelectronics, indirect intrinsic transitions refer to electronic transitions in semiconductors where the energy and momentum of the involved electrons do not directly match. These transitions occur between energy levels in the conduction band and the valence band, and they require additional mechanisms, such as phonon interactions, to conserve both energy and momentum.

- The momentum or wavevector change required in an indirect transition may be provided by single or multiple phonons, although the probability of the latter to occur is very small. There are optical and acoustic phonons.
- Each of these has transverse and longitudinal modes of vibrations, with characteristic energy and momentum.
- In indirect transition process conservation of momentum requires:

$$k" \pm k_p = k' + k_{ph}$$

Where $k"$ and k' are the electron wavevectors for the final and initial states, k_p is the wavevector of the phonon, and k_{ph} is the wavevector of the absorbed photon.

Since the latter is small, the conservation of momentum for an indirect transition can be expressed as $k" - k' = \pm kp$

Similarly, the conservation of energy for the two cases of phonon emission and absorption can be expressed as

$$\hbar\omega_e = \varepsilon C - \varepsilon V + \varepsilon p$$

$$\hbar\omega_a = \varepsilon C - \varepsilon V - \varepsilon p$$

Where the left- hand side represents the energy of the photon absorbed.

From this energy state the electron finally reaches the indirect valley by phonon scattering. The intermediate energy state of the electron is termed a virtual state, in which the carrier resides until a phonon of the right energy and momentum is available for the scattering process. Indirect transition probabilities involving virtual state can be calculated using a second-order time dependent perturbation theory. The total probability is obtained by a summation over these energy states, as long as each particular transition conserves energy between initial and final states.

Let's explore indirect intrinsic transitions in more detail:

4.1. Direct vs. Indirect transitions:

In semiconductors, electronic transitions can be categorized as direct or indirect based on their momentum conservation properties.

- Direct Transitions: In direct transitions, the minimum energy level of the conduction band aligns with the maximum energy level of the valence band in momentum space. This means that the involved electrons have the same momentum before and after the transition, resulting in efficient absorption and emission of photons. Direct transitions have higher absorption coefficients and are commonly observed in direct bandgap materials such as III-V compounds (e.g., GaAs, InP) and II-VI compounds (e.g., ZnSe, CdS).
- Indirect Transitions: In indirect transitions, the minimum energy level of the conduction band does not align with the maximum energy level of the valence band in momentum space. This means that the momentum of the electrons before and after the transition does not match, leading to a lower probability of absorption and emission of photons. Indirect transitions require additional mechanisms to conserve both energy and momentum, typically involving the interaction with lattice vibrations known as phonons. Indirect

transitions are commonly observed in indirect bandgap materials such as silicon (Si), germanium (Ge), and other group IV elemental semiconductors.

4.2. Phonon participation:

In an indirect intrinsic transition, the conservation of both energy and momentum is achieved through the participation of phonons. Phonons are quantized lattice vibrations or collective oscillations of atoms in a crystal lattice. When an electron makes an indirect transition, it absorbs or emits a photon with an energy that is slightly lower or higher than the bandgap energy. The additional energy needed for momentum conservation is exchanged with a phonon, which carries away or supplies the necessary momentum.

4.3. Absorption and emission characteristics:

Indirect transitions have lower absorption coefficients compared to direct transitions because of the momentum mismatch. The lower absorption efficiency results in a longer optical absorption length for indirect bandgap materials. Additionally, the emission of photons in indirect transitions is less efficient compared to direct transitions due to the involvement of phonons and the lower probability of radiative recombination.

4.4. Applications:

Despite the lower efficiency, indirect bandgap materials like silicon (Si) are widely used in optoelectronic devices such as photodetectors, image sensors, and solar cells. The abundance and compatibility of silicon with complementary metal-oxide-semiconductor (CMOS) technology make it a popular choice in integrated optoelectronic systems. Additionally, indirect bandgap materials have been explored for applications in silicon photonics, where light can be manipulated and guided on a silicon chip for data transmission and optical communication.

In summary, indirect intrinsic transitions in optoelectronics refer to electronic transitions in semiconductors where the energy and momentum of the involved electrons do not directly match. These transitions require additional mechanisms, such as phonon interactions, to conserve both energy and momentum. Indirect transitions have lower absorption and emission efficiencies compared to direct transitions, but they are still important in various optoelectronic applications, particularly in silicon-based devices.

5. Exciton absorption

Exciton absorption in semiconductors refers to the process by which an exciton, a bound state of an electron and a hole, absorbs a photon and undergoes an electronic transition from the ground state to an excited state. Excitons are formed due to the Coulomb attraction between an excited electron in the conduction band and the resulting hole in the valence band. Here is a detailed explanation of exciton absorption in semiconductors:

- **Exciton formation**: In a semiconductor material, when a photon is absorbed, it can create an electron-hole pair. The absorbed photon transfers its energy to an electron, promoting it from the valence band to the conduction band, leaving behind a hole in the valence band. The electron and hole are bound together by the attractive Coulomb force, forming an exciton.

- **Bound exciton**: In the exciton, the electron and hole orbit around their center of mass due to their opposite charges. The exciton is a quasiparticle with characteristics different from a free electron or hole. The binding energy of the exciton is typically on the order of a few millielectron volts (meV) and depends on the specific semiconductor material.
- **Absorption process**: When an incident photon with energy equal to or greater than the exciton binding energy interacts with a semiconductor, it can be absorbed by the exciton. The photon's energy is transferred to the exciton, exciting it to a higher energy state. The energy of the absorbed photon must match the energy difference between the ground state and the excited state of the exciton.
- **Exciton energy levels**: Excitons in semiconductors exhibit quantized energy levels similar to atomic energy levels. The lowest energy level is the ground state, where the electron is in the lowest energy level of the conduction band, and the hole is in the highest energy level of the valence band. Excitons also have excited states corresponding to higher energy levels in the conduction and valence bands.
- **Exciton absorption spectrum**: The absorption spectrum of a semiconductor material shows the energy dependence of the material's absorption coefficient. In the case of exciton absorption, the absorption spectrum exhibits peaks corresponding to the exciton energy levels. The exciton absorption peaks appear at energies below the bandgap energy of the semiconductor material.
- **Exciton dynamics**: Excitons in semiconductors have finite lifetimes due to several processes that can occur after absorption. These processes include radiative recombination, where the exciton emits a photon and returns to the ground state, and non-radiative processes such as phonon-assisted relaxation, Auger recombination, or exciton dissociation. The specific dynamics depend on the material properties and the surrounding environment.
- **Exciton effects on optical properties**: The presence of excitons in semiconductors has significant effects on their optical properties. Excitons have an influence on the absorption coefficient and the refractive index of the material, leading to features such as absorption edges and excitonic peaks in the optical spectra. The energy and intensity of excitonic absorption can be modified by external factors such as temperature, strain, and doping.
- **Applications**: Exciton absorption and excitonic properties are important in various optoelectronic devices. For example, excitons play a crucial role in the operation of organic light-emitting diodes (OLEDs), where the recombination of excitons leads to the emission of light. Excitonic effects are also relevant in photovoltaic devices, such as excitonic solar cells, where the absorption of photons by excitons contributes to the energy conversion process.

In summary, exciton absorption in semiconductors involves the absorption of photons by bound electron-hole pairs known as excitons. The exciton absorbs photons of specific energies, causing transitions from the ground state to excited states. Exciton absorption leads to distinctive features in the absorption spectrum and has important implications for the optical properties and performance of optoelectronic devices.

6. Donor-acceptor & impurity-band absorption

Donor-acceptor and impurity band absorption are two mechanisms of absorption in semiconductors involving the presence of impurities or dopants. These mechanisms play a crucial role in modifying the optical properties of semiconductors. Let us explore each mechanism in detail:

6.1. Donor-acceptor absorption:

In donor-acceptor absorption, impurities or dopants are intentionally added to a semiconductor material during the fabrication process. These impurities introduce energy levels within the bandgap of the host semiconductor, resulting in additional absorption processes. The impurities are typically classified as donors or acceptors based on their electronic properties.

- ➢ Donors: Donor impurities introduce energy levels near the conduction band of the host semiconductor, providing additional electronic states that can be occupied by electrons. Common donor impurities include elements such as phosphorus (P) or arsenic (As) in silicon (Si) or germanium (Ge) semiconductors.
- ➢ Acceptors: Acceptor impurities introduce energy levels near the valence band of the host semiconductor, creating additional states that can accommodate holes. Common acceptor impurities include elements such as boron (B) or aluminium (Al) in Si or Ge semiconductors.

The absorption process occurs when photons with energies matching the energy difference between the donor or acceptor level and the conduction or valence band are absorbed. This absorption leads to the promotion of an electron from the donor or acceptor level to the conduction or valence band, respectively.

Donor-acceptor absorption modifies the absorption spectrum of the semiconductor, introducing additional absorption peaks corresponding to the energies of the donor and acceptor levels. These absorption peaks can be used to identify and characterize the dopant impurities in the material. See figure 3.

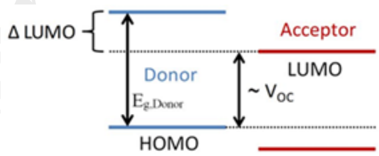


Figure 3. : Illustration of photon absorption due to donor-acceptor transition.

6.2. Impurity band absorption:

Impurity band absorption occurs when a high concentration of impurities is present in a semiconductor material, leading to the formation of an impurity band within the bandgap. This mechanism is more relevant in heavily doped or alloyed semiconductors.

When the impurity concentration is high, the energy levels of the impurity atoms overlap and form a broad band of energy states within the bandgap. This impurity band can extend over a range of energies, partially or fully filling the bandgap.

The impurity band serves as an additional absorption channel for photons. Photons with energies corresponding to the energy difference between the impurity band and the conduction or valence band can be absorbed, promoting electrons or holes from the impurity band to the conduction or valence band, respectively.

The presence of the impurity band can significantly enhance the absorption properties of the semiconductor material, allowing for absorption in energy ranges that are typically inaccessible in undoped or low-doped materials.

6.3. Applications:

Donor-acceptor absorption and impurity band absorption have practical applications in various optoelectronic devices. For example:

Photodetectors: Donor-acceptor absorption and impurity band absorption extend the spectral sensitivity of photodetectors to a wider range of wavelengths. This enables detection of light in specific regions of the electromagnetic spectrum.

Solar cells: The modification of the absorption spectrum through donor-acceptor absorption or impurity band absorption can enhance the efficiency of solar cells. By tuning the impurity concentration and energy levels, the absorption of a broader range of photons can be achieved, increasing the conversion efficiency of solar energy into electricity.

Infrared sensors: Impurity band absorption is particularly relevant for infrared sensors that require high sensitivity to infrared radiation. The presence of impurity bands allows for efficient absorption and detection of infrared light.

In summary, donor-acceptor absorption and impurity band absorption are mechanisms in which impurities or dopants introduce energy levels within the bandgap of a semiconductor material. These mechanisms modify the absorption spectrum, enabling absorption of photons with energies corresponding to the energy differences between the impurity levels and the conduction or valence band. Donor-acceptor absorption is achieved through intentional doping, while impurity band absorption occurs in heavily doped or alloyed semiconductors. These mechanisms have applications in various optoelectronic devices, expanding their spectral sensitivity and improving performance.

7. Effect of electric field on absorption

Absorption in semiconductors: Absorption in semiconductors refers to the process by which incident photons are absorbed, resulting in the excitation of electrons from the valence band to the conduction band. This absorption process is governed by the energy band structure of the semiconductor material.

Effect of electric field: The presence of an electric field in a semiconductor can significantly influence the absorption properties. The electric field modifies the band structure, alters the energy levels, and affects the absorption coefficient of the material.

Quantum confined stark effect (QCSE): One of the main effects of an electric field on absorption is the Quantum Confined Stark Effect (QCSE). QCSE occurs in semiconductor hetero-structures, where layers of different materials with different bandgaps are stacked together.

Band bending: When an electric field is applied across a semiconductor hetero-structure, it causes band bending at the interfaces between the layers. Band bending refers to the redistribution of charge and the modification of energy levels near the interface.

Shift in energy levels: The electric field induces a shift in the energy levels of the semiconductor material. In the presence of an electric field, the energy levels in the conduction and valence bands are shifted in opposite directions. This energy level shift alters the absorption spectrum of the semiconductor.

Stark shift: The shift in energy levels due to the electric field is known as the Stark shift. It results in a change in the energy difference between the valence and conduction bands. Consequently, the absorption edge of the material is shifted to higher or lower energies depending on the polarity and magnitude of the electric field.

Exciton Stark effect: The Stark shift induced by the electric field also affects excitons, which are bound electron-hole pairs. The energy levels of excitonic states are modified by the electric field, leading to changes in their absorption properties. This effect is known as the Exciton Stark Effect.

Modulation of absorption coefficient: The electric field can modulate the absorption coefficient of the semiconductor material. By controlling the electric field strength, it is possible to enhance or suppress absorption at specific wavelengths. This modulation of the absorption coefficient has applications in devices such as electro-absorption modulators and electro-optic switches.

Quantum well structures: In quantum well structures, which are thin semiconductor layers sandwiched between barriers, the electric field affects the quantized energy levels. By changing the electric field strength, the energy levels in the quantum well can be tuned, resulting in tunable absorption properties.

7.1. Applications:

The influence of an electric field on absorption in semiconductors has numerous applications. It is utilized in devices such as electro-absorption modulators, quantum well infrared photodetectors, electro-optic switches, and electro-optic modulators. These devices rely on the control of absorption properties through electric field manipulation.

In summary, the presence of an electric field in semiconductors, particularly in hetero-structures, has a significant impact on absorption properties. The electric field induces band bending, shifts energy levels, modifies excitonic states, and alters the absorption coefficient. Understanding and manipulating the effect of electric fields on absorption is crucial for the design and optimization of various optoelectronic devices.

8. Radiation in semiconductor-relation between absorption and emission spectra

In semiconductors, the absorption and emission spectra are intimately related and provide valuable information about the interaction of radiation with the material. Understanding the relationship between absorption and emission spectra is crucial for the design and characterization of optoelectronic devices. Let's explore this relationship in detail:

Absorption Spectrum: The absorption spectrum of a semiconductor material represents the energy-dependent absorption coefficient, which describes the material's ability to absorb incident photons at different energies. It provides information about the energy levels and transitions that occur in the material upon photon absorption.

Energy levels and transitions: In a semiconductor, energy levels exist in the valence band (VB) and the conduction band (CB). Absorption occurs when a photon with energy matching the energy difference between the VB and CB is incident on the material. This promotes an electron from the VB to the CB, leaving behind a hole in the VB. The absorption spectrum displays peaks at energies corresponding to these electronic transitions.

Bandgap energy: The bandgap energy (Eg) is the minimum energy required to promote an electron from the VB to the CB. Photons with energies lower than the bandgap energy are not absorbed, while those with energies higher than the bandgap energy are absorbed with varying efficiency.

Direct and indirect transitions: In some semiconductors, the energy difference between the VB and CB is nearly equal to the photon energy, resulting in direct transitions. In other cases, the energy difference is different, leading to indirect transitions. Direct transitions have a sharper absorption peak, while indirect transitions have a more gradual absorption edge.

Emission spectrum: The emission spectrum of a semiconductor material represents the energy distribution of photons emitted by the material when it transitions from an excited state to a lower energy state. The emission spectrum is often studied using photoluminescence or electroluminescence techniques.

Radiative recombination: In semiconductors, radiative recombination is a process where an electron in the CB recombines with a hole in the VB, resulting in the emission of a photon. The emitted photon carries energy equal to the energy difference between the CB and VB.

8.1. Relationship between Absorption and Emission:

The relationship between the absorption and emission spectra is governed by the principle of detailed balance. According to this principle, the absorption and emission processes are in equilibrium when the material is at thermal equilibrium. In this equilibrium, the rates of absorption and emission are equal.

The absorption peaks in the absorption spectrum correspond to the energies at which photons are absorbed and excite electrons across the bandgap. On the other hand, the emission peaks in the emission spectrum correspond to the energies at which photons are emitted during radiative recombination. The emission spectrum generally exhibits a broader range of energies compared to the absorption spectrum.

Stokes Shift: In some cases, the emission peak energy is lower than the absorption peak energy. This energy difference is known as the Stokes shift. The Stokes shift occurs due to nonradiative relaxation processes, such as phonon interactions, that cause energy loss before photon emission.

8.2. Applications:

The relationship between absorption and emission spectra is crucial for various optoelectronic devices. For example, in light-emitting diodes (LEDs), the emission spectrum is engineered to match desired wavelengths by selecting appropriate semiconductor materials and doping levels. In solar cells, the absorption spectrum is maximized to cover a broad range of incident photon energies for efficient light harvesting.

Understanding the relationship between absorption and emission spectra in semiconductors provides insights into the underlying electronic transitions and the behavior of photons within the material. This knowledge enables the design and optimization of semiconductor devices for specific applications in areas such as photonics, optoelectronics, and energy conversion.

9. Near band gap radioactive transitions

Near-bandgap radiative transitions, also known as optical transitions, refer to electronic transitions that occur close to the energy bandgap in a semiconductor material. These transitions involve the absorption or emission of photons with energies near the bandgap energy. Near-bandgap radiative transitions play a crucial role in the optical properties and applications of semiconductors. Let's delve into the details:

9.1. Energy bandgap:

The energy bandgap (Eg) is the energy difference between the valence band (VB), which contains occupied electron states, and the conduction band (CB), which contains unoccupied electron states, in a semiconductor. The bandgap energy determines the minimum energy required to excite an electron from the VB to the CB.

9.1.2. Direct and Indirect Transitions:

In semiconductor materials, electronic transitions near the bandgap can occur through direct or indirect processes.

- Direct Transitions: In direct transitions, the momentum of the electron in the CB and the hole in the VB is conserved during the transition. The absorption or emission of a photon allows the electron to move directly from the VB to the CB (or vice versa). Direct transitions are characterized by sharp absorption and emission peaks in the optical spectra.
- Indirect Transitions: In indirect transitions, the momentum of the electron and hole is not conserved during the transition. Additional mechanisms, such as phonon interactions, are involved to compensate for the momentum mismatch. Indirect transitions have a lower probability compared to direct transitions and typically exhibit a more gradual absorption or emission edge in the optical spectra.

9.1.3. Absorption:

Near-bandgap absorption occurs when a photon with energy close to the bandgap energy is incident on the semiconductor material. The absorbed photon provides the necessary energy to promote an electron from the VB to the CB. The absorbed energy is typically equal to or slightly higher than the bandgap energy. The absorption coefficient and the shape of the absorption spectrum depend on the nature of the transition (direct or indirect) and the density of states in the bands.

9.1.4. Emission:

Near-bandgap emission, also known as photoluminescence, involves the recombination of an electron in the CB with a hole in the VB, resulting in the emission of a photon. This radiative recombination process occurs when the electron- hole pair reaches a lower energy state. The emitted photon carries energy equal to the energy difference between the CB and VB.

9.1.5. Radiative Efficiency:

The radiative efficiency of near-bandgap radiative transitions refers to the probability of a radiative recombination process compared to nonradiative processes. Nonradiative processes involve energy loss through mechanisms like phonon interactions or defects. High radiative efficiency is desirable in optoelectronic devices as it ensures efficient light emission or absorption.

9.1.6. Optical Spectra:

The optical spectra of semiconductors exhibit characteristic features related to near-bandgap radiative transitions. The absorption spectrum shows a sharp increase in absorption near the bandgap energy, corresponding to the direct or indirect transitions. The emission spectrum displays peaks corresponding to the energies of radiative recombination processes. The shape, intensity, and position of these peaks depend on factors such as the material's band structure, doping levels, and temperature.

9.2. Applications:

Near-bandgap radiative transitions play a crucial role in various optoelectronic devices and technologies:

Light-Emitting Diodes (LEDs): Efficient radiative recombination enables LEDs to emit light at specific wavelengths. By engineering the bandgap energy and band structure, LEDs can cover a wide range of colors for applications in lighting and displays.

Photovoltaics: Near-bandgap absorption in solar cells allows for the efficient absorption of sunlight and subsequent generation of electron-hole pairs. By optimizing the absorption properties, solar cell efficiency can be enhanced.

Lasers: Laser devices rely on the stimulated emission of photons through radiative recombination processes. Near-bandgap transitions contribute to laser action by providing the necessary energy levels for population inversion and light amplification.

Photodetectors and Sensors: Near-bandgap absorption allows for the detection of photons in specific energy ranges. Photodetectors and sensors utilize these absorption processes for applications such as imaging, spectroscopy, and optical communications.

In summary, near-bandgap radiative transitions in semiconductors involve the absorption and emission of photons with energies close to the bandgap energy. These transitions are essential for understanding and manipulating the optical properties of semiconductors, enabling advancements in optoelectronic devices and technologies.

10. Summary

In this unit, you have studied about absorption in semiconductors. Indirect intrinsic transitions, Exciton absorption, Donor Acceptor and impurity-band absorption, Low energy (long Wavelength) absorption have been studied. Effect of electric field on absorption has been discussed in detail. Radiation in semiconductor has also been explained. Near band gap radioactive transitions explained in detail.

11. Lexicon

Absorption: the process of absorbing or soaking up something

Intrinsic: belonging to something as part of its nature.

Exciton: a bound state of an electron and an electron hole which are attracted to each other by the electrostatic Coulomb force

Range: to a variety of things or to an area in which something operates

Transition: a change from one state or form to another

Optical: connected with the sense of sight

12. References

1. Holger T. Grahn, Introduction to Semiconductor Physics, World Scientific Publishing Co Pte Ltd.

2. S.M. Sze and Kwok K. Ng, Physics of Semiconductor Devices, John Wiley & Sons.

3. Simon M. Sze and Ming-Kwei Lee, Semiconductor Devices: Physics and Technology, Wiley, New York.

4. Otfried Madelung, Semiconductors: Basic Data, Springer.

5. Donald A. Neamen, Semiconductor Physics and Devices: Basic Principles, McGraw Hill.

13. Suggested readings

1. S.M. Sze, Semiconductor Devices - Physics and Technology, Wiley, New York.

2. J. Singh, Semiconductor Optoelectronics: Physics and Technology, McGraw Hill.

3. P. Bhattacharya, Semiconductor Optoelectronic Devices, Pearson Education,

4. J. Singh, Optoelectronics: An Introduction to Materials and Devices, Tata McGraw Hill.

14. Terminal questions

1. Explain absorption in semiconductors and indirect intrinsic transitions in detail.

2. Explain exciton absorption‖ and donor acceptor and impurity-band absorption‖.

3. Discuss effect of electric field on absorption. Also explain Stark effect in detail.

4. Describe radiation in semiconductors and also explain relation between absorption and emission spectra.

Chapter 3: Optoelectronic detectors

1. Introduction

Optoelectronic detectors are devices that convert light signals into electrical signals. They are widely used in various applications, including telecommunications, imaging systems, medical devices, and scientific instruments. Optoelectronic detectors utilize the principles of both optics and electronics to sense and measure light in different forms, such as visible light, infrared, or ultraviolet radiation.

There are several types of optoelectronic detectors, each designed to detect light within a specific range of wavelengths and with different performance characteristics. Here are some common types:

1.1. Photodiodes:

Photodiodes are semiconductor devices that generate a current when exposed to light. They are widely used for detecting light in applications such as optical communication systems, light sensors, and barcode readers.

1.2. Phototransistors:

Phototransistors are similar to photodiodes but with an additional amplification stage. They offer higher sensitivity and gain compared to photodiodes, making them suitable for low-light applications.

1.3. Photomultiplier tubes (PMTs):

PMTs are extremely sensitive light detectors that can amplify weak light signals by several orders of magnitude. They consist of a photocathode, a series of dynodes, and an anode. PMTs are commonly used in applications requiring high sensitivity, such as scientific research, nuclear medicine, and astronomy.

1.4. Avalanche photodiodes (APDs):

APDs are semiconductor devices that operate in the reverse bias mode, allowing for internal avalanche multiplication of photo-generated carriers. This multiplication process provides higher gain and sensitivity compared to conventional photodiodes.

1.5. Charge-coupled devices (CCDs):

CCDs are image sensors consisting of an array of pixels that detect and record optical information. They are commonly used in digital cameras, scanners, and astronomical imaging devices.

1.6. CMOS sensors:

CMOS sensors are another type of image sensor used in many consumers electronic devices. They offer advantages such as low power consumption, high integration with other electronics, and fast readout speeds.

These are just a few examples of optoelectronic detectors. The choice of detector depends on the specific application requirements, such as sensitivity, speed, wavelength range, and cost.

2. Objectives

After studying this unit, you should be able to-

- Understand different Optoelectronic detectors
- Explain Photoconductors
- Explain different types of Photodiodes
- Understand Phototransistors

3. Photoconductors

Photoconductors are optoelectronic devices that exhibit changes in electrical conductivity when exposed to light. They are widely used in various applications, including light sensors, photocopiers, barcode scanners, and imaging devices. The theory, working principle, and applications of photoconductors are explained in detail below:

3.1. Theory

Photoconductors are typically made of semiconducting materials, such as amorphous silicon, cadmium sulphide, or lead sulphide. These materials have a unique property called the photoconductive effect, where their electrical conductivity changes when light is absorbed. The photoconductive effect arises from the generation and recombination of charge carriers (electrons and holes) within the material. "When radiant energy (photons) falls upon a photoconductor, it changes its conductance (resistance). As more carriers are produced in the detector by the radiant energy, the conductance increases. When a photoconductor operates in a mode where an applied electric field results in, a current that is modulated by additional carriers generated by photon excitation; in other words, radiation quanta are absorbed and free (photogenerated) charge carriers are produced in the semiconductor. The semiconductor's conductivity is raised as a result of these additional carriers. The name of these phenomena is photoconduction.

"Semiconductors are used to make photoconductors. Energy gaps are what determine spectral responsiveness. The only photons that will be absorbed and cause current to flow are those with energies greater than the energy gap. Free carriers can only be produced when radiation photons have enough energy to push electrons across the energy barrier. As a result, a semiconductor's ability to detect radiation at a certain wavelength has a limit.

3.2. Working principle

When light illuminates a photoconductor, photons with sufficient energy can excite electrons from the valence band to the conduction band, creating electron-hole pairs. In an intrinsic photoconductor, the excited electrons become free carriers, contributing to an increase in the material's electrical conductivity. However, the holes left behind in the valence band also contribute to the conductivity. See figure1.

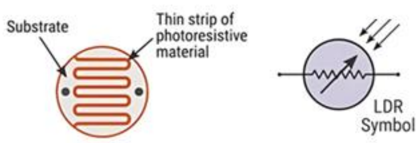


Fig 1. Photoconductor construction and symbol

The increase in conductivity due to light exposure can be explained by the creation of additional charge carriers that are available to participate in electrical conduction. The concentration of charge carriers is directly proportional to the intensity of light, meaning that the conductivity of the photoconductor increases as the light intensity increases.

The covalent bond can release an electron when an optical frequency of v, or $v = Eg/h$ photon is present. If this limiting condition were expressed in terms of wavelength, it would be $\lambda c = 1.24/Eg$. where λc is the maximum wavelength of light that can cause an electronic transition.

Energy gap is expressed in units of electron volts (eV).

In the dark or low-light conditions, the photoconductor has fewer free carriers, resulting in lower conductivity. When light is applied, the increased number of free carriers enhances the conductivity of the photoconductor, allowing it to conduct more electric current.

Photoconductors can be further categorized into two types based on their conductivity behaviour:

Intrinsic photoconductors: Intrinsic photoconductors are made of semiconducting materials with a low concentration of impurities. They exhibit increased conductivity when exposed to light due to the generation of electron-hole pairs.

Extrinsic photoconductors: Extrinsic photoconductors are doped with impurities to enhance their conductivity. The impurities introduce energy levels within the bandgap of the material, allowing for improved photo response. Doping can be done with elements like arsenic, antimony, or indium. See figure 2.

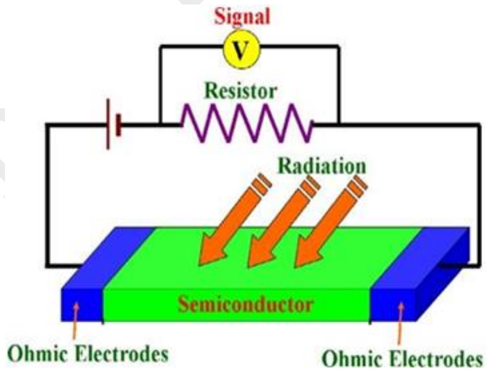


Fig 2. Schematic structure of Photoconductors

3.3. Applications

Light Sensors: Photoconductors are commonly used as light sensors in various applications. They can detect the presence and intensity of light and convert it into an electrical signal. These sensors are found in automatic lighting systems, light meters, and optical switches.

Photocopiers: In photocopiers, photoconductors play a crucial role in the process of electrostatic reproduction. The photoconductor is charged, and when exposed to light, it becomes conductive in the illuminated areas. This allows the transfer of toner particles to create a replica of the original document.

Imaging devices: Photoconductors are used in imaging devices like flatbed scanners and facsimile machines. These devices use the photoconductor to capture the optical image and convert it into an electrical signal, which can be processed and stored digitally.

Barcode scanners: Barcode scanners utilize photoconductors to detect the reflected light from the barcode. The varying reflectivity of the barcode lines changes the light intensity falling on the photoconductor, allowing the scanner to decode the barcode.

Xerography: Photoconductors are a fundamental component of xerographic processes used in laser printers and photocopiers. In these devices, a photoconductor drum is used to form an electrostatic image, which is then developed and transferred to paper.

3.3.1. Advantages of photoconductors:

High sensitivity to light: Photoconductors can exhibit high sensitivity to even low levels of light, allowing for accurate detection and measurement.

Fast response time: Photoconductors can rapidly respond to changes in light intensity, enabling real-time applications.

Broad spectral range: Different types of photoconductors can be designed to detect light across a wide range of wavelengths, including visible, ultraviolet, and infrared.

3.3.2. Limitations of photoconductors:

Dark current: Photoconductors can exhibit a small amount of electrical current even in the absence of light, known as dark current. This can affect the accuracy of light measurements and may require additional signal processing techniques.

Nonlinear response: The conductivity of photoconductors may not always have a linear relationship with light intensity, requiring calibration for accurate measurements.

Slow recovery time: In some photoconductors, there may be a delay in returning to their original state after exposure to light, which can limit their use in applications requiring fast response times.

Overall, photoconductors are versatile devices that find extensive use in various optoelectronic applications that require light detection, sensing, and imaging.

4. Junction photodiodes

Junction photodiodes are a type of semiconductor device that convert light energy into electrical current. They are widely used as light sensors in various applications, including optical communication systems, imaging devices, and light detection systems. Junction photodiodes operate based on the principle of the internal photoelectric effect and utilize the characteristics of a p-n junction.

Here is a detailed explanation of junction photodiodes:

4.1. Structure

Junction photodiodes are typically constructed using a p-n junction, which is formed by joining a p-type semiconductor material (with an excess of positively charged carriers or "holes") and an n-type semiconductor material (with an excess of negatively charged carriers or electrons). The p-n junction is carefully designed to have specific doping levels and material properties to optimize its light-detection capabilities. See figure 3.

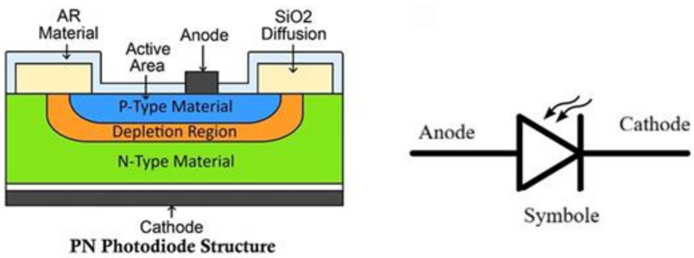


Figure 3: Photodiode

4.2. Working principle

When light strikes the surface of a junction photodiode, photons with sufficient energy can be absorbed, leading to the creation of electron-hole pairs within the depletion region of the p-n junction. The depletion region is a region near the junction where no free carriers are present due to the diffusion of carriers from the p-side to the n-side and vice versa.

The absorbed photons transfer their energy to the electrons in the valence band, allowing them to break free from their bonds and become free carriers. The electrons move towards the n-side of the junction, while the holes move towards the p-side, creating a photo-generated current. See figure 4

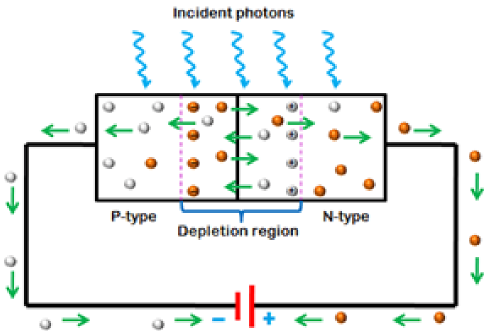


Fig 4. Working principle of Photodiode

The key concept in a junction photodiode is the internal electric field created by the p-n junction. This electric field separates the photo-generated electron-hole pairs, preventing recombination and allowing the collection of charges as a current. The larger the internal electric field, the more efficient the collection of charges and the higher the sensitivity of the photodiode.

To improve the performance of junction photodiodes, they are often operated in reverse bias mode. Applying a reverse bias voltage increases the width of the depletion region, enhancing the sensitivity of the photodiode by enlarging the region available for charge collection.

4.3. Responsivity and quantum efficiency

The performance of a junction photodiode is characterized by its responsivity and quantum efficiency.

Responsivity: Responsivity refers to the ratio of the output current to the incident optical power. It is usually expressed in amps per watt (A/W) and indicates the sensitivity of the photodiode. Higher responsivity values indicate greater sensitivity to light.

Quantum efficiency: Quantum efficiency represents the ratio of the number of photo-generated carriers to the number of incident photons. It is a measure of how efficiently the photodiode converts photons into electrons. Quantum efficiency is expressed as a percentage and can vary depending on the wavelength of light and the material properties of the photodiode.

4.4. Applications

Junction photodiodes find widespread use in various applications that require light detection and measurement. Some common applications include:

Optical communication systems: Junction photodiodes are used as receivers in fiber optic communication systems to convert optical signals into electrical signals.

Imaging Devices: Junction photodiodes are used in imaging devices such as digital cameras, scanners, and CCD (Charge-Coupled Device) sensors. They capture and convert light signals into electrical signals for image formation and processing.

Light Detection Systems: Junction photodiodes are employed in light detection systems for applications like environmental monitoring, industrial automation, and scientific instrumentation.

Medical Devices: Photodiodes are used in medical equipment such as pulse oximeters to measure oxygen saturation levels in blood.

4.4.1. Advantages:

High sensitivity: Junction photodiodes offer high sensitivity to light signals, enabling accurate detection even in low-light conditions.

Fast response time: Junction photodiodes can rapidly respond to changes in light intensity, making them suitable for applications requiring real-time measurements.

Wide spectral range: Different types of junction photodiodes

5. Pin photodiodes

PIN photodiodes are a type of semiconductor device that is widely used as a light detector in various applications, including optical communication systems, imaging devices, and light sensing applications. The name "PIN" is derived from the device's structure, which consists of a p-type region, an intrinsic (undoped) region, and an n-type region. PIN photodiodes are designed to provide high sensitivity, low noise, and fast response time. A modified PN-junction called a PIN-diode is used for particular applications. The initial application of the PN-junction diode was as a high-power, low-frequency rectifier in 1952 after it developed in the 1940s. The breakdown voltage for high-voltage applications can be greatly raised by the presence of an intrinsic layer. When the system uses high frequencies in the radio wave and microwave spectrum, this intrinsic layer also offers intriguing features. A PIN diode is a specific form of diode with a large, undoped intrinsic semiconductor region sandwiched between a P-type and N-type semiconductor region. Due to their role as Ohmic contacts, these regions are typically extensively doped. Contrary to a typical p-n diode, the broader intrinsic area is unaffected. The diode is manufactured.

Here is a detailed explanation of the working principle and structure of PIN photodiodes:

5.1. Structure

A PIN photodiode is constructed using three layers of semiconducting materials: a p-type layer(p+), an intrinsic layer, and an n-type layer(n+). The layers are typically made of materials such as silicon or germanium. The intrinsic layer, which is sandwiched between the p and n layers, has low doping levels and provides the active region for light absorption. See figure 5

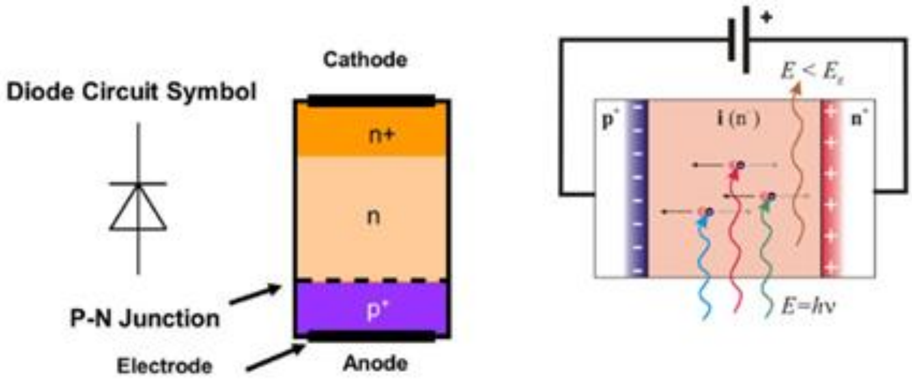


Figure 5: Symbol and structure of a PIN diode

5.2. Working principle

When light enters the device through the transparent window or the backside, photons with sufficient energy can be absorbed in the intrinsic region of the PIN photodiode. The absorbed photons transfer their energy to the electrons in the valence band, creating electron-hole pairs. The electric field present in the depletion region separates these photo-generated carriers.

The p-type and n-type regions of the PIN photodiode are heavily doped to provide a large number of free carriers. The high doping concentration results in a wider depletion region, which enhances the device's ability to absorb photons and increases the chance of carrier collection.

The intrinsic region, with its low doping concentration, serves two main purposes. Firstly, it reduces the number of recombination centres, minimizing the loss of carriers and maximizing the collection efficiency. Secondly, the intrinsic region provides a wider depletion region, allowing for a greater absorption depth and improving the device's sensitivity to light.

When the PIN photodiode is reverse biased by applying a voltage across the p and n regions (with the p-side connected to the positive terminal), an electric field is established across the intrinsic region. This electric field accelerates the photo-generated carriers towards the respective electrodes, creating a photocurrent.

The generated photocurrent is proportional to the intensity of the incident light. As more photons are absorbed, more electron-hole pairs are generated, resulting in a higher photocurrent.

5.3. Advantages of PIN photodiodes

High sensitivity: PIN photodiodes offer high sensitivity to light, making them suitable for low-light applications.

Low noise: The low doping concentration in the intrinsic region reduces the number of recombination centers, resulting in low noise levels.

Fast response time: PIN photodiodes have a relatively fast response time, enabling them to detect and respond to changes in light intensity quickly.

Wide spectral range: PIN photodiodes can be designed to detect a broad range of wavelengths, including visible, infrared, and ultraviolet.

5.4. Applications

PIN photodiodes find widespread use in various applications, including:

Optical communication systems: They are commonly used as receivers in fiber optic communication systems to convert optical signals into electrical signals.

Imaging devices: PIN photodiodes are used in digital cameras, CCD (Charge-Coupled Device) sensors, and imaging devices to capture and convert light signals into electrical signals for image formation and processing.

Light detection systems: PIN photodiodes are employed in light detection systems for applications like environmental monitoring, industrial automation, and scientific instrumentation.

Remote sensing: They are used in remote sensing applications to measure and analyze the properties of light reflected or emitted by Earth's surface or the atmosphere.

Medical devices: PIN photodiodes are used in medical equipment such as pulse oximeters and blood glucose monitors for light sensing and detection.

Overall, PIN photodiodes offer excellent sensitivity, low noise, and fast response time, making them a popular choice for a wide range of light detection and measurement applications.

6. Heterojunction diodes

Heterojunction diodes, also known as heterostructure diodes, are semiconductor devices that are formed by joining two different semiconductor materials with dissimilar bandgaps. The junction between these materials creates a heterojunction, which exhibits unique properties not found in homojunction diodes. Heterojunction diodes are used in various applications, including high-speed electronics, optoelectronics, and solar cells. Here is a detailed explanation of the advanced aspects of heterojunction diodes:

6.1. Structure and Types of Heterojunction Diodes

Heterojunction diodes consist of two semiconductor layers with different bandgap energies stacked together to form a junction. The materials used for these layers can be compound semiconductors such as GaAs (gallium arsenide), InP (indium phosphide), GaN (gallium nitride), or other combinations.

There are different types of heterojunction diodes based on the combination of materials used. Some common types include:

- Strained-layer Heterojunction Diodes: In strained-layer heterojunction diodes, one semiconductor layer is grown on top of another with a lattice mismatch. The strain resulting from the lattice mismatch alters the electronic band structure, leading to enhanced carrier transport properties.
- Type-I Heterojunction Diodes: Type-I heterojunction diodes have conduction and valence bands that align across the junction. As a result, the majority of the carriers are confined to one side of the junction, leading to unique charge transport properties.
- Type-II Heterojunction Diodes: Type-II heterojunction diodes have conduction and valence bands that do not align across the junction. This band offset causes carrier confinement in different regions of the heterojunction, enabling various applications such as efficient electron-hole separation in photovoltaic devices.

6.2. Working principle and advanced features

The unique properties of heterojunction diodes arise from the band offset and energy band alignment at the heterojunction. Here are some advanced features and working principles of heterojunction diodes:

- Band Engineering: Heterojunction diodes allow for precise control over the electronic band structure by selecting suitable materials with specific bandgap energies. This band engineering enables the design of devices with tailored properties such as improved carrier confinement, reduced leakage currents, and enhanced carrier transport.
- Enhanced Carrier Transport: Heterojunction diodes can exhibit improved carrier transport characteristics compared to homojunction diodes. This is achieved by carefully selecting materials with different bandgaps, effective masses, and carrier mobilities. The carrier confinement and reduced scattering can result in higher electron or hole velocities, leading to faster switching speeds and improved device performance.
- Reduced Forward Voltage Drop: Heterojunction diodes can have lower forward voltage drops compared to homojunction diodes. The band offset at the heterojunction facilitates more efficient carrier injection across the junction, resulting in reduced resistance and lower power dissipation.
- Tunnelling and Barrier Height Control: Heterojunction diodes with varying bandgap energies can exhibit different barrier heights at the heterojunction. This feature allows precise control over carrier tunneling processes, enabling applications such as resonant tunneling diodes (RTDs) with high-frequency performance.

6.3. Applications

Heterojunction diodes find applications in various advanced electronic and optoelectronic devices, including:

- **High-speed Electronics**: Heterojunction bipolar transistors (HBTs) and high-electron-mobility transistors (HEMTs) utilize heterojunction diodes to achieve high-frequency operation and low-power consumption. These devices are used in telecommunications, microwave amplifiers, and high-speed integrated circuits.

- **Optoelectronics**: Heterojunction diodes play a crucial role in the development of optoelectronic devices such as light-emitting diodes (LEDs), laser diodes, and photodetectors. The heterojunction enables efficient carrier injection and confinement, resulting in improved device efficiency and performance.
- **Solar cells**: Heterojunction solar cells, such as the heterojunction with intrinsic thin layer (HIT) solar cell, utilize the band offset and carrier confinement properties of heterojunction diodes to achieve high conversion efficiencies. The heterojunction enables efficient charge separation, reduced recombination, and improved light absorption, leading to enhanced solar cell performance.
- **Quantum well devices**: Heterojunction diodes are used in quantum well devices such as quantum well lasers and quantum cascade lasers. The precise control over the band structure and carrier confinement allows for the creation of narrow energy states and efficient emission of photons at specific wavelengths.

In summary, heterojunction diodes offer advanced features and capabilities due to the combination of different semiconductor materials. Their unique band alignment and carrier confinement properties make them well-suited for high-speed electronics, optoelectronic devices, and solar cells, among other applications.

7. Avalanche photodiodes

Avalanche photodiodes (APDs) are specialized semiconductor devices that are designed to detect light with high sensitivity by utilizing the avalanche effect. APDs are widely used in applications that require low-light detection, such as optical communication systems, lidar systems, and scientific instrumentation. They offer higher levels of sensitivity compared to standard photodiodes.

Here is a detailed explanation of the advanced aspects of avalanche photodiodes:

7.1. Structure and working principle

An avalanche photodiode consists of a p-n junction, similar to a regular photodiode, but with an additional region called the avalanche region. The avalanche region is typically formed by heavily doping the p-type or n-type layer, creating a high electric field. The PIN photodiode and the Avalanche photodiode are both constructed similarly. This diode includes two heavily doped & two lightly doped regions. P+ and N+ indicate heavily doped regions in this case, while I and P indicate lightly doped regions. See figure 6.

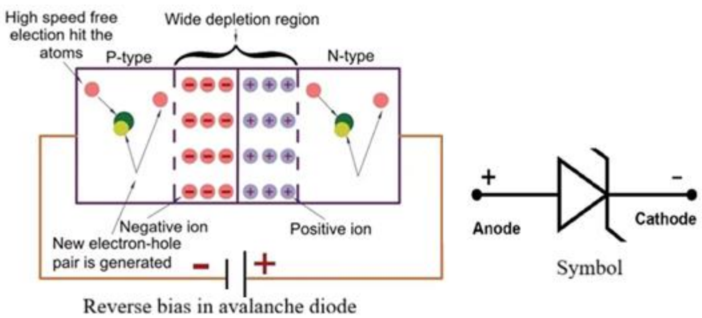


Fig 6: Symbol and Structure of Avalanche photodiode

As compared to other photodiodes, this one operates in a high reverse bias condition, allowing avalanche multiplication of the charge carriers generated by the light impact or photon, which allows the gain of the photodiode to be increased several times. In the intrinsic region, the depletion layer width is comparatively thinner in this diode than in the PIN photodiode.

The working principle of APDs is based on the avalanche multiplication process, which occurs when a high reverse bias voltage is applied across the p-n junction. When photons strike the depletion region of the APD, they generate electron-hole pairs. These carriers are accelerated by the high electric field in the avalanche region.

The electric field is high enough to cause impact ionization, where the accelerated carriers gain sufficient energy to ionize other atoms, creating additional electron-hole pairs. This process leads to an avalanche effect, where the number of carriers increases exponentially as they undergo successive ionization events.

The avalanche multiplication results in a significant increase in the photocurrent compared to a regular photodiode. This allows APDs to achieve higher levels of sensitivity and lower detection limits, making them suitable for applications where weak light signals need to be detected. See figure 7.

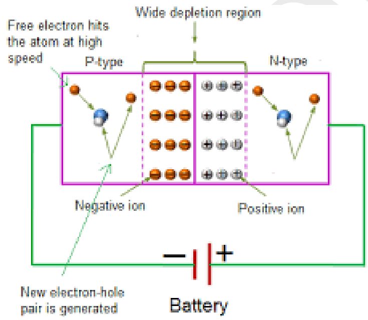


Fig 7. Working of an Avalanche diode

7.2. Advanced Features and characteristics

Gain: The avalanche multiplication process in APDs introduces gain, which is the ratio of the output current to the input current. APDs can achieve gain values ranging from 10 to several hundred or even thousands. The gain allows APDs to detect weak light signals that would be challenging for regular photodiodes.

High sensitivity: APDs offer higher sensitivity compared to conventional photodiodes. The avalanche multiplication enables the detection of low-light levels, making them ideal for applications in which signal-to-noise ratios are crucial.

Noise characteristics: APDs exhibit noise characteristics that are different from regular photodiodes. They are susceptible to excess noise caused by the avalanche process itself. This excess noise can be quantified by the excess noise factor (F). Efforts are made to reduce excess noise by optimizing the design and operating conditions of APDs.

High speed: Avalanche photodiodes can achieve high-speed response due to their internal gain mechanism. They are capable of detecting fast optical signals and can be used in high- speed optical communication systems.

Geiger Mode Operation: APDs can be operated in a mode called Geiger mode, where a single photon detection is possible. In Geiger mode, the APD operates in a switched-on state when a photon is detected, leading to a large output signal. This mode is particularly useful for applications such as single-photon counting and quantum key distribution.

7.3. Applications

Avalanche photodiodes find applications in various fields, including:

Optical communication systems: APDs are used as high-sensitivity receivers in long-range optical communication systems. They allow for extended transmission distances and improved signal quality.

Lidar systems: APDs are utilized in lidar systems for long-range and high-precision distance measurements, atmospheric sensing, and object detection.

Imaging and sensing: APDs can be used in low-light imaging applications such as night vision cameras, surveillance systems, and scientific instrumentation.

Quantum optics and photon counting: APDs operating in Geiger mode are employed in quantum optics experiments, single-photon counting, and other applications that require the detection of single photons.

In summary, avalanche photodiodes offer advanced features such as gain, high sensitivity, and the ability to detect low-light levels. Their unique design and operation make them well- suited for applications that require high-performance light detection in fields such as communications, sensing, and quantum optics.

8. Phototransistor

In a modern electrical circuit, different kinds of sensors are used. The photosensor is one of these sensors, used for sensing and keeping monitoring light intensity. Although it functions similarly to a photodiode as a type of photosensor, a phototransistor has an amplification factor. Using the intensity of the light, it increases the current between terminals.

Phototransistors are semiconductor devices that are widely used for light detection and amplification. They are essentially transistors with a light-sensitive region, allowing them to convert light signals into electrical signals. Phototransistors offer higher sensitivity and gain compared to photodiodes, making them suitable for applications where weak light signals need to be detected and amplified.

Phototransistor was invented in 1950 at bell telephone laboratories by Dr. John Northrup Shive. it was operated by light rather than electrical current.

Here is a detailed explanation of phototransistors:

8.1 Structure and working principle

A phototransistor is a light-controlled switch that switches a circuit and amplifies the current when exposed to light. Phototransistors are typically constructed using three semiconductor layers: the emitter, base, and collector. The base region is often made wider and less heavily doped compared to conventional transistors to enhance light absorption. When exposed to light, a phototransistor activates a circuit switch and increases current. A light-sensitive base at the bottom of a three-layer semiconductor device is visible. The current between the emitter and collector is amplified proportionately to the light's intensity when it strikes the base, increasing the current provided by a base current. They're employed for detecting fast- moving, minute light pulses. It is similar to BJT except for the exposed base instead of a terminal. See figure 8.

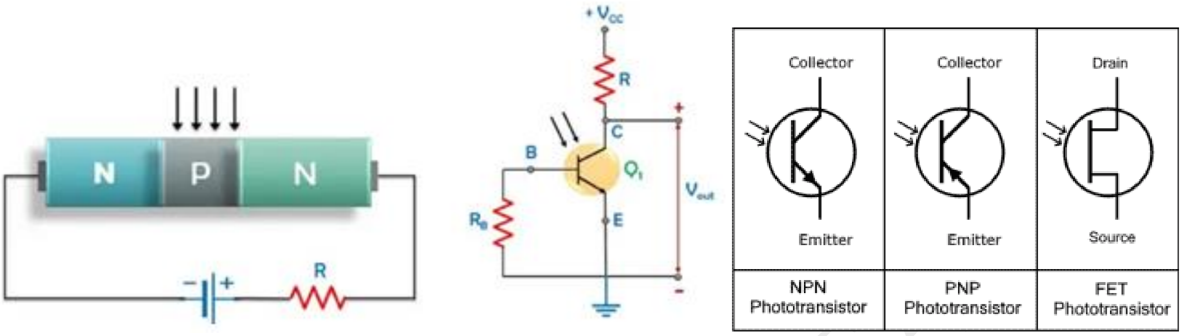


Figure 8: Phototransistor

The working principle of a phototransistor is similar to that of a regular transistor. When light strikes the base region, it generates electron-hole pairs. The photons transfer their energy to the valence electrons in the material, causing them to break free and create mobile charge carriers. If the base-emitter junction is forward-biased, the electrons from the base-emitter current flow into the base region. The presence of light increases the number of free carriers in the base region, leading to an increase in the base current. Therefore, the Phototransistor is 100 times more sensitive than the photodiode. The base current is generated on the principle of the photovoltaic effect. The amplified base current controls the flow of current from the collector to the emitter, resulting in an amplified output current. The collector current is proportional to the intensity of the incident light, allowing the phototransistor to detect and amplify light signals.

In NPN phototransistors, the collector is maintained at a greater voltage with respect to the emitter during biasing, whereas in PNP phototransistors, the collector is maintained at a lower voltage to the emitter. Furthermore, the collector to the base junction is reverse biased.

In the case of three lead phototransistors, the base terminal must be left unconnected or open otherwise, it will operate as a normal transistor.

A small reverse saturation current or leakage current known as dark current exists in the absence of light and is directly proportional to temperature, just like in photodiodes. The photovoltaic effect creates a base current when light strikes the phototransistor, focusing the light onto the collector-base junction. The base current is amplified hundreds of times.

8.2. Modes of operation

The phototransistor, like the BJT, can function in either linear or active and switch mode. Linear or Active Mode:

The output current is directly proportional to the intensity of the incident light while operating in linear mode. In practical terms, the response takes the form of a curve and is not very linear.

As a result, the correct term for this mode is Active mode. This mode is used for its amplification factor. The gain of the transistor determines how much the generated base current is amplified.

8.2.1. Switch mode:

In switch mode operation, the phototransistor operates in one of two states—"Off" or "On"—just like a switch. Therefore, the name is switch mode. Due to the non-linear response of the phototransistor to the light, this mode is typically used. The device is said to be in an "Off" state when there is no base current and no light. The output current increases as the light intensity increases. There comes a point when the device is saturated and the increase in light intensity has no effect on the output current. & It is said that the device is in the "On" state.

Just like a digital switch, it operates on two levels. Due to the non-linear nature of the active region, this mode is used for decoding, sending, object detection, signal conversion, etc.

8.3 Circuit configuration

It can be used in either common emitter or common collector configuration.

8.3.1. Common emitter:

In this configuration, as shown in the figure below, the collector is connected to the voltage source through a load resistor Rc, and the output is obtained from the collector. With the detection of light, the output voltage switches from a high to a low state. It is a frequently used configuration that acts as an amplifier. See figure 9

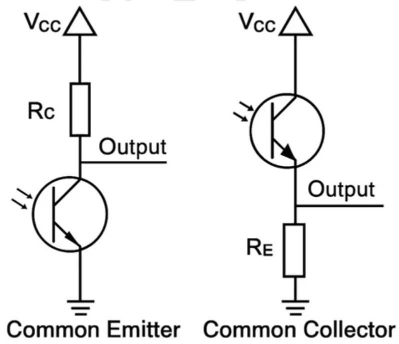


Figure 9: Common emitter and common collector configuration

8.4. Types of phototransistors

There are two main types of phototransistors:

NPN Phototransistors: In NPN phototransistors, the base region is p-type, and the emitter and collector regions are n-type. The light absorption occurs in the base region, and the generated carriers contribute to the base current, which controls the collector current.

PNP Phototransistors: In PNP phototransistors, the base region is n-type, and the emitter and collector regions are p-type. The operation and light absorption principles are similar to NPN phototransistors, but the carrier types are reversed.

FET Phototransistor: A field effect transistor (FET) phototransistor is one that has a light-sensitive channel but no junction. Either N-channel or P-channel can be used. Source and Drain are the names of its two terminals. From a construction standpoint, drain and source are interchangeable. With respect to the source, the drain is positive. The drain current is controlled by the incident light. Because of its quick switching, it can be used in high-frequency applications. However, it allows low current and gain.

8.5. Performance parameters

There are certain parameters that define the performance of the phototransistor. These parameters must be kept in mind when choosing a phototransistor to provide cost-efficient performance.

Current collector I_C: The collector current is the maximum allowed load current. If the load current is exceeded, the phototransistor could experience permanent damage.

Base current: The base current represents the current produced by incident light. It depends on the size of the base region. The capacitance, which affects switching speed, rises as the area of base region increases.

Dark current I_D: it is the leakage current between collector and emitter when there is no light. It is very small in milliamps. Ideally, it is meant to conduct no current. But due to temperature it never shut off completely. Dark current inversely affects the performance.

V_{CE} breakdown voltage: it is the maximum voltage applied between the collector and emitter. If the applied voltage exceeds the breakdown voltage, the device is permanently damaged.

V_{EC} breakdown voltage: it is the maximum allowed voltage applied between emitter and collector. It is relatively very lower than VCE breakdown voltage

Wavelength: Different photoconductive materials show different responses to a spectrum of wavelengths. They show high sensitivity and conversion efficiency at a narrow range of wavelengths. Therefore, the wavelength of the incident light is very important to have higher energy conversion.

Linearity: Linearity means how linearly the output current varies with change in light intensity. Linear response is precise and error-free. Therefore, it is necessary to know the linearity of the device.

8.6. Characteristics and advantages

Collector Characteristics of Phototransistor: The relationship between the collector-to- emitter voltage VCE and the collector current IC at different levels of light intensity is shown in the following graph. The voltage across the collector and emitter is shown on the x-axis, while the collector current is shown on the y-axis. See figure 10.

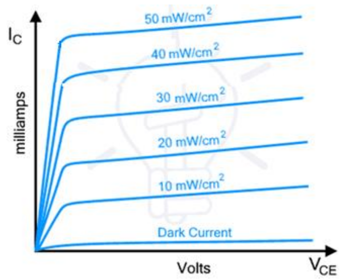


Fig.10: Collector characteristic of Phototransistor

Its characteristic curve is similar to that of BJT with the difference that the gain is controlled by the intensity of the light. With increasing light intensity, the collector current increases. There is a small leakage current or dark current when there is no light.

Spectral Response of Phototransistor: A small range of wavelengths is where phototransistors work at their best as they are made of a photoconductive material that does not respond to all wavelengths. The graph below illustrates how a phototransistor's spectral response relates to its percentage response in terms of wavelength. See figure 11.

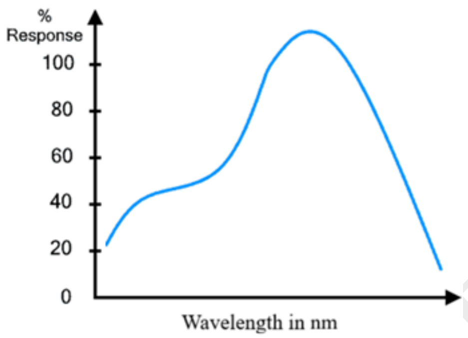


Fig.11: Spectral response of Phototransistor

8.6.1. Advantages:

Higher sensitivity: Phototransistors offer higher sensitivity compared to photodiodes. The amplification provided by the transistor configuration allows for the detection of weaker light signals.

Amplification: Phototransistors can amplify the weak current generated by the light signals, making them suitable for applications that require signal amplification.

Gain: Phototransistors exhibit gain, which is the ratio of the output current to the input current. The gain can be controlled by adjusting the biasing conditions of the transistor.

Response time: Phototransistors have relatively fast response times, enabling them to detect and respond to changes in light intensity quickly.

Configurability: Phototransistors can be used in various configurations such as common-emitter, common-base, or common-collector, allowing for flexibility in circuit design.

8.7. Applications

Phototransistors find applications in a wide range of fields, including:

Optical communication systems: Phototransistors are used as receivers in fiber optic communication systems to convert optical signals into electrical signals for further processing.

Light Sensing and detection: Phototransistors are utilized in light sensing applications such as light barriers, optical switches, light meters, and ambient light detectors.

Imaging devices: Phototransistors can be used in imaging devices, such as scanners and barcode readers, for light detection and image formation.

Industrial automation: Phototransistors are employed in industrial automation for tasks such as object detection, position sensing, and assembly line monitoring.

9. Metal semiconductor -metal photodiode

A metal-semiconductor-metal (MSM) photodiode is a type of photodetector that consists of two metal electrodes separated by a semiconductor material. It is designed to convert light signals into electrical signals and is commonly used in high-speed optical communication systems, photonic integrated circuits, and other applications requiring fast and sensitive light detection. Here is a detailed explanation of the MSM photodiode:

9.1. Structure and Working Principle

The structure of an MSM photodiode consists of two metal electrodes, typically made of materials such as titanium (Ti), platinum (Pt), or gold (Au), separated by a thin layer of semiconductor material, such as silicon (Si) or III-V compounds like gallium arsenide (GaAs). The distance between the electrodes is typically on the order of micrometers.

When light strikes the surface of the MSM photodiode, it generates electron-hole pairs within the semiconductor material. The incident light is absorbed in the depletion region or the active region of the semiconductor layer, depending on the specific design.

The two metal electrodes, often referred to as the Schottky contacts, create a built-in electric field within the semiconductor material. The electric field serves two main purposes: to separate the generated electron-hole pairs and to facilitate the collection of charge carriers by the metal electrodes.

The metal electrodes are typically designed with interdigitated fingers or asymmetric shapes, creating a series of parallel or interleaved Schottky junctions. This design allows for efficient collection of carriers generated in the semiconductor layer.

When, the photodiode is biased with a voltage, a current flows through the device. The incident light generates photocurrent, which is directly proportional to the intensity of the light. The metal electrodes collect the photogenerated carriers and transport them to the external circuit for further processing.

9.2. Advanced Features and Advantages

High-Speed Operation: MSM photodiodes are capable of operating at high speeds due to their low capacitance and short transit time of carriers. They are suitable for applications requiring high-speed light detection and demodulation.

Broadband Response: MSM photodiodes offer a wide spectral response range, from ultraviolet (UV) to infrared (IR) wavelengths, depending on the choice of semiconductor material. This makes them versatile for various applications across the electromagnetic spectrum.

Low Dark Current: Dark current refers to the current flowing through a photodiode in the absence of light. MSM photodiodes can achieve low dark currents, resulting in improved signal-to-noise ratios and sensitivity.

Ease of Fabrication: MSM photodiodes are relatively simple to fabricate using standard semiconductor manufacturing processes. The planar structure and the absence of complex pn-junctions simplify the fabrication and integration of the devices in photonic integrated circuits.

9.3. Applications

MSM photodiodes find applications in various fields, including:

Optical Communication Systems: MSM photodiodes are used as high-speed receivers in fiber-optic communication systems for data transmission and demodulation.

Optical Sensing and Detection: They are used in optical sensing applications such as optical position sensing, beam profiling, and optical time-domain reflectometry (OTDR).

Photonic Integrated Circuits: MSM photodiodes are integrated into photonic integrated circuits for optical signal processing, including modulation, demodulation, and wavelength conversion.

Optical Interconnects: They are used in high-speed optical interconnects for data communication between electronic components and integrated circuits.

In summary, metal-semiconductor-metal (MSM) photodiodes offer high-speed operation, broad spectral response, and low dark currents. They are widely used in optical communication systems, photonic integrated circuits, and various optical sensing applications.

10. Summary

In this unit, you have studied the different optoelectronic detectors. Photoconductors have been discussed. Different types of photodiodes such as Junction photodiode, PIN photodiode, Heterojunction photodiode, Avalanche photodiode, Modulated barrier photodiode and Metal-semiconductor-metal photodiode have been explained in detail. Explanation of phototransistors was given in detail.

11. Lexicon

1. Tunnelling- barrier penetration

2. Avalanche- a sudden increase in the flow of an electrical current through a nonconducting or semiconducting solid

3. Sensitivity- the ratio of the changes in the output of an instrument to a change in the value of the quantity being measured

4. Photonic- the branch of technology concerned with the properties and transmission of photons

5. Optical-connected with the sense of sight

6. Domain- an area of knowledge or activity

7. Depletion- a reduction in something

8. Saturation- a physical and chemical state where a system can take no more.

9. Detector- an instrument used to detect or identify high-energy particles

10. Fabrication- the action or process of manufacturing or inventing something

12. References

1. Holger T. Grahn, Introduction to Semiconductor Physics, World Scientific Publishing Co Pte Ltd.

2. S.M. Sze and Kwok K. Ng, Physics of Semiconductor Devices, John Wiley & Sons.

3. Simon M. Sze and Ming-Kwei Lee, Semiconductor Devices: Physics and Technology, Wiley, New York.

4. Otfried Madelung, Semiconductors: Basic Data, Springer.

5. Donald A. Neamen, Semiconductor Physics and Devices: Basic Principles, McGraw

Hill.

6. Dereniak and Crowe, Optical Radiation Detectors, 1984, Wiley, New York.

7. https://www.electricaltechnology.org/2022/08/phototransistor

13 Suggested readings

1. S.M. Sze, Semiconductor Devices - Physics and Technology, Wiley, New York.

2. J. Singh, Semiconductor Optoelectronics: Physics and Technology, McGraw Hill.

3. P. Bhattacharya, Semiconductor Optoelectronic Devices, Pearson Education,

4. J. Singh, Optoelectronics: An Introduction to Materials and Devices, Tata McGraw Hill.

5. Donald A. Neamen, Semiconductor physics and devices, McGraw Hill, 3rd Edition.

14 Terminal questions

1. What are Photoconductors? Explain the working principle and characteristics of Photoconductors.

2. Explain the structure, working and characteristics of a Junction Photodiode. What are its applications?

3. What do you understand by a PIN Photodiode? Explain its working principle and characteristics.

4. Explain the structure, working and characteristics of an Avalanche Photodiode. What are its applications?

5. What are Phototransistors? Explain the working principle and characteristics of Phototransistors. Also explain its applications.

6. Explain working principle and characteristics of a metal-semiconductor- metal Photodiode.

Chapter 4: Photovoltaic devices

1. Introduction

So far, time-independent perturbations and only periodic time dependent perturbations have been considered. One of the general time-dependent difficulties in quantum mechanics is the on/off switching of a perturbing factor, such as an external field. In general, solving the details of turning on or off time-dependent disturbances is too difficult. The abrupt and adiabatic approximations, however, are two significant limiting situations that may be examined in depth and with some degree of accuracy.

2. Objectives

After studying this unit, you should be able to-

- Explain Solar Energy Spectrum
- Describe device principles of Solar cell
- Understand I-V characteristics of Photovoltaic devices
- Understand equivalent circuits
- Explain efficiencies of photovoltaic devices

3. Solar energy spectrum

Solar energy spectrum refers to the distribution of electromagnetic radiation emitted by the Sun across a wide range of wavelengths. The Sun emits radiation across the entire electromagnetic spectrum, from ultraviolet (UV) to visible light to infrared (IR) wavelengths. Understanding the solar energy spectrum is crucial for harnessing solar energy for various applications, such as solar power generation and solar thermal systems. Here is a detailed explanation of the solar energy spectrum:

3.1. Ultraviolet (UV) Radiation:

The solar spectrum begins with ultraviolet (UV) radiation, which has shorter wavelengths and higher energy than visible light. UV radiation is typically divided into three regions:

UVA (315-400 nm): Also known as long-wave UV, UVA radiation is responsible for tanning and aging effects on the skin. It has lower energy than other UV regions.

UVB (280-315 nm): UVB radiation causes sunburn and plays a role in the synthesis of vitamin D in the human body. It has higher energy than UVA radiation.

UVC (100-280 nm): UVC radiation is the most energetic and damaging form of UV radiation. Fortunately, it is almost entirely absorbed by the Earth's atmosphere and does not reach the surface.

3.2. Visible Light:

The visible light spectrum ranges from approximately 400 to 700 nanometres (nm). It consists of different colours, each corresponding to a specific wavelength. The colours of the visible spectrum, in order of increasing wavelength, are violet, blue, green, yellow, orange, and red. Visible light is the region of the solar spectrum that is most easily detected by the human eye.

3.3. Infrared (IR) radiation:

Beyond the visible light range, the solar spectrum extends into the infrared (IR) region. IR radiation has longer wavelengths and lower energy than visible light. It is further divided into three main regions:

- Near-Infrared (NIR) (700-1400 nm): NIR radiation is often used in remote sensing applications, such as vegetation monitoring, as it provides valuable information about plant health and composition.
- Mid-Infrared (MIR) (1400-3000 nm): MIR radiation is commonly used in spectroscopy and thermal imaging applications. It can provide insights into molecular vibrations and heat signatures.
- Far-Infrared (FIR) (3000 nm - 1 mm): FIR radiation is associated with heat and thermal energy. It is used in applications such as thermal imaging, heat detection, and astronomy. See figure 1.

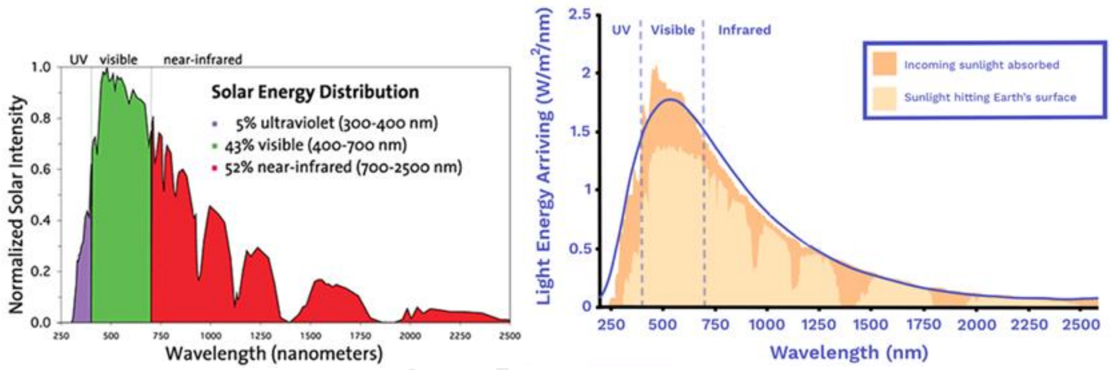


Fig 1: Solar Energy Distribution and solar radiation spectrum

3.3.1. Solar Spectrum Intensity:

The intensity of solar radiation varies across the spectrum. The distribution of intensity is influenced by factors such as the Sun's temperature and atmospheric conditions. The solar spectrum is often represented by the Solar Irradiance Spectrum, which shows the amount of solar energy received per unit area per unit time at each wavelength or frequency.

The solar spectrum is not constant and can vary depending on factors such as the time of day, latitude, altitude, atmospheric conditions, and solar activity. Additionally, the Earth's atmosphere filters and absorbs certain portions of the solar spectrum, affecting the amount and type of radiation that reaches the surface.

3.3.2. Applications:

Understanding the solar energy spectrum is essential for various applications, including:

Solar Power Generation: Solar photovoltaic (PV) systems convert sunlight into electricity. PV cells are designed to efficiently capture and convert photons from the solar spectrum, particularly in the visible and near-infrared regions.

Solar Thermal Systems: Solar thermal systems capture solar energy in the form of heat. They utilize the entire solar spectrum, including the visible and infrared regions, to heat water, generate steam, or provide space heating.

Solar Radiation Measurements: Understanding the solar spectrum helps in accurately measuring solar radiation for meteorological, climatological, and solar energy system design purposes.

Solar Spectroscopy: Spectroscopy techniques utilize different regions of the solar spectrum to analyse and study the composition, temperature, and properties of various celestial objects, including the Sun.

In summary, the solar energy spectrum encompasses a wide range of electromagnetic radiation emitted by the Sun, including ultraviolet, visible, and infrared radiation. This spectrum is crucial for harnessing solar energy through various technologies and applications.

4. Device principles

Photovoltaic (PV) cells, also known as solar cells, are semiconductor devices that convert sunlight directly into electrical energy. They are the fundamental building blocks of solar panels and play a crucial role in generating renewable solar power. The device principles of photovoltaic cells involve the interaction of light with semiconductors, the generation and separation of charge carriers, and the creation of an electric current. Here is a detailed explanation of the device principles of photovoltaic cells:

4.1. Semiconductor material:

Photovoltaic cells are typically made of semiconductor materials, most commonly silicon (Si). Silicon is abundant, cost-effective, and has suitable electronic properties for PV applications. Other semiconductor materials, such as gallium arsenide (GaAs) and cadmium telluride (CdTe), are also used in specific PV technologies.

4.2. PN junction:

The basic structure of a PV cell involves the creation of a PN junction within the semiconductor material. This junction is formed by doping one region of the semiconductor with a p-type dopant (electron acceptor) and another region with an n-type dopant (electron donor). The p-type region has an excess of positively charged holes, while the n-type region has an excess of negatively charged electrons.

4.3. Absorption of photons:

When sunlight, which is composed of photons, strikes the surface of the PV cell, the semiconductor material absorbs some photons. The energy of the absorbed photons must be higher than the bandgap energy of the semiconductor for absorption to occur. The bandgap energy determines the wavelengths of light that can be effectively absorbed.

4.4. Generation of electron-hole pairs:

The absorbed photons transfer their energy to the valence electrons in the semiconductor material, allowing them to break free from their bonds and creating electron-hole pairs. The electrons are excited from the valence band to the conduction band, leaving behind positively charged holes in the valence band.

4.5. Electric field:

The p-n junction creates an electric field due to the difference in charge carriers on either side of the junction. The positively charged holes in the p- region are attracted to the negatively charged electrons in the n-region, resulting in the formation of the electric field.

4.6. Separation and collection of charge carriers:

The electric field at the p-n junction facilitates the separation of the generated electron-hole pairs. The negatively charged electrons are repelled towards the n-region, while the positively charged holes are repelled towards the p-region. This separation prevents immediate recombination of the charge carriers.

4.7. Formation of an electric current:

As the separated charge carriers move towards their respective regions, an electric current is generated. The electrons flow through an external circuit from the n-region to the p-region, creating the desired electrical power. This flow of electrons constitutes the photovoltaic effect and is the basis for generating electricity in PV cells.

4.8. Conductive contacts:

To extract the generated current efficiently, metallic contacts are placed on the top and bottom surfaces of the PV cell. These contacts collect the electrons and holes from the respective regions and provide the pathways for the generated current to flow.

4.9. External load:

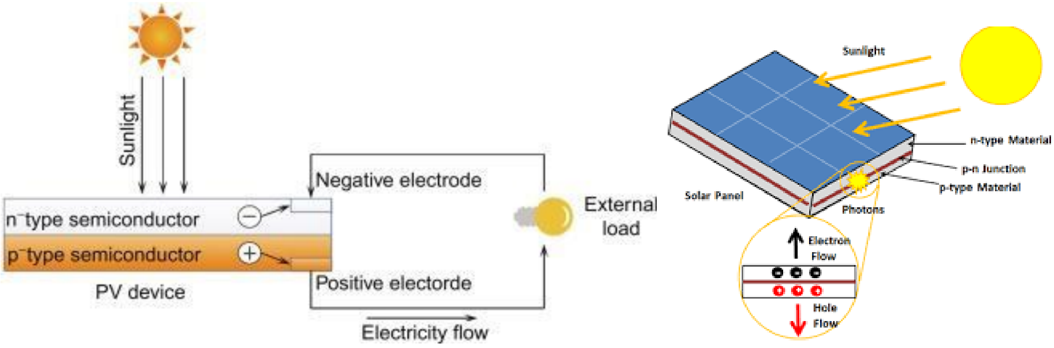
The generated electric current can be used to power electrical devices or stored in batteries. By connecting, an external load to the PV cell, current flows through the load, supplying power for various applications.

4.10. Efficiency and performance:

The efficiency of a PV cell is a measure of how effectively it converts sunlight into usable electrical energy. The efficiency depends on several factors, including the semiconductor material, cell design, light management, and manufacturing processes. Researchers continually strive to improve PV cell efficiency to maximize energy conversion and reduce costs.

4.11. PV Module and system:

PV cells are typically interconnected and encapsulated in a PV module (solar panel) to form larger arrays. Multiple PV modules can be combined to create PV systems capable of generating significant amounts of electricity for residential, commercial, and utility-scale applications. See figure 3.



(a) (b)

Fig 3: (a) Photovoltaic Effect (b) Photovoltaic cell

In conclusion, photovoltaic cells harness the principles of semiconductor physics to convert sunlight into electrical energy. The absorption of photons, generation of electron-hole pairs, separation of charge carriers, and the creation of an electric current enable the direct conversion of solar energy into usable power. PV cells are at the forefront of renewable energy technologies and continue to advance in efficiency and affordability, driving the transition towards sustainable solar power generation.

5. Current-Voltage (I-V) characteristics

The current-voltage (I-V) characteristics of photovoltaic (PV) devices(cells) describe the relationship between the generated electrical current and the applied voltage across the device. These characteristics are fundamental in understanding the performance and behavior of PV devices, including solar cells and modules. The I-V characteristics provide insights into the device's efficiency, power output, and operating conditions. Here is a detailed explanation of the current-voltage characteristics of photovoltaic devices:

- **Open Circuit Voltage** ($\boldsymbol{V_{oc}}$): The open circuit voltage (Voc) is the voltage across the
- PV device when no external load is connected, and no current is flowing. At this point, the generated current is zero, and the maximum voltage is obtained. The open circuit voltage represents the maximum potential voltage that the device can produce.
- **Short Circuit Current** ($\boldsymbol{I_{sc}}$) The short circuit current (Isc) is the current flowing through the PV device when the voltage across it is zero (short-circuited). At this point, the generated voltage is zero, and the maximum current is obtained. The short circuit current represents the maximum current that the device can produce.
- **Fill Factor (FF):** The fill factor (FF) is a key parameter in the I-V characteristics and is defined as the ratio of the maximum power point (P_{max}) to the product of $\boldsymbol{V_{oc}}$ and $\boldsymbol{I_{sc}}$. Mathematically, $FF = P_{max} / (\boldsymbol{V_{oc}} \times \boldsymbol{I_{sc}})$. The fill factor provides an indication of how effectively the PV device utilizes the available voltage and current.
- **Maximum Power Point (**P_{max}**):** The maximum power point (P_{max}) corresponds to the operating point at which the PV device delivers the maximum electrical power. It occurs at a specific combination of voltage (V_{MP}) and current (I_{MP}). P_{max} is the product of (V_{MP}) and (I_{MP}).
- **Efficiency**: The efficiency of a PV device is a measure of how effectively it converts sunlight into electrical energy. It is determined by the ratio of the maximum power output (P_{max}) to the incident solar power (P_{in}). Mathematically, $Efficiency = P_{max} / P_{in}$.

- The I-V characteristics help determine the efficiency of the device by providing information about the power output at different voltage and current levels.
- **Operating Point**: The operating point of a PV device corresponds to the specific combination of voltage and current at which the device operates under given external conditions. The operating point depends on the load connected to the device. It is essential to find the optimal operating point for maximum power output and efficiency.
- **Shading Effects**: Shading or partial shading of a PV device affects its I-V characteristics. When a portion of the device is shaded, it reduces the amount of incident light, resulting in reduced current output. Shading causes a non-linear response in the I-V curve, with a drop in current and power output.
- **Temperature Effects**: Temperature also influences the I-V characteristics of PV devices. As the temperature increases, the current output typically increases due to increased carrier generation. However, the voltage output decreases due to increased recombination losses. Therefore, temperature variations can affect the overall performance and efficiency of the PV device.
- **I-V Curve Shapes**: The shape of the I-V curve varies depending on the type of PV device and its characteristics. Different technologies, such as crystalline silicon, thin- film, and multi-junction solar cells, exhibit unique I-V curve shapes. Factors such as material properties, fabrication techniques, and device design influence the I-V curve shape.
- **Non-Ideal Effects**: Non-ideal effects, such as series and shunt resistances, can also influence the I-V characteristics of PV devices. Series resistance (Rs) is the resistance

encountered by the current flow within the device, while shunt resistance (Rsh) represents undesired leakage paths. These resistances can result in power losses and affect the overall performance of the device.

- **I-V Measurement and Analysis**: To obtain the I-V characteristics of a PV device, it is typically subjected to controlled external conditions, and measurements are made at various voltage levels. These measurements help analyze the performance of the device, evaluate its efficiency, and determine its suitability for specific applications.

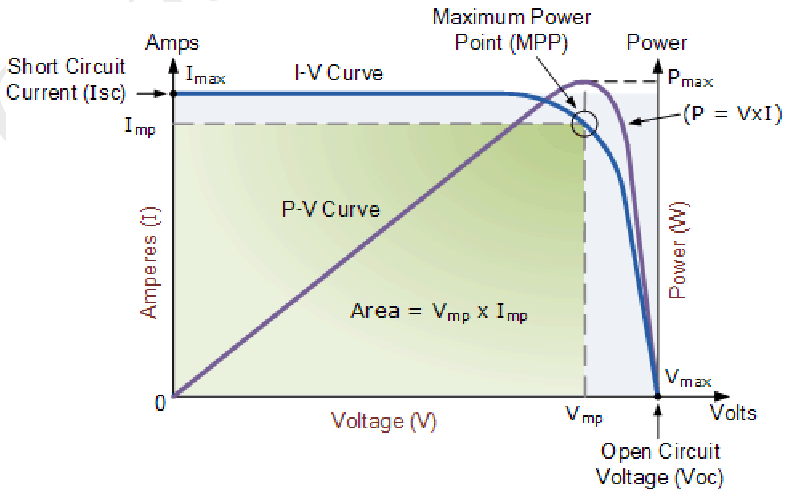


Fig 4: I-V characteristics of a Photovoltaic cell

Understanding the current-voltage characteristics of photovoltaic devices is essential for assessing their performance, optimizing their operation, and designing efficient PV systems. By analyzing the I-V curves, researchers and engineers can evaluate the device's efficiency, power output, and operating conditions, enabling the development of more advanced and efficient solar energy technologies.

6. Equivalent circuits

Equivalent circuits are electrical models that represent the behavior of photovoltaic (PV) devices, such as solar cells and modules, in a simplified form. These circuits provide a useful tool for analyzing and understanding the electrical characteristics and performance of PV devices. Here, we will discuss two commonly used equivalent circuits: the single-diode model and the double-diode model.

- **Single-Diode Model**: The single-diode model is a widely used and relatively simple representation of a PV device. It consists of a current source (I_{ph}) representing the photocurrent generated by the device, a diode representing the junction behavior, a series resistance (R_s) and a shunt resistance (R_{sh}) accounting for non-ideal effects, and an external load resistor (R_L)) representing the connected load. See figure 5.

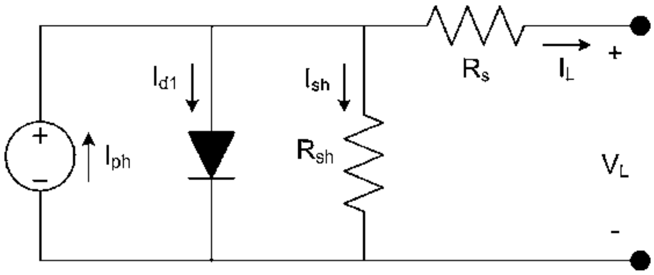


Fig 5: The equivalent circuit diagram of the single-diode model

The current source (I_{ph}) represents the photocurrent generated by the device under illumination. The diode models the junction behavior, representing the non-linear current-voltage relationship. The series resistance (R_s) accounts for the resistance encountered by the current flow within the device, while the shunt resistance (R_{sh}) represents any undesired leakage paths. The external load resistor (R_L) represents the connected load.

The single-diode model allows for the calculation of various parameters, such as the open circuit voltage (V_{oc}) the short circuit current (I_{sc}), and the maximum power point (P_{max}). It also provides insights into the impact of non-ideal effects, such as series resistance and shunt resistance, on the device's performance.

- **Double-Diode Model**: The double-diode model is a more advanced representation of PV devices, offering improved accuracy for analyzing their electrical behavior. It accounts for additional phenomena, such as recombination and ideality factor variations. The double-diode model includes two diodes (D1 and D2) and additional components similar to the single-diode model. See figure 6

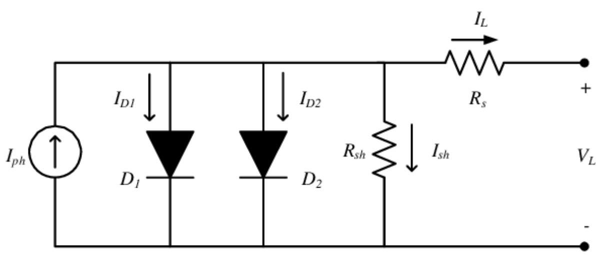


Fig 6: The equivalent circuit diagram of the double-diode model

In the double-diode model, D1 represents the main junction behavior, while D2 represents additional recombination paths. The additional components, including series resistance (Rs), shunt resistance (Rsh), and the load resistor (RL), are similar to the single-diode model.

The double-diode model provides more accurate predictions of the device's electrical characteristics, such as voltage and current responses, and can better account for the impact of recombination and other non-ideal effects. It is particularly useful for analyzing devices with complex structures or materials, such as multi-junction solar cells.

It's important to note that these equivalent circuit models are simplified representations of the complex electrical behavior of PV devices. While they offer valuable insights and analysis capabilities, they may not capture all the nuances and intricacies of the actual device. The accuracy of the models can vary depending on the specific device characteristics and operating conditions. Nonetheless, the equivalent circuit models serve as practical tools for understanding and analyzing the electrical performance of PV devices.

7. Temperature effects on photovoltaic devices

Temperature has a significant impact on the performance and efficiency of photovoltaic (PV) devices, including solar cells and modules. Understanding the temperature effects is crucial for accurate system design, performance prediction, and optimization. Here is a detailed explanation of the temperature effects on photovoltaic devices:

- **Temperature Coefficient of Voltage (TCV)**: The voltage output of PV devices decreases with increasing temperature. This is captured by the temperature coefficient of voltage (TCV), which represents the percentage change in voltage per degree Celsius. The TCV is typically negative, indicating a decrease in voltage with increasing temperature. The TCV is an important parameter for estimating the decrease in voltage output due to temperature rise.
- **Temperature Coefficient of Current (TCC):** The current output of PV devices is also affected by temperature changes. The temperature coefficient of current (TCC) represents the percentage change in current per degree Celsius. The TCC can be positive or negative, depending on the device's characteristics. Generally, crystalline silicon-based solar cells have negative TCCs, indicating a decrease in current with increasing temperature.
- Temperature Coefficient of Power (TCP): The temperature coefficient of power (TCP) represents the percentage change in power output per degree Celsius. It combines the TCV and TCC to provide an indication of how the power output of the device is affected by temperature changes. The TCP is typically negative, reflecting the decrease in power output with increasing temperature.
- **Reduction in Voltage and Power Output**: As the temperature rises, the output voltage and power of PV devices decrease. This reduction is primarily attributed to
- the increase in the saturation current of the diode within the device. The increase in temperature leads to more electron-hole pairs being thermally generated, resulting in increased recombination and reduced output current. The reduced voltage and power output due to temperature effects need to be considered in system design and performance estimation.

- **Impact on Maximum Power Point (MPP):** The maximum power point (MPP) of PV devices, represented by the voltage and current combination that yields the highest power output, is also affected by temperature. The MPP tracking algorithm in PV systems needs to adjust the operating point according to the temperature to maintain optimal power generation. This adjustment compensates for the changes in voltage and current caused by temperature variations.
- **Impact on Efficiency**: The efficiency of PV devices is influenced by temperature changes. The efficiency represents the ratio of the output power to the input solar power. As the temperature rises, the decrease in voltage and power output reduces the overall efficiency. It is important to consider temperature effects when evaluating the performance and efficiency of PV devices.
- **Thermal Management**: Temperature management is crucial for maintaining the performance and longevity of PV devices. High operating temperatures can accelerate aging and degradation processes, leading to reduced efficiency and reliability. Proper thermal management techniques, such as heat sinks, ventilation, and cooling methods, are employed to mitigate the adverse effects of temperature and maintain optimal operating conditions.
- **Performance in Extreme Temperatures**: PV devices exhibit different behaviors at extremely high or low temperatures. High temperatures can cause thermal runaway and accelerated degradation, leading to performance losses. On the other hand, extremely low temperatures can decrease the conductivity of materials, increase resistive losses, and reduce the performance of PV devices. PV devices are designed to operate within specific temperature ranges to ensure optimal performance and longevity.
- Th**ermal Coefficient**: The thermal coefficient represents the change in the electrical parameters of PV devices with temperature. It includes the temperature coefficients of voltage, current, and power. Manufacturers provide specifications regarding the thermal coefficient to assist in performance estimation and system design.
- **Temperature-Dependent Efficiency Models**: To accurately estimate the performance of PV systems under varying temperature conditions, temperature-dependent efficiency models are used. These models incorporate temperature effects on voltage, current, and power to predict the performance accurately and optimize system design and energy output.

In conclusion, temperature has a significant impact on the performance and efficiency of photovoltaic devices. Understanding the temperature effects is crucial for accurate performance estimation, system design, and optimization. Proper thermal management techniques and consideration of temperature-dependent characteristics are necessary to maintain optimal performance and maximize the energy output of PV systems.

8. Materials

Photovoltaic (PV) devices, such as solar cells and modules, employ various materials to convert sunlight into electrical energy. The choice of materials is crucial for achieving efficient and cost-effective solar energy conversion. Here is a detailed explanation of the materials used in photovoltaic devices:

- Silicon (Si): Silicon is the most widely used material in PV devices due to its abundance, stability, and favorable electronic properties. It exists in two main forms: crystalline silicon (c-Si) and amorphous silicon (a-Si).

- Crystalline Silicon (c-Si): Crystalline silicon is used in the majority of commercial PV cells. It can be further classified into monocrystalline silicon (mono-Si) and multicrystalline silicon (multi-Si). Mono-Si cells offer higher efficiency but are more expensive, while multi-Si cells provide a cost-effective option with slightly lower efficiency. The high purity and ordered crystal structure of c-Si contribute to its excellent electronic properties.

- Amorphous Silicon (a-Si): Amorphous silicon is a non-crystalline form of silicon with a disordered atomic structure. It can be deposited on a variety of substrates, allowing for flexible and lightweight PV devices. However, a-Si cells generally have lower efficiency compared to c-Si cells.

- Thin-Film Technologies: Thin-film PV technologies utilize various materials to create layers of semiconductors with thicknesses typically in the nanometer to micrometer range. Thin-film technologies offer advantages such as flexibility, lower material usage, and potential for lower manufacturing costs.

- Cadmium Telluride (CdTe): CdTe is a compound semiconductor used in thin-film PV cells. It has excellent light absorption properties and relatively high efficiency, making CdTe-based cells commercially competitive. CdTe thin-film modules are known for their high throughput and low manufacturing costs.

- Copper Indium Gallium Selenide (CIGS): CIGS is another compound semiconductor used in thin-film PV cells. It offers high efficiency and good performance under low light conditions. CIGS-based cells are known for their flexibility and potential for high power conversion efficiency.

- Copper Zinc Tin Sulfide/Selenide (CZTS/Se): CZTS/Se is an emerging thin-film material that consists of abundant and non-toxic elements. It shows promise for low- cost, environmentally friendly PV devices, although commercialization is still in progress.

- III-V Compound Semiconductors: III-V compound semiconductors are a group of materials formed by combining elements from group III (such as gallium and indium) and group V (such as arsenic and phosphorus) of the periodic table. They offer excellent electrical and optical properties but are relatively expensive compared to silicon-based technologies. III-V compounds are mainly used in high-efficiency multi-junction solar cells.

- Gallium Arsenide (GaAs): GaAs is a prominent III-V compound semiconductor used in high-efficiency solar cells, particularly in space applications and concentrated photovoltaics. GaAs cells have excellent efficiency and superior performance under high light concentration.

- Perovskite Materials: Perovskite solar cells are a rapidly advancing PV technology that utilizes perovskite-structured materials. Perovskites are a class of materials with a specific crystal structure that can be easily synthesized and offer high light absorption and charge transport properties. While perovskite solar cells have achieved remarkable efficiency improvements in recent years, their commercialization is still being explored, and challenges such as stability and scaling need to be addressed.

- Organic Materials: Organic solar cells, also known as organic photovoltaics (OPV), use organic materials as the active layer. These materials offer advantages such as low-cost processing, flexibility, and lightweight characteristics. However, OPV cells generally have lower efficiency compared to inorganic PV technologies, and research is ongoing to improve their performance.

- Tandem and Multijunction Devices: Tandem and multijunction devices incorporate multiple semiconductor layers of different materials to efficiently capture a broader range of the solar spectrum. By combining materials with different bandgap energies, each layer can absorb light at specific wavelengths. This allows for increased overall efficiency compared to single-junction devices. Tandem and multijunction designs often utilize combinations of III-V compound semiconductors or hybrid structures such as perovskite-silicon tandems.

- Transparent Conductive Oxides (TCOs): Transparent conductive oxides, such as indium tin oxide (ITO) and fluorine-doped tin oxide (FTO), are used as transparent electrodes in PV devices. These materials allow light to pass through while providing electrical conductivity.

The selection of materials depends on various factors, including cost, efficiency, stability, availability, and application requirements. Researchers and engineers continue to explore new materials and device architectures to improve efficiency, reduce costs, and enhance the sustainability of photovoltaic devices.

9 Efficiencies

Efficiency is a crucial parameter for assessing the performance and effectiveness of photovoltaic (PV) devices, such as solar cells and modules. It measures how effectively these devices convert sunlight into usable electrical energy. Higher efficiency directly translates to more electricity production from the same amount of incident solar energy. In this explanation, we will discuss the various efficiency metrics used for PV devices and factors that influence their efficiency.

- **Conversion Efficiency**: Conversion efficiency is the primary efficiency metric used to evaluate PV devices. It represents the ratio of the electrical power output of the device to the incident solar power. Mathematically, efficiency (η) is calculated as: $\eta = (Electrical\ Power\ Output\ /\ Incident\ Solar\ Power)\ x\ 100\%$
  Conversion efficiency is usually expressed as a percentage. The higher the efficiency, the more effective the device is at converting sunlight into electricity.

- **Factors Influencing Efficiency**: Several factors affect the efficiency of PV devices: Material Properties: The choice of materials in PV devices plays a significant role in determining efficiency. Materials with suitable bandgap energies and high carrier mobility help maximize light absorption and minimize energy losses.

- **Absorption of Sunlight**: The ability of the device to absorb a broad range of wavelengths in the solar spectrum affects efficiency. Higher absorption means more photons are converted into electrical energy.

- **Carrier Recombination**: Efficient charge carrier separation and minimal recombination are essential for high efficiency. Reduced recombination losses result in a higher number of charge carriers contributing to the electrical output.

- **Surface Reflection**: The surface of PV devices should have anti-reflective coatings or textured structures to minimize light reflection and enhance light absorption.

- **Series Resistance**: Series resistance within the device can reduce efficiency by causing voltage drops and power losses. Minimizing series resistance helps maintain higher voltage output.
- **Shunt Resistance**: Shunt resistance represents undesired leakage paths in the device. Higher shunt resistance leads to improved efficiency by reducing leakage current and power losses.
- **Temperature Effects**: Temperature impacts the performance of PV devices. Higher temperatures can increase recombination rates, decrease open-circuit voltage, and reduce efficiency.

3. **Energy Conversion Efficiency Limits:** The efficiency of PV devices is subject to physical and material limitations. The Shockley-Queisser limit defines the maximum conversion efficiency possible for a single-junction solar cell based on the solar spectrum and the material's bandgap. For silicon-based solar cells, the theoretical limit is around 29%. However, practical limitations, such as losses due to recombination and resistive losses, make achieving this limit challenging.

4. **Single-Junction and Multijunction Efficiency:** Single-junction solar cells are composed of a single semiconductor material. Multijunction solar cells, on the other hand, consist of multiple layers of semiconductors with different bandgaps.

Multijunction cells can achieve higher efficiencies by capturing a broader range of the solar spectrum.

5. **Certified Efficiency**: Certified efficiency is the efficiency value obtained from independent testing laboratories using standard measurement procedures. It provides a reliable benchmark for comparing the performance of different PV devices.

6. **Module Efficiency**: Module efficiency refers to the efficiency of an entire PV module, which consists of multiple interconnected solar cells. Module efficiency takes into account losses due to inactive areas, electrical interconnections, and other module- level factors.

7. **Power Conversion Efficiency (PCE):** Power conversion efficiency is a measure of how effectively a PV device converts sunlight into electrical power. It is calculated as the ratio of the electrical power output to the input power. PCE considers additional losses such as optical losses and electrical losses beyond the conversion efficiency.

8. **Energy Conversion Efficiency (ECE):** Energy conversion efficiency quantifies the efficiency of a PV device in converting sunlight into usable electrical energy over a given period. It takes into account the total energy output over time, considering factors such as daily and annual variations in sunlight.

9. **Tracking Maximum Power Point**: Maximizing efficiency requires operating PV devices at their maximum power point (MPP). Maximum power point tracking (MPPT) techniques are employed to continuously adjust the operating point to maintain optimal power generation even under varying environmental conditions.

10. **Efficiencies of Different PV Technologies**: PV technologies have different efficiency ranges. Crystalline silicon solar cells have achieved efficiencies exceeding 25%, with monocrystalline cells generally being more efficient than multi-crystalline cells. Thin- film

technologies, such as CdTe and CIGS, have efficiencies in the range of 10-22%. Emerging technologies like perovskite solar cells have shown remarkable efficiency improvements, with record values surpassing 25%.

In conclusion, efficiency is a critical factor in evaluating the performance of photovoltaic devices. Various factors influence efficiency, including material properties, absorption of sunlight, carrier recombination, resistive losses, and temperature effects. Conversion efficiency, module efficiency, power conversion efficiency, and energy conversion efficiency are key metrics used to quantify the effectiveness of PV devices. Continuous advancements in materials, device design, and manufacturing processes aim to improve efficiency and drive the widespread adoption of solar energy as a clean and renewable power source.

10. Summary

In this unit, you have studied about Photovoltaic devices (Photo cell or Solar cell). Solar cell works on the principle of photovoltaic effect. I-V characteristics of a photovoltaic cell have been explained. Single diode model and double diode model of a photovoltaic cell have been discussed. Temperature effects, materials used in photovoltaic cell and efficiencies of photovoltaic cell have also been discussed.

11. Lexicon

Spectrum– a band of coloured lights in order of their wavelengths or frequencies

Device – an object that has been invented for a particular purpose

Characteristics – a typical or noticeable feature of something

Equivalent – equal in value, amount, meaning, importance

Efficiency– ability to produce a desired effect

12. References

1. Green, M. A. (2018). Solar Cells: Operating Principles, Technology, and System Applications. University of New South Wales Press.

2. Arora, P. (2017). Solar Cell Devices: Physics, Processing, Simulations and Characterization. John Wiley & Sons.

3. Photovoltaics: Overview. (n.d.). National Renewable Energy Laboratory (NREL).

4. Photovoltaic Solar Energy: From Fundamentals to Applications. (2016). CRC Press.

5. Green, M. A., Emery, K., Hishikawa, Y., Warta, W., & Dunlop, E. D. (2018). Solar cell efficiency tables (version 52). Progress in Photovoltaics, 26(7), 427-436.

6. Green, M. A., & Zhao, J. (2019). Solar cell efficiency tables (version 55). Progress in Photovoltaics, 27(7), 565-575.

7. Würfel, P. (2005). Physics of Solar Cells: From Principles to New Concepts.

8. Handbook of Photovoltaic Science and Engineering. (2003).

9. Nishimura, N., Nitta, K., Sakai, J., & Kasamatsu, N. (2012). Crystalline Silicon Solar Cells: Technology and Systems Applications.

13. Suggested readings

1. S.M. Sze, Semiconductor Devices - Physics and Technology, Wiley, New York.

2. J. Singh, Semiconductor Optoelectronics: Physics and Technology, McGraw Hill.

3. P. Bhattacharya, Semiconductor Optoelectronic Devices, Pearson Education,

4. J. Singh, Optoelectronics: An Introduction to Materials and Devices, Tata McGraw Hill.

14. Terminal questions

1. What do you understand by Spectrum? Explain Solar Energy Spectrum in detail?

2. Describe the device principle of a Solar cell or Photovoltaic cell?

3. Explain the I-V characteristics of a Photovoltaic cell in detail.

4. Describe the effect of temperature on PV cells.

5. What do you understand by equivalent circuit? Explain single diode model and double diode model in detail.

6. Explain about the materials used in PV cells.

7. What do you understand by efficiency of a PV cell? Explain in detail.

Chapter 5: Light-emitting diodes

1. Introduction

A light-emitting diode (LED) is a semiconductor device that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons. The color of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor. White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor on the semiconductor device. In 1962, when it first appeared as a practical electronic component, it emitted low-intensity infrared (IR) light. Infrared LEDs are used in remote-control circuits, such as those used with a wide variety of consumer electronics. The first visible-light LEDs were of low intensity and limited to red. Early LEDs were often used as indicator lamps, replacing small incandescent bulbs, and in seven-segment displays. Later developments produced LEDs available in visible, ultraviolet (UV), and infrared wavelengths, with high, low, or intermediate light output, for instance, white LEDs suitable for room and outdoor area lighting. LEDs have also given rise to new types of displays and sensors, while their high switching rates are useful in advanced communications technology with applications as diverse as aviation lighting, fairy lights, automotive headlamps, advertising, general lighting, traffic signals, camera flashes, lighted wallpaper, horticultural grow lights, and medical devices.

LEDs have many advantages over incandescent light sources, including lower power consumption, longer lifetime, improved physical robustness, smaller size, and faster switching. In exchange for these generally favorable attributes, disadvantages of LEDs include electrical limitations to low voltage and generally to DC (not AC) power, inability to provide steady illumination from a pulsing DC or an AC electrical supply source, and lesser maximum operating temperature and storage temperature. In contrast to LEDs, incandescent lamps can be made to intrinsically run at virtually any supply voltage, can utilize either AC or DC current interchangeably, and will provide steady illumination when powered by AC or pulsing DC even at a frequency as low as 50 Hz. LEDs usually need electronic support components to function, while an incandescent bulb can and usually does operate directly from an unregulated DC or AC power source. As a transducer of electricity into light, LEDs operate in reverse of photodiodes.

2. Objectives

After reading this unit we will able to understand:

1. The basic idea of LED

2. Structure of LED

3. Classification of LED

4. Working principle and characteristics of LED

5. Specifications of LED

6. Applications of LED

3. Working of led and electro-luminescence

We all are familiar with LEDs as it is very widely used indicator or optical source. But nowadays its application domain is changing from indicators to lighting applications. It has become possible because of recent developments in the fabrication technology of LEDs. Reliable, cheaper power LEDs are available nowadays. These are nothing but p-n junction diodes that emit light when forward-biased. The circuit symbol and actual LED device are shown below. The outward arrows in the circuit symbol symbolize the radiated light. Observe the actual device carefully. It has two terminals having different lengths. The longer one is the “Anode” and the shorter one is the “Cathode” terminal. See figure 1.

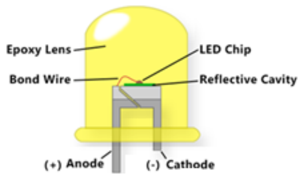


Fig 1: LEDs

LEDs differ from normal p-n junction diodes in working principle, fabrication material, specifications, and hence the application. The basic difference between rectifier diode and LED is that p and n-type semiconductors of LED are heavily doped (more than 1026/m3). So other diodes give off heat when forward biased, while LEDs emit light when forward biased. The process of giving light energy by applying an electrical voltage is called electro-luminescence. When LED is forward biased electrons are injected into the n-region and holes into the p-region. Electrons cross the p-n junction from the n-type material and recombine with holes in the p-type material. The free electrons are in the conduction band and the holes are in the valence band. The electron-hole recombination takes place and during this process, the energy is released in the form of radiation. Thus, in LED, emitted light comes from the hole-electron recombination. See figure 2.

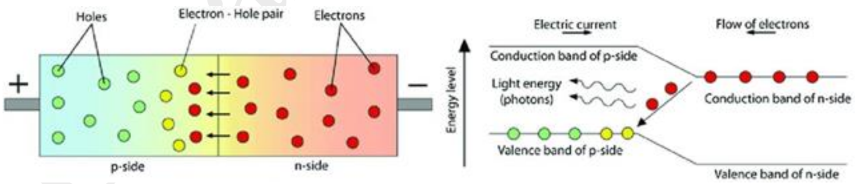


Figure 2: Working principal for LED

The electro-luminescence phenomenon will be more cleared using an Energy-band diagram. Free electronspresent in the conduction band are at a higher energy level than holes in the valence band. Radiative and nonradiative recombination take place in LED. In all semiconductors, these two types of radiations are occurring when forward-biased. The only difference is that in some radiative phenomenon is predominant and, in some cases, nonradiative. Accordingly, energy is released either in the form of light or heat. In Si or Ge semiconductors greater percentage of energy is in the form of heat and the percentage of light energy is less.

Since semiconductors used for LED fabrication are mostly compounds of Gallium and Indium, the behavior of LED is different from normal diode when forward biased. During recombination, the light of wavelength λ is emitted where λ is related to the bandgap energy, of the semiconductor by the formula:

$$Eg = h\upsilon = h\frac{c}{\lambda}$$

where $h = \text{plank's constant} = 4.14 \text{ X } 10 - 15 \text{ V.s}$

$c = \text{velocity of light} = 3 \text{ X108 m/s}$

Thus, it is clear from the equation that the wavelength of light emitted is dependent on the bandgap energy. If material is changed then Eg changes and hence the color of emitted light also changes.

Under reverse bias no carrier injection takes place and consequently, no photon (light) is emitted.

4. Characteristics of led devices

Broadly LED characteristics can be categorized as Electrical and Optical Characteristics.

4.1. Electrical Characteristics

The electrical characteristic of LED is basically current voltage variations across the diode. The forward characteristic of an LED is the same as that of rectifying diode except for a change in forward voltage drop. Typically, the forward voltage drop across an LED is between 1.2 V to 3.2 V, while the forward voltage drop across the diode is 0.2 V (for Ge diode) or 0.6V (for Si diode). In the figure, the forward characteristics of several LED materials are shown. One should note that although the color of light is determined by the material used, the amount of light produced by an LED is dependent on the forward current flowing through the circuit. The current can be controlled by its driving circuit and hence the light intensity.

It is seen from the characteristic that knee voltage for the red LED is the lowest and it increases for shorter wavelength materials. See figure 3.

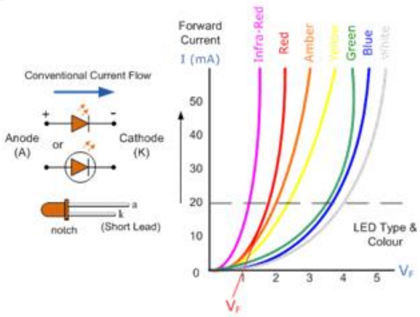


Fig: 3: Electrical characteristic of LED

4.2. Optical Characteristics

Since now a day LEDs are used for illumination purposes the optical characteristics of LED are also becoming important. The optical characteristics give the idea about the color of emitted light and spectral power distribution. There are two important optical characteristics viz. spectral and spatial need to be studied.

(a) Spectral characteristic: It represents the light output versus wavelength. The following curves show the spectral response of coloured LEDs in the visible range. LEDs have a single peak occurring at the corresponding colour wavelength. See figure 4

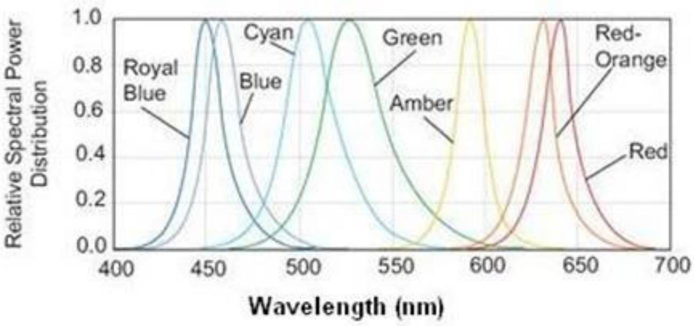


Fig 4: Spectral characteristic

(b) Spatial characteristics: It gives the radiation pattern of LEDs. It shows the spread of light output with respect to the space. In short, it gives directionality to emitted light. The following graph shows the typical radiation pattern of LED. The pattern depends upon the lens structure of the LED. The narrower the radiation pattern, the more the light is concentrated in a particular direction. See figure 5.

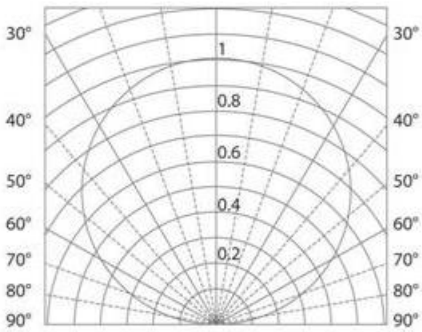


Fig 5. Spatial characteristics

5. Structure and fabrication of LED

LEDs are a specialized form of p-n junction diodes that have been designed to optimize their optical output. As a result, the LED structure and fabrication techniques need to ensure that electro-luminescence is optimized. LEDs are basically consist of three main components as given below, see figure 6.

1. p-n junction

2. Electrical contacts

3. Transparent plastic encapsulation

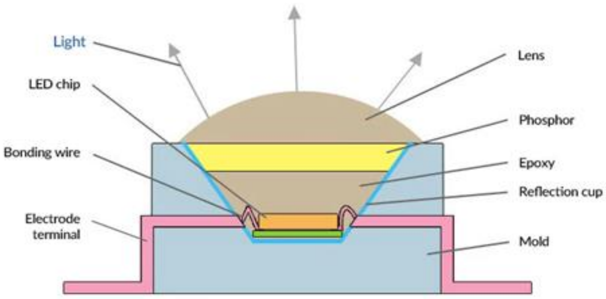


Figure 6: Structure of a LED

The major part of the structure is a p-n junction. Active films of the LED structure are normally grown epitaxially - often by liquid phase or vapor phase epitaxy. Common substrates used are compounds of Gallium, Arsenic, and Phosphorus. The PN junction can be created by either impurity diffusion, or ion implantation, or it can be incorporated during the epitaxial growth phase. Once a shallow p-n junction is formed, electrical contacts are taken out from both regions. The junction is encapsulated in a transparent plastic medium. The plastic is molded into an approximately hemispherical shape. Other geometries are also possible which improves the light emission direction and conversion efficiency from electrical to optical.

On the basis of structure, and working operation, there are two types of LED Surface Emitting LED and Edge Emitting LED. Two basic configurations for the LED structure are given in figure 7.

Fig 7: Different type shapes of LED

5.1 Homojunction and heterojunction LED structure

If the p side and n side of the p-n junction of a LED are made of the same type of material then it is called homojunction LED. In other words, if the p-type material and n-type material of LED is made of the same material, the only difference is doping. For example, GaAs it is called homojunction LED. On the other hand, if the material of n type and p type of LED is different than it is called heterojunction LED. For example, if the p-type material is made of GaAs and the n-type material is made of SiO2 then it is called a heterojunction

LED. Homo junction LED is also called surface-emitting LED. The heterojunction LED is also called edge-emitting LED. Since the homo junction has more cross-sectional area thus it has low terminal impedance but it emits non-directional light. On the heterojunction the light emitting area is small thus fight is fine with a high data rate.

5.2 Surface-emitting LED

The structure of the Surface Emitting LED is given in Figure 5.9. Surface-emitting LED can be used for optical fiber. As its name, light emits from the surface of the LED and the emitted light is perpendicular to the surface of the LED. The optical fiber is also placed perpendicular to the LED so that light can easily be coupled to the optical fiber. The structure of LED is shown in Figure 6. There are different layers as the active layer is made of p-type GaAs material and above p-layer, n-layer of AlGaAs, and n+ layer of GaAs.

Below the active layer p-layer of AlGaAs and p+ layer of GaAs. These are hetero junction

layers and by using an etched shape n-type surface, the distance between the active region and light emitting surface is minimized so that maximum light can be obtained. The contact layers are made of metal to provide an electric supply to the LED and below the metal layer we generally used a heat sink to make the LED cool.

5.2.1. Properties of surface-emitting LED

- High irradiance is obtained.
- Low terminal impedance is obtained.
- Due to multiple p types of layers and double hetero-junctions the coupling efficiency is increased.
- Emission pattern is anisotropic with maximum light intensity at the center and half at 1200.
- The disadvantages or drawbacks of Surface Emitting LED low life time and low modulation bandwidth. See figure 8.

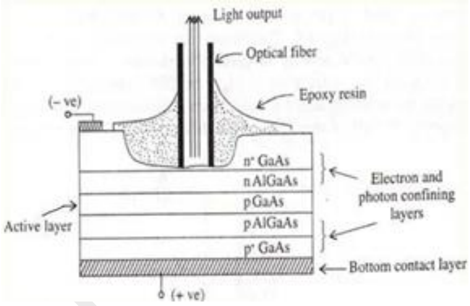


Fig 8: Surface-emitting LED.

5.3. Edge emitting LED structure

In Edge emitting LED there are two optical light guiding layers as shown by the black- shaded region in Figure 5.10. The active region is in between these layers. Both guiding layers have a refractive index lower than the active region and higher than the surrounding materials (SiO2 substrate above the upper light guiding layer and n-type

GaAs substrate below the lower light guiding layer). Above the SiO2 substrate layer,

there is a metallic layer used for the electric contact. Similarly, below the n-type GaAs substrate, another metallic layer is used for the electric contact. Below the lower metallization, there is a heat sink that absorbs heat generation during light emission. If the numerical aperture is less the Edge emitting LED couples more power than the surface-emitting diode and the modulation bandwidth is higher than the surface-emitting diode. The light emitted from the edge-emitting LED is elliptical as shown in Figure 10.

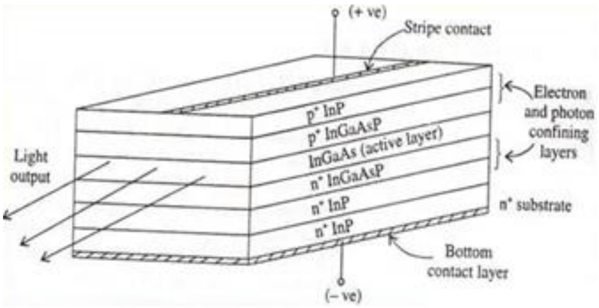


Fig 10: Edge-emitting LED structure

5.3.1. Properties of edge-emitting LED

- ➢ It has high irradiance.
- ➢ Beam divergence is narrowing compared to surface emitting diode and couples more optical power.
- ➢ High modulation bandwidth.

6. Materials used for LEDS

Light-emitting diodes are available in a wide range of colors with the most common being red, amber, yellow and green are thus widely used as indicators. The actual color of a light emitted by LED is determined by the actual semiconductor compound used for fabrication. The different materials emit different wavelengths of light and hence different colors. The following table shows the used semiconductor material to produce particular color. See table 1.

Table 1: Material used for LEDs

Semiconductor Material	Wavelength of emitted Light (nm)	Color
GaAs	850-940	Infra-Red
GaAs0.6P0. 4	630-660	Red
GaAs0.25P 0.75	605-620	Amber
GaAsP:N	585-595	Yellow
AlGaP	550-570	Green
SiC	430-505	Bleu
GalnN	450	white

From the above table, it is clear that the main P-type dopant used in the manufacture of Light Emitting Diodes is Gallium (Ga, atomic number 31) and that the main N-type dopant used is Arsenic (As, atomic number 33). Other colors are produced by adding nitrogen or phosphorus impurities.

Thus, it should be noted that the color of the light emitted by an LED is not determined by the coloring of the LED's plastic body although these are slightly colored to both enhance the light output and to indicate its color when not illuminated. Most light-emitting diodes produce just a single output of colored light however, multi-colored LEDs are now available that can produce a range of different colors from within a single device. Most of these are actually two or three LEDs fabricated within a single package.

Up to the 1970s, only colored LEDs were available which were mainly used as indicators. The use of LEDs for signaling applications started about 35 years ago. These are low- power LEDs radiating low light intensity. The development of white power LEDs started when high-quality GaN crystal was deposited on Sapphire substrate in 1986 and high brightness blue LEDs were developed in 1993 and have been continuously improved. The

first white-colored OLED was launched around 1990 and made the LEDs more and more interesting to use as light bulbs. White LEDs were developed using blue LEDs combined with yellow phosphors and commercialized in 1996. Nowadays LEDs, colored or white, surpass the incandescent and halogen bulbs and are widely accepted as light bulbs. Still, a lot of research is going on to produce high-intensity LEDs.

7. Led light power & efficiency

7.1. LED Light Power:

The power (P) of any electrical device including a LED light is measured in Watts (W), which is equal to the current or electricity drawn (I), measured in ampere, multiplied by the voltage (V). $P = V \times I$

Therefore, the power of the LED light is proportional to voltage and/or current such that a device may have a low voltage but may still draw a very high current and have high power consumption.

LED lights by their nature are low voltage but also relatively low current making them lower in power and more efficient than traditional incandescent bulbs and halogen lights. Generally, we are talking about between 100 to 750 milli-amps depending on the forward voltage required to turn on the LED. There is some advantage to having higher voltage LEDs where long distances occur between the LED and power supply such as in Strip LED lighting. However, for most applications, it does not really matter.

Typical power ranges for general-purpose residential and commercial bulbs range from as little as 3W to 15W. Generally, the higher the power the greater the current and therefore the greater the light output. However, this is not always the case which brings us to the concept of efficiency and power factor.

7.2. LED Light Efficiency

The efficiency of the LED light is measured in lumens per watt (Lm/W) which refers to the total quantity of light the LED lamp produces per 1 W of energy.

$$Efficiency = total\ lumen\ output\ /\ total\ power$$

Older LED chips found in older generation LED bulbs from as recent as 2008 – 2010 produce less light per watt than the 2011 – 2012 LED chips found in more modern LED bulbs. For example, a 2012 7W bulb with a CREE XT-E chip can produce more light or lumen output than a 12W bulb with an older CREE XP-E chip. More modern LED bulbs also have better heat sink designs which enable higher light outputs.

7.3. LED efficiency and lamp efficiency

As discussed in the above section we must ensure that the retailer information is specifying the Lamp Efficiency rather than the LED efficiency. Due to the inherent loss in the bulb, the lamp efficiency will always be less than the LED efficiency depending on the design. This includes thermal effects, driver losses, and optical inefficiencies which all combine to reduce the overall efficiency of the LED bulb or luminaire compared to the internal LED package or chip. Collectively, these losses can decrease the efficiency by more than 30%. In such cases, a manufacturer may specify a LED MR16 bulb has 720lm but in reality for the LED lamp, it is only approximately 500lm.

7.4. LED Lighting and power factor

A further complication is Power Factor (PF) which is a value less than 1.0 and measures the efficiency of the LED driver or power supply. Essentially an electrical device may be rated at a Power of 100W but actually consume more than 100W due to a phase delay between the instantaneous voltage and the instantaneous current. Remember that Mains power is AC or alternating current and it is made up of sinusoidal waveforms of oscillating voltage and oscillating current. Ideally, these two waveforms are synchronous (PF=1) but due to the nature of electronics or inductive loads such as electric motors a delay emerges between the voltage waveform and the current waveform leading to a wastage of electrical power or a Reactive Power which is incapable of doing any work. Therefore, a device may be rated at 1000W Real Power but consume 1500W Apparent or Active power due to a PF of 0.67 and end up wasting 500W or 1/3 of the total power consumed due to the current being out of phase. Note that for the electrical device to make use of the current it must be in phase with the voltage given power is equal to voltage x current or P=VI.

PF is generally only a problem in commercial applications in inductive devices which use very high power such that the delays between current and voltage add up to produce significant power losses. Other components which will cause delays between current and voltage include transformers and voltage regulators and ballasts in fluorescent lighting. In residential settings, such losses are relatively minimal and electricity companies will only charge for the real power anyway. However, there is still a loss so those energy-conscious or green individuals may wish to examine the power factor of their LED lighting power supplies to ensure that have a PF of greater than 0.8 to ensure minimal energy loss. In fact, the US Department of Energy (DOE) Energy Star program mandates minimum acceptable power factors of 0.7 and 0.9 respectively for domestic and commercial LED lights.

Most power supply devices these days will have some form of either passive or active power factor correction leading to PF of > 0.9 so minimal power losses can be achieved. One exception is ultra-high dimming drivers which dim down to 1%. Due to the high capacitive loads required to stabilize the current at very low dimming levels to avoid flicker PF is poor, generally approx 0.65 meaning that a 10W rated LED bulb will consume approximately 15.4W (or VA, apparent power) near full load. However, in practice, this is not a big problem given these drivers are generally used in applications where the lamps will be dimmed down to low levels for most of their life such that the real power is 2 or 3W and the Apparent power is still very low at up to 4.6W.

8. Specifications of LEDS

While selecting an LED for a particular application it is necessary to comprehend the different LED specifications or LED parameters. Some of the major LED specifications are given below. LED specifications can be categorized as Electrical and Optical.

8.1. Electrical specifications

Since basically LED is a diode, forward voltage and forward current are two important parameters. Low-power LEDs are capable of driving forward current up to 100mA while power LEDs can have forward current as high as 1A. Typical forward voltage drop varies between 1.2V to 3V. It is necessary to ensure that the maximum current rating is not exceeded. This could give rise to excessive heat dissipation within the LED chip itself which could result in reduced light output and reduced operating lifetime.

Reverse voltage: LEDs are not tolerant to large reverse voltages. They should never run above their stated maximum reverse voltage, which is normally quite small. If they are then permanent destruction of the device will almost certainly result. If there is any chance of a reverse voltage appearing across the LED, then it is always best to build in protection into the circuitry to prevent this. Normally simple diode circuits can be introduced and these will adequately protect any LED.

- Operating and storage junction temperature
- Thermal resistance (junction to ambient)
- Operating life: The light intensity of a LED does diminish gradually with time. This means that a LED has an operational life. This LED specification is of particular importance when a LED or LEDs are to be used for lighting applications. It is not normally as crucial when the LED is used as an indicator - here a catastrophic failure is of greater importance.
- Turn on and turn off time.

8.2. Optical specifications

In this one has to consider the Light colour, maximum intensity, and radiation pattern of LED.

Light output: The LED light intensity specification is not of crucial importance for most indicator applications, but with LEDs being used for lighting, this parameter is needed to be able to specify exactly what is needed in many situations. The light output from an LED is quantified as luminous intensity value and is expressed in millicandella, mcd. The luminous intensity value for an LED must be quoted for a given current. Many LEDs operate at currents of around 20mA, but the light output of an LED increases with an increase in forward current.

It is sometimes specified as radiation intensity at a particular current in watt/steradian. Operating Wavelength of LED: It signifies the color of emitted light. In the datasheet, the direct numerical value of wavelength is given for color LED. In the case of white LED, the graphical spectral response of the device is provided.

Radiation Pattern: It describes the relative intensity strength in any direction from the light source. Practical light sources have various forms of radiation patterns based on different emission mechanisms, materials used for the fabrication of sources, and manufacturing techniques. Datasheets of LED manufacturers provide radiation patterns in terms of relative intensity versus angle. The patterns may be symmetrical or non- symmetrical. In the case of symmetric radiation patterns, manufacturers mention view angles.

9. Applications of LED

Widely LEDs are used as an indicator or as an optical source or bulb. Let us focus on these applications.

9.1. LED as an indicator:

LEDs that produce visible radiation (400 to 700nm) are useful in instruments, calculators, and so on for display purposes. When used as a simple indicator

it is used in forward biased. The circuit is as follows. The value of the resistor, Rs, decides the forward current of the LED thus by deciding light intensity. See figure 10.

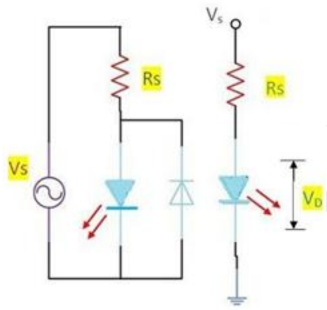


Figure 10: LED as idicator working pricipal

When used as an indicator LED can have several forms like individual color or multi-color LEDs, several light-emitting diodes can be combined together within a single package to produce displays such as bar graphs, strips, arrays, seven-segment displays, dot matrix displays, etc.

9.2. LED as an optical source:

LED is a potential light source for optical fiber communicationand in opto- isolators. One of the key components in optical communication is the monochromatic light source. In optical communications, light sources must be compact, monochromatic, stable, and long- lasting (many years). LEDs can form continuous wave (CW) light sources for optical communication. The LEDs used in communications are constructed to allow light to emerge from the device's edge. See figure 11.

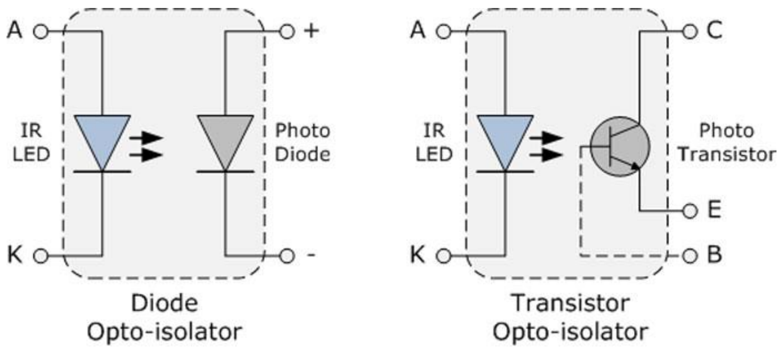


Figure 11: Use of LED in optical communication system

Opto-isolator is nothing but an optical source and optical detector used in pair. It finds application in burglar alarm systems, CD players, and other devices requiring invisible radiation. Here IR LED is used instead of the visible range LED along with IR photodiode. The advantage of optoisolators is that it provides electrical isolation between two circuits while connecting two circuits optically.

9.3. LED as light bulb:

Incandescent bulbs and CFLs are the traditional light sources used for lighting purposes. Previously LEDs were available with a light output of only a few lumens and didn't even achieve the light intensity level of standard incandescent bulbs. More recent breakthroughs in LED fabrication processes have precipitated a vigorous discussion of the depth and pace with which LEDs are penetrating the lighting market. LEDs are gaining widespread acceptance as the most efficient light source due to their advantages of low power consumption, long life, more reliability, small size, lightweight, and above all eco- friendliness. LEDs are replacing conventional light sources due to various advantages like low power consumption, cost, long life, eco-friendly, etc.

10. Summary

- A light-emitting diode (LED) is a semiconductor device that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons.
- The color of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor.
- Basic difference between rectifier diode and LED is that p and n-type semiconductors of LED are heavily doped (more than 1026/m3). So other diodes give off heat when forward biased, while LEDs emit light when forward biased. The process of giving light energy by applying an electrical voltage is called electro-luminescence.
- Electrical characteristics of LED are basically current voltage variations across the diode. The forward characteristic of an LED is the same as that of rectifying diode except for a change in forward voltage drop.
- The optical characteristics give the idea about the color of emitted light and spectral power distribution. There are two important optical characteristics viz. spectral and spatial need to be studied. One has to know the electrical and optical characteristics of the LED before using it for a particular application.
- If the p side and n side of the p-n junction of a LED are made of the same type of material then it is called homojunction LED.
- If the material of n type and p type of LED is different than it is called heterojunction LED.
- As its name, in surface-emitting LED, light emits from the surface of the LED and light is perpendicular to the surface of the LED.
- In Edge emitting LED the light is emitted from the edge of the semiconductor layer which is guided by two layers called light-guiding layers.

- The efficiency of the LED light is measured in lumens per watt (Lm/W) which refers to the total quantity of light the LED lamp produces per 1 W of energy. Efficiency = total lumen output / total power
- LED has got very wide domain of applications. Commonly it is used as a light indicator for various appliances and instruments. It is widely used as an optical source either in optical communication or in optical isolator devices. Now it is widely accepted as an illumination source because of the availability of reliable, high-power, and energy-efficient LEDs. They are replacing incandescent and CFL, traditional light bulbs.

11. Lexicon

LED: light-emitting diode

Electro-luminescence: the process of giving light energy by applying an electrical voltage

Homojunction: the p side and n side of the p-n junction of a LED is made of the same type of material

Heterojunction: material of n type and p type of LED are different

12. References

1. https://epgp.inflibnet.ac.in/

2. https://en.wikipedia.org/wiki/LED_lamp

3 https://www.liteonled.com.au/buying-guide/understanding-led-lighting/led-power-levels/ 4. https://www.thetechnicaltalk.com/2020/04/edge-emitter-led-construction-and.html

13. Suggested reading

1. S.M. Sze, Semiconductor Devices - Physics and Technology, Wiley, New York.

2. J. Singh, Semiconductor Optoelectronics: Physics and Technology, McGraw Hill.

3. P. Bhattacharya, Semiconductor Optoelectronic Devices, Pearson Education,

4. J. Singh, Optoelectronics: An Introduction to Materials and Devices, Tata McGraw Hill.

14. Terminal questions

1. What do you mean by a light-emitting diode (LED)? How it emits light? And how the color of LED light can be decided?

3. Explain the process of electro-luminescence. What is the difference between rectifying a diode and an LED?

4. With the help of a diagram explain the electrical characteristic of LED and the optical characteristics of LED.

6. What are homojunction LED and heterojunction LED?

7. With the help of a diagram explain the working advantage and disadvantages of surface-emitting LED.

8. What is Edge emitting LED gives its structure working and advantage of edge-emitting LED?

Chapter 6: Laser diode

6.1 Introduction

Like many other semiconductor devices, a laser diode is created by doping a very thin layer of a crystal wafer's surface. A p-n junction, or diode, is created when the crystal is doped to form an A laser diode (LD, also known as an injection laser diode or ILD, or diode laser) is a semiconductor device that works similarly to a light-emitting diode in that it may produce lasing conditions at its junction when it is directly pumped with electrical current. n- type zone and a p-type region stacked one on top of the other.

The laser diode operates on the premise that every excited atom has the ability to generate photons if electrons at higher energy levels are given access to an external energy source. An atom can emit light energy through three main processes: absorption, spontaneous emission, and stimulated emission. There are several significant distinctions between light-emitting diodes (LEDs), which are similar to laser diodes in some fibre optic communication systems, and laser diodes. The narrow frequency coherent light that laser diodes can produce enables the transmission of numerous channels of data over a single fibre optic cable.

Nearly every facet of these fields from 'light shows' to CDs, DVDs, and special effects in movies involves laser technology. Laser pointers, barcode scanners, laser printers, etc. are a few other common uses for lasers. In laser pointers, laser diodes are utilised. Communications through fibre optics employ laser diodes. Barcode readers employ laser diodes. In laser printing, laser diodes are utilised.

2. Objective

After studying this unit, you will learn about-

- Different types of Laser Diode
- Principle and working Laser Diode
- Application of Laser Diode

3 Laser diode

A laser diode (LD, also known as an injection laser diode or ILD, or diode laser) is a semiconductor device that works similarly to a light-emitting diode in that it may produce lasing conditions at its junction when it is directly pumped with electrical current.

The doped p-n-transition, which is driven by voltage, enables the recombination of an electron and a hole. Radiation in the form of an emitted photon is produced when an electron drops from a higher energy level to a lower one. This is an unintentional emission. When the procedure is carried out repeatedly and new light with the same phase, coherence, and wavelength is created, stimulated emission can result.

The wavelength of the emitted beam, which in modern laser diodes ranges from the infrared to the ultraviolet (UV) spectrum, is determined by the semiconductor material selected. The most prevalent form of lasers manufactured are laser diodes, which are used in a variety of applications such as fibre optic communications, barcode readers, laser pointers, reading/recording CD, DVD, and Blu-ray discs, laser printing, laser scanning, and light beam illumination. Laser diodes can be utilised for general illumination with the use of a phosphor similar to that present in white LEDs.

3.1. Theory

Electrically speaking, a laser diode is a PIN diode. The carriers (electrons and holes) are pumped into the intrinsic (I) region of the laser diode, which houses the active region, from the N and P regions, respectively. All contemporary lasers use the double-hetero-structure implementation, where the carriers and the photons are restricted to maximise their chances for recombination and light emission. The original diode laser research was carried out on straightforward P-N diodes. A laser diode's objective, in contrast to a conventional diode, is to recombine all carriers in the I region and generate light.

Thus, direct band-gap semiconductors are used to create laser diodes. One of the crystal growth processes is used to produce the laser diode epitaxial structure, typically beginning with an N-doped substrate and progressing through the I-doped active layer, P-doped cladding, and contact layer. Quantum wells are most frequently used in the active layer because they offer a lower threshold current and greater efficiency.

4. Electrical and optical pumping

A subset of the broader category of semiconductor p-n junction diodes is laser diodes. The two charge carrier species, holes and electrons, are "injected" into the depletion area from opposing sides of the p-n junction by a forward electrical bias across the laser diode. In a semiconductor, holes from a p-doped material are injected into an n-doped material, and vice versa. Wherever n- and p-type semiconductors are in physical contact, the difference in electrical potential between them causes a depletion area to emerge that is devoid of any charge carriers. This class of lasers is occasionally referred to as "injection lasers" or "injection laser diode" (ILD) due to the charge injection used to power the majority of diode lasers. Diode lasers can alternatively be categorised as semiconductor lasers because they are semiconductor devices. Diode lasers can be distinguished from solid-state lasers using either identifier.

Some diode lasers can also be powered through the use of optical pumping. Optically pumped semiconductor lasers (OPSL) use another laser (typically another diode laser) as the pump source and a III-V semiconductor chip as the gain medium. In terms of wavelength selection and the absence of interference from internal electrode structures, OPSL have a number of benefits over ILDs. The invariance of the beam parameters divergence, shape, and pointing across a 10:1 output power ratio, as well as the pump power (and consequently output power) variations, is another benefit of OPSLs.

5. Generation of spontaneous emission

When an electron and a hole are present in the same space, they may "annihilate" or recombine, causing a spontaneous emission, in which the electron may once again occupy the hole's energy state and release a photon with energy equal to the difference between the electron's initial state and the hole's state. (In a typical semiconductor junction diode, the energy liberated during the recombination of electrons and holes is transported away as phonons, or lattice vibrations, as opposed to photons.) Similar characteristics to those of an LED are produced by spontaneous emission below the lasing threshold. Although spontaneous emission is required to start a laser oscillating, it is only one of many sources of inefficiency once the laser has started. See figure 1.

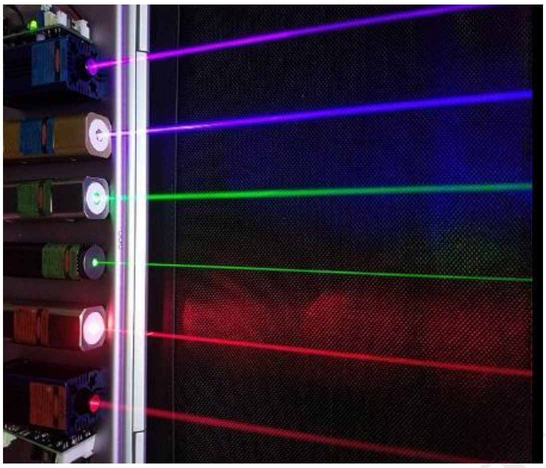


Figure: 1: Semi-conductor lasers (Bottom to Top: 660 nm, 635 nm, 532 nm, 520 nm, 445 nm, 405 nm)

6. Direct and indirect bandgap semiconductors

The type of semiconductor employed, one whose physical and atomic structure grants the possibility for photon emission, distinguishes a photon emitting semiconductor laser from a standard phonon-emitting (non-light-emitting) semiconductor junction diode. These so called "direct band gap" semiconductors are the ones that emit photons. Band gaps in silicon and germanium, two single-element semiconductors, do not line up in a fashion that would permit photon emission; hence they are not regarded as having "direct" band gaps. Other substances, the so-called compound semiconductors, break the symmetry by alternately arranging two different atomic species in a checkerboard like pattern, although having almost identical crystalline structures to silicon or germanium.

The crucial "direct band gap" feature is produced by the change in materials in the alternating pattern. The compound semiconductors gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride can all be utilised to make junction diodes that emit light. See figure 2.

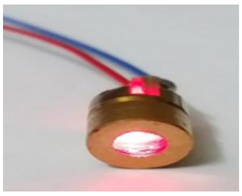


Figure: 2: A simple and low power metal enclosed laser diode

7. Optical cavity and laser modes

The gain zone is encircled by an optical cavity, just like in other lasers, to create a laser. The most basic type of laser diode creates an optical waveguide on the surface of the crystal, which confines the light to a relatively narrow line. A Fabry-Pérot resonator is created when the crystal's two ends are sliced into absolutely smooth, parallel edges. When photons are emitted into a waveguide mode, they move along the waveguide and encounter several reflections from each end face before leaving. A light wave is stimulated to emit lighter as it travels through the cavity, but some light is also lost due to absorption and incomplete reflection from the end facets. Finally, the diode starts to "lase" if there is more amplification than loss. The optical cavity's geometry affects a few key characteristics of laser diodes. Typically, only one optical mode in the direction perpendicular to the layers is supported by the structure, and the light is contained within a very thin layer. The laser is referred to as "multi-mode" if it can support several transverse optical modes in the transverse direction and is wider than the wavelength of light. These transversely multi-mode lasers are suitable for applications that require very high power but not a narrow TEM00 beam, such as printing, chemical activation, microscopy, or pumping other laser types. The waveguide needs to be made narrower in applications where a small focussed beam is required, on the order of the optical wavelength. This results in the support of a single transverse mode and a beam that is diffraction-limited. These single spatial mode components are employed in fibre optics, laser pointers, and optical storage. It should be noted that these lasers may still support several longitudinal modes, allowing them to emit light simultaneously at multiple wavelengths. The band-gap of the semiconductor material and the modes of the optical cavity influence the wavelength that is emitted. In general, the modes closest to the top of the gain curve will lase most intensely, and the maximum gain will happen for photons with energy that is slightly above the band-gap energy. Depending on the operating circumstances, the width of the gain curve will determine how many extra "side modes" may also lase. Fabry-Perot (FP) lasers are single spatial mode lasers that can support numerous longitudinal modes. Within the gain bandwidth of the lasing medium, an FP laser will lease at a variety of cavity modes. An FP laser typically has an unstable number of lasing modes, which can change as a result of variations in temperature or current. Single longitudinal mode operation is a design option for single spatial mode diode lasers. These highly stable single frequency diode lasers are employed in spectroscopy, metrology, and as frequency standards. Distributed-feedback (DFB) and distributed Bragg reflector (DBR) lasers are two different categories for single- frequency diode lasers.

8. Formation of laser beam

After leaving the chip, diffraction causes the beam to rapidly diverge (expand), usually at an angle of 30 degrees vertically and 10 degrees laterally. A lens is required to create a collimated beam similar to what a laser pointer produces. Cylindrical lenses and other optics are used to create circular beams when they are needed. Due to the difference in the vertical and lateral divergences, the collimated beam for single spatial mode lasers utilising symmetrical lenses takes on an oval shape. A red laser pointer makes it simple to see this. The ellipse's long axis is perpendicular to the chip's plane.

9. Types

The above-mentioned straightforward laser diode construction is ineffective. Such gadgets can only operate in pulsed mode without being damaged due to their high-power requirements. Such technologies are not useful, while being significant historically and being simple to explain.

9.1. Double hetero-structure lasers

In these devices, two high bandgap layers are placed between a layer of low bandgap material. Gallium arsenide (GaAs) and aluminum gallium arsenide (AlxGa(1-x) As) are two materials that are frequently utilised together. The term "double heterostructure laser" or DH laser refers to a laser with two heterostructures, each of which is a junction between two distinct bandgap materials. For comparison with these more widely used gadgets, the type of laser diode discussed in the first section of the article may be referred to as a homojunction laser. See figure 3.

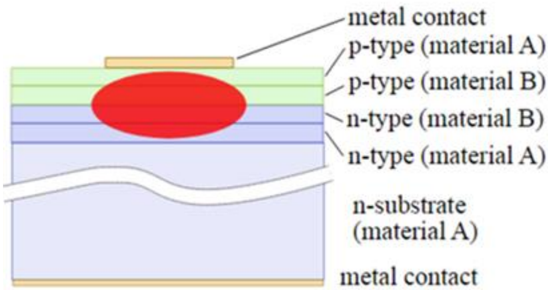


Figure: 6.3: Double Heterostructure Laser Diode

The benefit of a DH laser is that the active zone, where free electrons and holes coexist simultaneously, is limited to the middle layer's thinness. This implies that a lot more electron-hole pairs can contribute to amplification and that fewer are left out in the peripheral regions that amplify poorly. Additionally, light is reflected within the hetero junction, which limits the amount of light to the area where the amplification occurs.

9.2. Quantum well lasers

The middle layer can function as a quantum well if it is thin enough. This indicates that a portion of the electron's energy, as well as the wave function's vertical variation, is quantized. Because the electron density of states function in the quantum well system has an abrupt edge that concentrates electrons in energy states that contribute to laser activity, the efficiency of a quantum well laser is higher than that of a bulk laser. See figure 4.

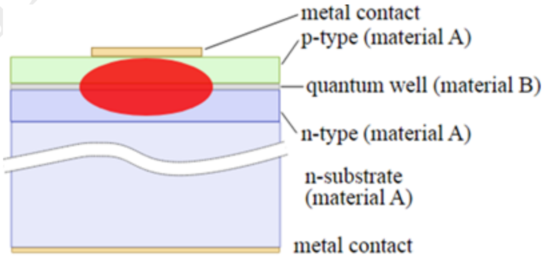


Figure: 4: Simple Quantum Well Laser Diode

Several quantum well lasers are those that have several quantum well layers. The overlap between the gain region and the optical waveguide mode is improved by using several quantum wells.

Reducing the quantum well layer to a quantum wire or to a sea of quantum dots has also shown to increase laser efficiency further.

6.9.3. Quantum cascade lasers

A particular kind of laser diode known as an interband cascade laser (ICL) is capable of producing coherent radiation over a sizable portion of the mid-infrared spectrum.

9.4. Separate confinement heterostructure lasers

The thin layer in the above-mentioned straightforward quantum well diode is simply too thin to efficiently restrict the light. Outside of the first three layers, an additional two are added as compensation. These layers efficiently limit the light because they have a lower refractive index than the central layers. A separate confinement heterostructure (SCH) laser diode is one such design. See figure 5.

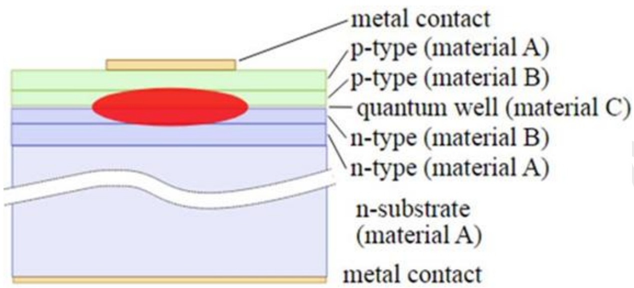


Figure: 5: Separate Confinement Heterostructure Quantum Well Laser Diode

9.5. Distributed Bragg reflector lasers

A single frequency laser diode is referred to as a distributed Bragg reflector laser (DBR). It is distinguished by an optical cavity with feedback producing electrically or optically pumped gain area sandwiched between two mirrors. The gain is favoured on a single longitudinal mode, leading in lasing at a single resonant frequency. One of the mirrors is a broadband reflector and the other mirror is wavelength selective. To enable emission, the broadband mirror is typically coated with a low reflectivity coating. A high reflectivity regularly constructed diffraction grating serves as the wavelength selective mirror. The diffraction grating is located in a passive, or non-pumped, area of the cavity.

A monolithic, single-chip device known as a DBR laser has the semiconductor's grating engraved into it. Edge emitting lasers or VCSELs can be used as DBR lasers. Extended cavity diode lasers and volume Bragg grating lasers are other hybrid architectures that have the same topology; however, they shouldn't be referred to as DBR lasers.

9.6. Distributed-feedback lasers

A single frequency laser diode is a distributed feedback laser (DFB). In DWDM systems, DFBs are the most prevalent transmitter type. A diffraction grating is etched close to the diode's p-n junction in order to stabilise the lasing wavelength. In order to feed back a single wavelength to the gain region and lase, this grating functions as an optical filter. Reflection from the facets is not necessary because the grating provides the feedback needed for lasing. Thus, a DFB has anti-reflection coating on at least one of its surfaces. The DFB laser has a constant wavelength that is determined by the grating's pitch during production and is only marginally tuneable by temperature. In optical communication applications where a precise and stable wavelength is crucial, DFB lasers are frequently utilised.

Based on its static characteristic, this DFB laser has a threshold current of around 11 mA. In a linear regime, 50 mA in the middle of the static characteristic might be used as the appropriate bias current. By adding a single phase-shift (1PS) or multiple phase-shifts (MPS) to the uniform Bragg grating, various methods have been suggested to improve the single-mode functioning in these types of lasers. However, because they have a combination of a better side-mode suppression ratio and lessened spatial hole burning, multiple phase shift DFB lasers represent the best option.

9.7. Vertical cavity surface-emitting laser

Unlike ordinary laser diodes, vertical cavity surface-emitting lasers (VCSELs) have the optical cavity axis parallel to the current flow rather than perpendicular to it. Since the active region length is much less than the lateral dimensions, the radiation exits the cavity from its surface rather than its edge as depicted in the image. Dielectric mirrors with alternating high and low refractive index quarter wave thick multilayer serve as reflectors at the ends of the cavity. See figure 6.

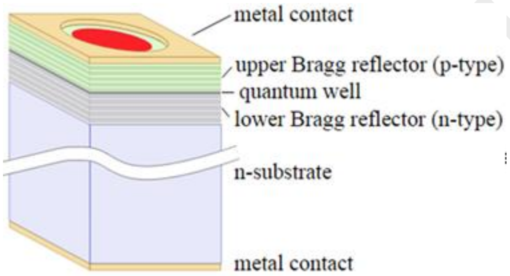


Figure: 6: Diagram of A Simple Vcsel Structure

Such dielectric mirrors provide a high degree of wavelength-selective reflectance at the required free surface wavelength λ if the thicknesses of alternating layers d_1 and d_2 with refractive indices n_1 and $n_2$are such that $n_1 d_1 + n_2 d_2 = \lambda/2$ which then leads to the constructive interference of all partially reflected waves at the interfaces. But there is a disadvantage: because of the high mirror reflectivity, VCSELs have lower output powers when compared to edge-emitting lasers.

There are several advantages to producing VCSELs when compared with the production process of edge-emitting lasers. Edge-emitters cannot be tested until the end of the production process. If the edge-emitter does not work, whether due to bad contacts or poor material growth quality, the production time and the processing materials have been wasted.

Additionally, tens of thousands of VCSELs can be processed concurrently on a three-inch gallium arsenide wafer because VCSELs emit the beam perpendicular to the active region of the laser rather than parallel as with an edge emitter. The yield can also be regulated to produce a more predictable result, despite the fact that the VCSEL production method is more laborious and resource intensive. They often exhibit a lower amount of power production, though.

9.8. Vertical external cavity surface emitting laser

Similar to VCSELs are vertical external cavity surface emitting lasers, or VECSELs. In VCSELs, the mirrors are normally generated either independently and then epitaxial bonded to the semiconductor that houses the active region, or they are grown separately and bonded to the diode structure. The architecture of VECSELs is unique in that one of the two mirrors is located outside the diode assembly. As a result, there is a free-space area in the cavity. A normal spacing of 1 cm would exist between the diode and the external mirror.

The thin semiconductor gain area, less than 100 nm thick in the direction of propagation, is one of the most intriguing characteristics of any VECSEL. A typical in-plane semiconductor laser, in contrast, requires light to propagate over distances of 250 m and up to 2 mm or longer. The effect of "antiguiding" nonlinearities in the diode laser gain area is minimised as a result of the short propagation distance. The end result is a single-mode optical beam with a huge cross-section that is not possible with in-plan diode lasers.

Due to their extraordinarily high power and efficiency when pumped by multi-mode diode laser bars, optically pumped VECSELs have been shown by several workers and are still being developed for a variety of applications, including high power sources for use in industrial machining (cutting, punching, etc.). Optically pumped VECSELs are categorised as semiconductor lasers rather than "diode lasers" due to the absence of a p-n junction.

Additionally displayed are VECSELs that are electrically pumped. Projective displays are among the uses for electrically pumped VECSELs, which are supported by the frequency doubling of near-IR VECSEL emitters to create blue and green light.

9.9. External cavity diode lasers

Tuneable lasers with double hetero structures of the AlxGa(1-x) As type are external cavity diode lasers. Intracavity etalon technology and basic tuning Littrow gratings were employed in the first external cavity diode lasers. Other designs include multiple-prism grating arrangements and gratings with grazing incidence.

10. Reliability

The reliability and failure difficulties with laser diodes are the same as those with light emitting diodes. Additionally, when used at higher power, they are vulnerable to catastrophic optical damage (COD).

The developers of the diode lasers still have exclusive rights to many of the reliability improvements made in the last 20 years. The distinctions between more dependable and less reliable diode laser products are not always discernible through reverse engineering.

Surface-emitting lasers, like VCSELs, or in plane edge emitting lasers are two types of semiconductor lasers. The edge facet mirror for edge-emitting lasers is frequently created by cleaving the semiconductor wafer into a specular reflecting plane. The weakness of the crystallographic plane in III-V semiconductor crystals (such as GaAs, InP, GaSb, etc.) in comparison to other planes facilitates this method.

The end of the perfectly periodic lattice at the cleavage plane changes the atomic states there in comparison to their bulk characteristics within the crystal. Surface states at the cleft plane have energy levels that fall within the semiconductor's (otherwise prohibited) band gap.

As a result, when light leaves the semiconductor crystal through the cleavage plane and moves into free space, some of the light's energy is absorbed by the surface states, where phonon-electron interactions turn it into heat. In turn, the cleaved mirror warms. Additionally, the mirror may heat due to imperfect contact between the edge of the electrically pumped diode laser and the mount, which creates a pathway for heat removal.

The band gap of the semiconductor contracts in the warmer regions as a result of the mirror heating. More electrical band-to-band transitions align with the photon energy as a result of the band gap narrowing, increasing the amount of absorption. The facet may melt as a result of thermal runaway, a type of positive feedback, which is referred to as catastrophic optical damage, or COD.

This issue, which is more problematic for GaAs based lasers emitting between 0.630 m and 1 m wavelengths (and less problematic for InP based long-haul telecommunications lasers emitting between 1.3 m and 2 m wavelengths), was discovered in the 1970s. A solution was developed by Michael Ettenberg, a researcher and then Vice President of the Princeton, New Jersey-based David Sarnoff Research Centre of RCA Laboratories. On the facet, a thin coating of aluminium oxide formed. If the thickness of the aluminium oxide is chosen properly, it serves as an anti-reflective coating that lessens reflection at the surface. The heating and COD at the facet were reduced as a result.

Since then, numerous other improvements have been used. Making a so called non absorbing mirror (NAM) that is non-absorbing at the wavelength of interest for the final 10 m or so before the light emanates from the cleaved facet is one method.

SDL, Inc. started delivering high power diode lasers with good reliability characteristics in the very early 1990s. At events like the 1980s SPIE Photonics West conferences, CEO Donald Scifres and CTO David Welch presented new dependability performance data. As of June 2006, the strategies employed by SDL to combat COD were regarded as highly confidential and had not been made public.

IBM Research (Ruschlikon, Switzerland) reported in the middle of the 1990s that it had developed the so called "E2 process," which gave GaAs based lasers a remarkable resistance to COD. As of June 2006, nothing was known about this procedure either.

Despite these exclusive advancements, the reliability of high-power diode laser pump bars (used to pump solid-state lasers) continues to be a challenging issue in a variety of applications. In fact, research on this topic is still ongoing, albeit under proprietary conditions, and the mechanics of diode laser failure are still being worked out.

In order for laser diodes to continue to be adapted to a wide range of applications, their lifespan must be increased.

11. Applications

With sales of almost 733 million units in 2004 compared to 131,000 of other types of lasers, laser diodes are numerically the most popular form of laser.

6.11.1. Telecommunications, scanning and spectrometry

As simple to modulate and simple to pair light sources for fibre optic communication, laser diodes are widely utilised in telecommunication. They are a component of several measurement devices, including rangefinders. Barcode readers are another popular application. As laser pointers, visible lasers typically red but subsequently also green are frequently used. The printing industry makes considerable use of both low-power and high- power diodes as light sources for image scanning (input) and the production of highly fast and high-resolution printing plates (output). In CD players, CD-ROMs, and DVD technology, infrared and red laser diodes are frequently used.

Both HD DVD and Blu-ray technology employ violet lasers. Laser absorption spectrometry (LAS) is a technique that uses diode lasers to quickly and affordably measure or monitor the concentration of different species in gas phase. Industrial processes including heat treating, cladding, seam welding, and pumping other lasers like diode-pumped solid-state lasers all make use of high-power laser diodes.

Different categories can be used to group laser diode applications. Larger solid-state lasers or optical parametric oscillators could handle the majority of applications, but diode lasers are necessary for mass-market applications due to their low cost. Since light has so many various characteristics (power, wavelength, spectral and beam quality, polarisation, etc.), it is helpful to categorise applications by these fundamental characteristics. Diode lasers are utilised in a wide variety of industries.

Utilising an optical beam's "directed energy" feature is the main component of numerous diode laser applications. Laser printers, barcode readers, image scanners, illuminators, designators, optical data recorders, combustion ignition, laser surgery, industrial sorting, industrial machining, wireless power transfer (as power beaming), and directed energy weapons could all be categorised under this heading. While some of these applications are established, others are just getting started.

11.2. Medical uses

Laser medicine: Diode lasers offer a wide range of novel applications in dentistry and medicine. Clinicians find the units to be particularly alluring for simple soft tissue operations due to their decreasing size, cost, and user-friendliness. Diode wavelengths, which range from 810 to 1,100 nm and are not suitable for cutting or ablation because they are little absorbed by soft tissue. Instead of being cut by the laser's beam, soft tissue is instead harmed by coming into touch with a hot, burnt glass tip. The distal end of the tip is significantly absorbed by the laser's irradiation, which raises its temperature to between 500 and 900 °C. The tip can be used to cut soft tissue because of how hot it is, and it can also cause haemostasis through cauterization and carbonization. Diode lasers when used on soft tissue can cause extensive collateral thermal damage to surrounding tissue.

Certain applications make use of the coherence of laser diodes since laser beam light is coherent by nature. These include holography, coherent communications, inter ferometric distance measuring, and coherent control of chemical reactions.

Range-finding, telecommunications, infrared countermeasures, spectroscopic sensing, radio-frequency or terahertz wave generation, atomic clock state preparation, quantum key cryptography, frequency doubling and conversion, water purification (in the UV), and photodynamic therapy (where a specific wavelength of light would cause a substance such as porphyrin to become chemically active as a pigment) all make use of laser diodes due to their "narrow spectral"

Laser diodes are employed because of their capacity to produce ultra-short light pulses through the process of "mode locking." High peak-power sources for laser-induced breakdown spectroscopy sensing, arbitrary waveform generation for radio-frequency waves, photonic sampling for analog to digital conversion, and optical code division multiple access systems for secure communication are some applications. Clock distribution for high performance integrated circuits is another.

11.3. Maskless photolithography

Laser diodes are used in maskless photolithography.

12. Laser diode rate equations

The laser diode rate equations model the electrical and optical performance of a laser diode. This system of ordinary differential equations relates the number or density of photons and charge carriers (electrons) in the device to the injection current and to device and material parameters such as carrier lifetime, photon lifetime, and the optical gain.

The rate equations may be solved by numerical integration to obtain a time domain solution, or used to derive a set of steady state or small signal equations to help in further understanding the static and dynamic characteristics of semiconductor lasers.

The laser diode rate equations can be formulated with more or less complexity to model different aspects of laser diode behavior with varying accuracy.

12.1. Multimode rate equations

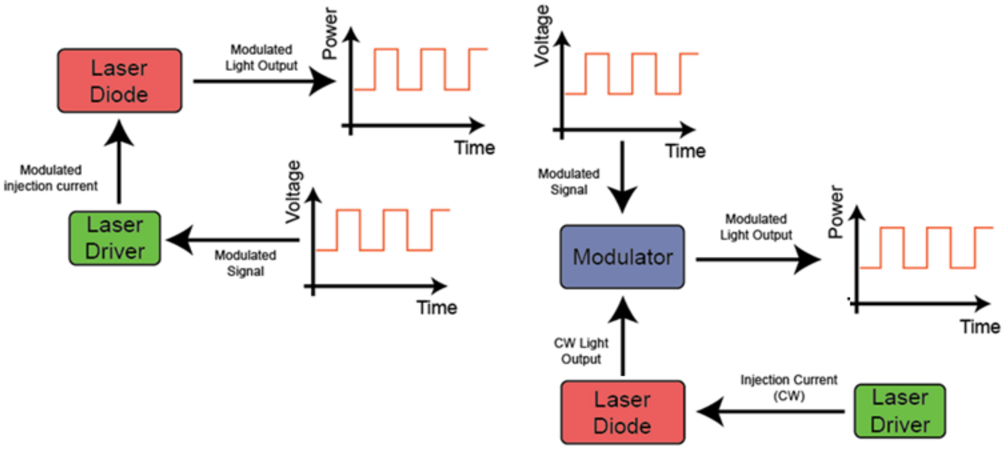
In the multimode formulation, the rate equations model a laser with multiple optical modes. This formulation requires one equation for the carrier density, and one equation for the photon density in each of the optical cavity modes,

Where, N is the carrier density, P is the photon density, I is the applied current, e is the elementary charge, V is the volume of the active region, is the carrier lifetime, G is the gain coefficient (s^{-1}), is the confinement factor, is the photon lifetime, is the spontaneous emission factor, is the radiative recombination time constant, M is the number of modes modelled, μ is the mode number, and subscript μ has been added to G, Γ, and β to indicate these properties may vary for the different modes.

The first term on the right side of the carrier rate equation is the injected electrons rate (I/eV), the second term is the carrier depletion rate due to all recombination processes (described by the decay time) and the third term is the carrier depletion due to stimulated recombination, which is proportional to the photon density and medium gain.

In the photon density rate equation, the first term ΓGP is the rate at which photon density increases due to stimulated emission (the same term in carrier rate equation, with positive sign and multiplied for the confinement factor Γ), the second term is the rate at which photons leave the cavity, for internal absorption or exiting the mirrors, expressed via the decay time constant and the third term is the contribution of spontaneous emission from the carrier radiative recombination into the laser mode.

Modulating the output power of a laser diode can happen in two ways: by changing the signal input/driving current or by alternating the continuous wave output after the light is generated. In laser modulation, the current or voltage varies with time to modulate the output signal from the laser. Direct Modulation is when the current, before reaching the laser diode, is modified with the desired signal for the application. This uses a function generator to create the modulation signal and a laser diode driver to apply the signal to the drive current for the laser. External Modulation is when the modulation is imposed onto the laser signal after the light is generated. Modulation such as Electro Optic Modulation (EOM), Acousto Optic Modulation (AOM), and Electro Absorption Modulation (EAM) can be used to manipulate the laser output with electric fields or sound waves. Both types of laser diode modulation are shown in Figure 7.



(a) (b)

Figure: 7: Direct modulation (a) and external modulation (b) schematics

Modulation can be useful for a variety of applications in the world of lasers. The capacity of transmitted data can be increased with high frequency sources and modulators for many communication applications. Laser modulation offers an alternative method for light detection and ranging (LIDAR) measurements with benefits of lower danger of eye damage and higher sensitivity than with continuous wave (CW) lasers. When, ultra-high output powers are not needed from pulsed lasers, as in the case of spectroscopy, modulated lasers can provide fast data acquisition, reduce the system costs, and enable high resolution without damaging the sample. Other types of research or experiments involving sample imaging have similar benefits from laser diode modulation.

Laser modulation can be analog or digital, with different benefits. Analog Modulation is a continuous and smooth signal that is limited to a range of values. A power vs. time graph in the shape of a sine wave is a perfect example of analog modulation where the signal changes smoothly over time. Digital Modulation has a set of finite, discreet values. A square wave is a signal with two set values to switch between. This is often used to turn a laser on and off with the low point being below threshold. The laser operates like an LED below the threshold current with spontaneous emission, and the laser operates with stimulated emission above threshold.

In direct modulation, using a digital signal through an analog input on the laser driver can cause distortion to the output power or signal of the laser. See figure 8.

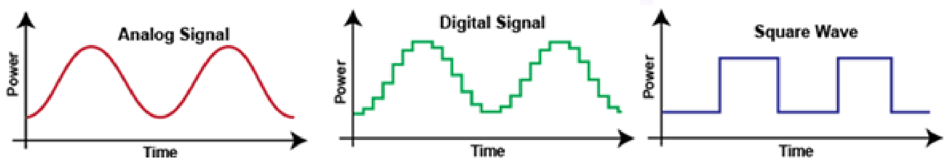


Figure: 8: Analog and Digital Modulation Signals and Square Wave Signal

12.2. Issues & solutions

There are a few problems that can arise when modulating a laser signal. Below are a few common issues and solutions or recommendations, mainly for direct modulation.

Exceeding Bandwidth – When directly modulating a laser, exceeding the bandwidth can cause distortions and output attenuation. Check with the laser driver and laser diode datasheets to ensure you are well below the listed modulation bandwidth.

Oscillation Frequency – If the laser is modulated at or around the oscillation frequency, relaxation oscillations can occur. Avoid the oscillation frequency of the laser for better signal response and reduced oscillation around the set point.

Noise – A laser driver with high noise can affect the clean output of the modulated laser. Select a low noise driver to ensure electronic noise does not propagate through the optical system.

High Current – High current operation as well as high modulation frequencies can expose underlining issues of the laser design. Careful selection of wires, power supplies, and capacitor banks can solve some of the issues created at higher currents (>10 A).

13. Summary

In this unit, you have studied about Laser diode, its principle and working. You learnt about various types of laser diodes. Laser diode is based on working of Laser therefore you learnt basic idea of Laser like spontaneous emission, stimulated emission, coherency, optical pumping and population inversion.

14 Lexicon

AOM: Acousto-Optic Modulation

CD: Compact discuss

CW: Continuous wave

DFB: Distributed feedback laser

EAM: Electro-Absorption Modulation

EOM: Electro-Optic Modulation

ICL: Interband cascade laser

15. References

1. Milan L. Mashanovitch, Larry A. Coldren, and Scott W. Corzine (2 March 2012). Photonic integrated circuits and diode lasers. Wiley & Sons, Inc. ISBN 978-1-118-14817-4.

2. Robert N. Hall, George E. Fenner, James D. Kingsley, Thomas J. Soltys, and Robert O. Carlson (November 1962). "Coherent Light Emission From GaAs Junctions" 9(9):366-368, Physical Review Letters. doi:10.1103/PhysRevLett.9.366. Bibcode: 1962PhRvL...9...366H.

3. Ajoy Chatak (2009). Tata McGraw-Hill Education, Optics, p. 1.14, ISBN 978-0-07-0262157.

4. External-cavity-controlled 32-MHz narrow-band cw GaA1As-diode lasers, C. Voumard, 1977. 1 (2): 61-3. Optics Letters. PMID 19680331. Bibcode:1977OptL....1...61V; doi:10.1364/OL.1.000061.

5. Zorabedian, P. (1995). "8". In F. J. Duarte (ed.). Tunable Lasers Handbook. Academic Press. ISBN 0-12-222695-X.

6. Deppe, Herbert; Horch, Hans-Henning (2007). "Laser applications in oral surgery and implant dentistry" (PDF). Lasers in Medical Science.

16 Suggested readings

1. Diode Lasers and Photonic Integrated Circuits
2. Open recourses
3. NPTL
4. You tube

17 Terminal questions

6.17.1 Short Answer type

1. What is radix LASER diode?
2. Differentiate Laser diode and Junction DIODE.
3. Define multimode rate equation.
5. Why LASER diode is better for communication?
6. Describe Electrical and optical pumping.
7. What is external cavity diode Laser?

Chapter 7: Optical fiber

1. Introduction

Everyday life depends heavily on light. From laser printers and digital cameras to compact disc players where a laser reflecting off a CD changes the returning signal into music, light is employed in optoelectronics and optical fibre telecommunication for data transport. It enables the use of optical fibre cables to connect telephone lines and computers. It was used in a variety of applications, including optical fibre modulators, sensors, and interferometers and lasers. In medical, lasers are utilised to perform eye surgery and image productions are employed in hospitals. The spectrum of light is much wider than what the human eye can see. The electromagnetic spectrum between 850 nm and 1310 nm and 1550 nm is referred to as the near infrared region and is used in a variety of applications, including optical fibre transmission. Fundamentally, light is made up of a collection of electromagnetic waves that resemble light particles. If light were thought of as a particle, it would be a stream of photons travelling from one location to another. Similar to electrons, photons are the fundamental building blocks of light. The particle nature of the light is less significant than its wave form when it is used for optical fibre transmission. Light is typically thought to have had a twofold nature. The electromagnetic spectrum is made up of waves with wavelengths ranging from thousands of kilometres (kilometres) down to the size of an atomic nucleus, and frequencies from one hertz to above 1025 Hz.

The electromagnetic frequency range therefore includes a number of distinct bands, each of which contains various electromagnetic waves known by various names, such as radio waves, microwaves, infrared, visible light, ultraviolet, and X-rays, starting from low frequencies (longer wavelengths) to high frequencies (shorter wavelengths). The electromagnetic spectrum contains electromagnetic energy, which includes light. The visible portion of the electromagnetic spectrum that can be seen by the human eye is referred to as the "light." The 430–750 THz (terahertz) frequency range corresponds to the visible spectrum. The optical fibres are used as waveguides to transmit light. The core of an optical fibre, which is often made of glass, is one of the three most crucial parts. Another glass or plastic layer known as the cladding surrounds the core and is distinguished by having a lower refractive index than the core material.

2. Objective

After studying this unit, you will learn about-

- Optical Fiber
- Different types of Optical Fiber
- Application of Optical Fiber

3. Optical fiber

A flexible, transparent fibre known as an optical fiber or optical fibre in Commonwealth English is created by pulling glass (silica) or plastic to a diameter just a hair's width thicker. In fiber-optic communications, where they enable transmission over greater distances and at higher bandwidths (data transfer rates) than electrical lines, optical fibres are most frequently employed as a way to send light between the two ends of the fibre. Fibres are employed in place of metal wires because they have lower transmission loss and are immune to electromagnetic interference, which metal wires are susceptible to. Additionally employed for illumination and imaging, fibres are frequently wrapped in bundles so they can be used, as in the case of a fiberscope, to carry light into or images out of small locations. Additional uses for specially created fibres include fibre optic sensors and fibre lasers, among many others. See figure 1.

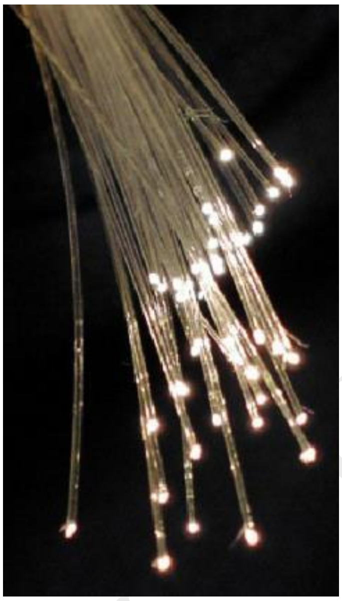


Figure: 1: A Bundle of optical Fiber

Optical fibres typically consist of a transparent cladding material with a reduced index of refraction surrounding the core. Total internal reflection, which makes the fibre function as a waveguide and keeps light inside the core, is a physical phenomenon. Multimode fibres (MMF) offer many propagation paths or transverse modes, whereas single mode fibres (SMF) only support a single mode. When significant power must be transmitted over short distances, multi-mode fibres are employed since they often have a greater core diameter. Most communication links longer than 1,000 metres (3,300 feet) employ single-mode fibres.

In fibre optic communication, the ability to link optical fibres with little loss is crucial. This requires meticulous fibre cleaving, exact alignment of the fibre cores, and coupling of these aligned cores. It is more difficult than combining electrical wire or cable. A fusion splice is frequently used for applications that require a lasting connection. This method involves melting the fibre ends together with an electric arc. A mechanical splice is another typical procedure in which the fibre ends are held together by mechanical force. Specialised optical fibre connectors are used to create temporary or semi-permanent connections.

Fibre optics refers to the branch of applied science and engineering that deals with the creation and use of optical fibres. Indian-American physicist Narinder Singh Kapany is credited with coining the phrase.

4 Applications

4.1. Communication

Because optical fibre is flexible and can be bundled into cables, it is utilised as a communication and networking medium. As opposed to electricity in electrical cables, infrared light propagates through the fibre with substantially reduced attenuation, making it particularly advantageous for long-distance communications. This enables the use of few repeaters to bridge large distances.

Each fibre can transport numerous separate channels, each using a different wavelength of light, thanks to the usage of wavelength-division multiplexing (WDM). The per channel data rate multiplied by the number of channels (often up to 80 in commercial dense WDM systems as of 2008) and divided by the forward error correction (FEC) overhead yields the net data rate (data rate sans overhead bytes) per fibre.

Fiber-optic cabling can free up space in cable ducts for short-distance applications, such as a network inside an office building (see fibre to the office). This is due to the fact that a single fibre has a far higher data capacity than electrical connections like category 5 cable, which normally operates at speeds of 100 Mbit/s or 1 Gbit/s.

Additionally, short-distance connections between devices are frequently made using fibres. A digital audio optical link, for instance, is available on the majority of high definition televisions. This enables the S/PDIF protocol over an optical TOSLINK connection to transport audio through light.

4.2. Sensors

In remote sensing, fibres are used extensively. The fibre itself serves as the sensor in some applications (the fibres transmit optical light to a processing unit that examines variations in the light's properties). Other times, a fibre connection is made between a sensor and a measurement system.

By altering an optical fibre so that the property being monitored alters the intensity, phase, polarisation, wavelength, or transit time of light in the fibre, optical fibres can be used as sensors to measure strain, temperature, pressure, and other parameters. The simplest sensors are those that adjust light intensity because they simply need a basic source and detector. Such fibre optic sensors have the ability to give distributed sensing over distances of up to one metre, which is a highly important characteristic. Among them is distributed acoustic sensing.

In contrast, by combining miniature sensing components with the fibre tip, small localised measurements can be produced. These can be created using a variety of micro and nanofabrication techniques so that they don't extend past the fibre tip's minuscule border, enabling uses like hypodermic needle insertion into blood arteries.

Extrinsic fibre optic sensors transfer modulated light from either a non-fiber optical sensor or an electronic sensor coupled to an optical transmitter using an optical fibre connection, typically a multi-mode one. Extrinsic sensors' capacity to access locations that would otherwise be inaccessible is a significant advantage. A pyrometer outside the engine is used to measure the temperature inside jet engines using a fibre to transmit radiation.

Electrical transformers have extremely strong electromagnetic fields that make it hard to use other measurement techniques. Extrinsic sensors can be used in the same way to monitor the internal temperature of electrical transformers. Vibration, rotation, displacement, velocity, acceleration, torque, and torsion are all measured by extrinsic sensors. The interference of light has been used to create a solid-state gyroscope. The Sagnac effect is used by the fibre optic gyroscope (FOG), which has no moving parts, to sense mechanical rotation.

Fibre optic sensors are frequently used in sophisticated intrusion detection security systems. On a fence, pipeline, or communication cable, light is transmitted along a fibre optic sensor cable, and the returned signal is watched and checked for anomalies. To identify disruptions and trigger an alert in the event of an intrusion, this return signal is digitally processed.

The components of optical chemical sensors and optical biosensors frequently include optical fibres.

4.3. Power Transmission

A photovoltaic cell can be used to turn light into electricity and transfer it across optical fibre. Although this method of power transfer is less effective than conventional ones, it is particularly helpful when MRI machines, which generate strong magnetic fields, are nearby and it is preferable to avoid having a metallic conductor. Other uses include supplying electricity to measurement devices in high voltage transmission equipment and the electronics in high powered antenna components.

4.4. Other uses

In medical and other applications where, intense light needs to be shone on a target without an obvious line-of-sight path, optical fibres are employed as light guides. Fiber optic light sources are frequently used in microscopes to produce powerful lighting of the samples being examined.

Imaging optics also uses optical fibre. A long, thin imaging tool called an endoscope is used to examine objects through a tiny hole. It is made of a coherent bundle of fibres, sometimes in conjunction with lenses. For minimally invasive exploratory or surgical operations, medical endoscopes are employed. Industrial endoscopes are used to examine anything that is difficult to reach, such as the interiors of jet engines.

Optical fibres in some structures carry sunlight from the roof to interior spaces. For illumination, optical-fiber lights are utilised in decorative applications such as signs, artwork, toys, and artificial Christmas trees. LiTraCon, a building material made of light transmitting concrete, is inextricably linked to optical fibre.

Optical fibre can also be used to check the health of structures. Stresses that could have a long-term effect on structures can be found with this kind of sensor. The idea behind it is to measure analogue attenuation.

Optical fibre bundles are used in spectroscopy to transfer light from a spectrometer to a substance outside of the spectrometer itself so that its composition can be determined. By reflecting light off and through substances, a spectrometer can examine them. A spectrometer can be used to study items remotely by employing fibres.

The gain medium of a fibre laser or optical amplifier can be an optical fibre doped with specific rare-earth elements, like erbium. By attaching a brief segment of rare earth doped optical fibre to a conventional (undoped) optical fibre connection, signal amplification can be achieved. In addition to the signal wave, a second laser wavelength is connected into the line and optically pumped into the doped fibre. The doped fibre transmits both light wavelengths, converting energy from the second pump wavelength to the signal wave. Stimulated emission is the mechanism responsible for the amplification.

The use of optical fibre as a nonlinear medium is also very common. Numerous nonlinear optical interactions can occur in the glass medium, and fiber's long interaction lengths enable a wide range of phenomena that can be used in practical applications and scientific research. On the other hand, fibre nonlinearity can have negative consequences on optical communications, and steps are frequently needed to reduce such unfavourable effects.

In physics investigations, wavelength-shifted optical fibres are used to gather scintillation light. To make the marks on the sight more visible, fiber-optic sights for pistols, rifles, and shotguns use pieces of optical fibre.

5. Principle of operation

Total internal reflection allows an optical fibre, a cylindrical dielectric waveguide (nonconducting waveguide), to transmit light down its axis. A core and cladding layer, both

of which are formed of dielectric materials, surround the core in the fibre. The refractive index of the core must be higher than that of the cladding in order to restrict the optical signal in the core. In step-index fibre, the transition between the core and cladding might be sudden, while in graded-index fibre, it can be progressive. Lasers or LEDs can be used to feed light into optical fibres.

Fibre is resistant to electrical interference; there is no signal interference between cables or environmental noise pickup. Even electromagnetic pulses produced by nuclear devices are impervious to the information moving inside the optical fibre.

Fibre cables are advantageous for protecting communications equipment in high voltage situations, such as power producing facilities or applications vulnerable to lightning strikes, because they do not conduct electricity. Ground loop issues are also prevented by the electrical isolation. Optical cables can be utilised in areas with explosive gases because they don't contain electricity, which could possibly ignite sparks. Comparing wiretapping to electrical connections, fibre tapping is more challenging.

Metal theft does not target fibre cables. Contrarily, during the commodities boom of the 2000s, copper cable infrastructures have been a target for attack.

5.1. Refractive index

The refractive index is a metric for determining how fast light travels through a substance. In a vacuum, such as in space, light moves the fastest. In a vacuum, light travels at a speed of around 300,000 km (186,000 mph) per second. By dividing the speed of light in a vacuum by the speed of light in that medium, the refractive index of a substance is determined. Therefore, by definition, a hoover has a refractive index of 1. A typical single-mode fibre used in communications has a core of doped silica with an index of roughly 1.4475 and a cladding comprised of pure silica with an index of 1.444 at 1500 nm. The index of refraction of a medium determines how slowly light moves through it. Based on this knowledge, a generalisation can be made that the speed of a signal travelling across optical fibre for communication is roughly 200,000 km/s. As a result, a phone call travelling via fibre between Sydney and New York, a distance of 16,000 kilometres, would experience a minimum latency of 80 milliseconds.

5.2. Total internal reflection

When light that is moving through an optically dense medium encounters a barrier at an acute angle one that is greater than the boundary's critical angle it is totally reflected. Total internal reflection is what we refer to as. In optical fibres, this phenomenon is utilised to focus light inside the core. The majority of contemporary optical fibre is weakly guiding, which means that there is only a very slight (usually less than 1%) change in refractive index between the core and the cladding. Light passes through the fibre core and bounces off the wall where the core and cladding meet.

Only light that enters the fibre within a specific range of angles can flow down the fibre without leaking out because the light must reach the border at an angle greater than the critical angle. The acceptance cone of the fibre is the name given to this set of angles. There is a maximum angle that light can enter the fibre from the fibre axis and still propagate, or travel, into the fiber's core. The numerical aperture (NA) of the fibre is the sine of this greatest angle. Splicing and working with fibre with a bigger NA requires less accuracy than

fibre with a smaller NA. The difference in refractive index between the fiber's core and cladding determines the size of this acceptance cone. The NA of single-mode fibre is modest.

5.3. Multi-mode fiber

Geometrical optics can analyse fibre with a large core diameter (more than 10 micrometres). Due to electromagnetic analysis, this type of fibre is known as multi-mode fibre. Total internal reflection directs light waves along the fibre core of a step-index multi-mode fibre. When rays cross the core-cladding boundary at an angle larger than the critical angle for this boundary, all of the light is reflected back to the source. The difference in the indexes of refraction between the materials used for the core and cladding determines the critical angle. Low angle rays that intersect the boundary are bent from the core into the cladding, where they come to an end. The acceptance angle of the fibre is determined by the critical angle, which is sometimes expressed as a numerical aperture. A high numerical aperture enables efficient light coupling into the fibre by allowing light to flow down the fibre in rays that are both parallel to the axis and at varied angles. However, due to the fact that rays travelling at different angles have varied path lengths and hence go through the fibre at varying speeds, this high numerical aperture increases the amount of dispersion.

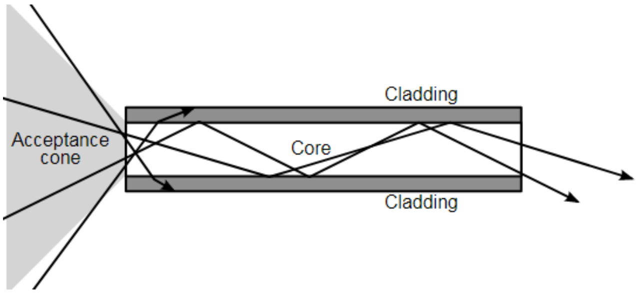


Figure: 2: The propagation of light through a multi-mode optical fiber

The index of refraction in the core of a fibre with a graded index constantly lowers between the axis and the cladding. As a result, light rays approach the cladding smoothly rather than suddenly reflecting from the core-cladding boundary. Because high angle rays flow more through the lower-index peripheral of the core than the high-index centre, the resulting curved routes reduce multi path dispersion. To reduce the variation in axial propagation speeds of the different rays in the fibre, the index profile is adopted. A parabolic relationship between the index and the distance from the axis is extremely near to this ideal index profile.

5.4. Single mode fiber

Geometric optics cannot be used to simulate a fibre with a core diameter less than roughly 10 times the wavelength of the propagating light. According to Maxwell's equations as simplified to the electromagnetic wave equation, it must instead be examined as an electromagnetic waveguide structure. The fibre supports one or more limited transverse modes that allow light to travel through the fibre as an optical waveguide. Single-mode fibre is defined as having just one mode. The waveguide study reveals that the fibre's light energy is not entirely contained within the core. Instead, a sizeable portion of the bound mode's energy, particularly in single-mode fibres, travels through the cladding as an evanescent wave. The most popular kind of single-mode fibre is made for use in the near infrared and has a core diameter of 8–10 micrometres. Comparatively, multi-mode fibre is produced with core sizes ranging from hundreds of micrometres to as little as 50 micrometres.

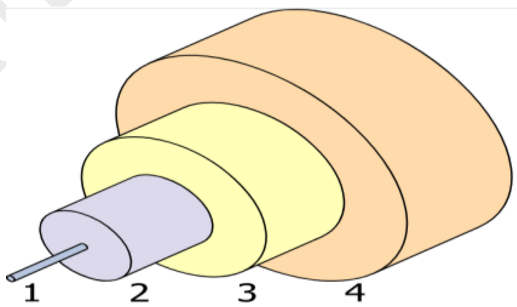


Figure: 3: The Structure of a typical Single-Mode Fiber

5.5. Special purpose fiber

A non-cylindrical core or cladding layer, often with an elliptical or rectangular cross-section, is used in the construction of some special-purpose optical fibre. These consist of fibre that maintains polarisation in fibre optic sensors and fibre made to prevent whispering gallery mode propagation.

A consistent pattern of index variation is used to create photonic-crystal fibre, frequently in the form of cylinder-shaped holes that run the length of the fibre. To limit light to the fiber's core, this type of fibre uses diffraction effects in place of or in addition to total internal reflection. The fibre's characteristics can be modified for a wide range of applications.

6. Mechanisms of attenuation

In fibre optics, attenuation, sometimes referred to as transmission loss, is the loss of light signal strength as it passes through the transmission medium. In fibre optics, attenuation coefficients are often stated in units of dB/km. The medium typically encloses the incident light beam inside a silica glass fibre. A key obstacle preventing the transmission of a digital signal over long distances is attenuation. As a result, extensive research has been done on both ways to maximise the optical signal's amplification while also minimising its attenuation. The constant improvement of manufacturing procedures, raw material purity, preform, and fibre designs over the course of four decades led to a four orders of magnitude reduction in the attenuation of silica optical fibres, enabling these fibres to approach the theoretical lower limit of attenuation.

Extremely low loss single-mode optical fibres are readily available. A typical single-mode fibre for telecommunications wavelengths, the SMF-28 fibre from Corning has a loss of 0.17 dB/km at 1550 nm. For instance, SMF-28 transmits over 75% of light a1,550 nm over an 8 km length. The Mariana Trench, which is located in the Pacific Ocean and has a depth of 11,000 metres (36,000 feet), could be seen all the way to the bottom if ocean water were as clear as fibre, according to a claim.

According to empirical studies, both scattering and absorption are the main causes of attenuation in optical fiber.

7 Light scattering

Total internal reflection is the basis for how light travels through the core of an optical fibre. Even at the molecular level, rough and uneven surfaces can cause light rays to reflect in erroneous directions. Diffuse reflection, also known as scattering, is this phenomenon and is frequently characterised by a wide range of reflection angles.

The wavelength of the light being scattered affects scattering. The frequency of the incident light wave and the physical dimension (or spatial scale) of the scattering centre, which is often in the shape of some unique micro-structural feature, determine the limitations to the spatial scales of visibility that result. As scattering centres will have dimensions on a comparable spatial scale, visible light, which has a wavelength of the order of one micrometre (one millionth of a metre), will have a similar wavelength.

Attenuation is the effect of light being scattered incoherently at internal surfaces and interfaces. In addition to pores, the majority of the internal surfaces or interfaces in (poly)crystalline materials like metals and ceramics take the form of grain boundaries, which divide minute regions of crystalline order. It has been demonstrated that scattering ceases to occur to any appreciable degree when the size of the scattering centre (or grain boundary) is decreased below that of the wavelength of the light being scattered. Transparent ceramic materials are already being produced as a result of this phenomenon. See figure 4.

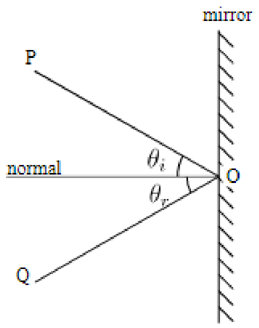


Figure: 4: Specular Reflection

Similarly, molecular level imperfections (compositional variations) in the glass structure are what cause light to scatter in optical quality glass fibre. Glass is only the limiting instance of a polycrystalline solid, according to one growing school of view. According to this concept, domains with varying degrees of short-range order serve as the foundation for metals, glasses, and ceramics. Micro structural flaws that are dispersed between and within these domains offer the best places for light scattering. The transparency of IR missile domes is thought to be constrained by the same phenomenon.

Nonlinear optical processes in the fibre can also result in scattering at high optical powers. See figure 5

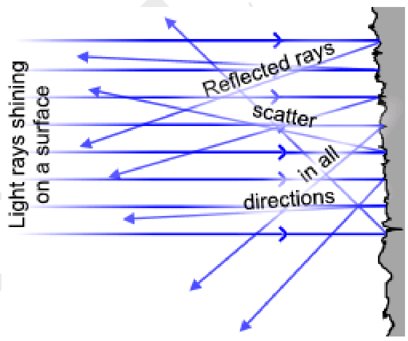


Figure: 5: Diffuse Réflexion

8 UV-Vis-IR absorption

In addition to light scattering, selective absorption of particular wavelengths can also result in attenuation or signal loss. Following are some primary material considerations for both electrons and molecules:

- At the electronic level, the ability to absorb a quantum of light (or photon) with a certain wavelength or frequency in the ultraviolet (UV) or visible ranges relies on how widely separated (or "quantized") the electron orbitals are. Colour is created as a result of this.
- At the atomic or molecular level, it depends on the vibrational frequencies of the atoms or molecules, the density of the atoms or molecules, and whether or not the atoms or molecules show long-range order. The ability of the material to transmit longer wavelengths in the infrared (IR), far infrared, radio, and microwave regions will depend on these variables.

Any optically transparent device must be designed with a material selection based on an understanding of its characteristics and limits. The material's maximum long wavelength transparency is determined by the crystal structure absorption properties that are visible in the lower frequency ranges (mid to far IR wavelength range). They are the outcome of the interaction between the incident light wave radiation and the thermally produced vibrations of the atoms and molecules that make up the solid lattice. Because of this, the far infrared (>10 m) limiting areas of absorption generated by atomic and molecular vibrations (bond stretching) surround all materials.

In other words, the reason why a certain substance selectively absorbs IR light is because the light wave's chosen frequency coincides with the frequency (or an integer multiple of the frequency, or harmonic) at which the material's particles vibrate. Since various atoms and molecules vibrate at various natural frequencies, they will preferentially absorb certain IR light frequencies (or spectrum regions).

9 Numerical aperture

The range of angles over which an optical system can take or emit light is defined by its numerical aperture (NA), which is a dimensionless number in optics. NA has the property that it is constant for a beam when it passes from one material to another by including index of refraction in its definition, provided there is no refractive power at the interface. varied branches of optics have slightly varied definitions for the term.

Numerical aperture is frequently used in fibre optics to define the range of angles within which light that is incident on the fibre will be transmitted along it as well as in microscopy to describe the acceptance cone of an objective (and hence its light-gathering ability and resolution).

Numerical aperture is the light gathering capability of the fiber. It is also called a figure of merit of fiber. A high value of numerical aperture is required in order to have a good coupling. If fiber has a low numerical aperture then coupling losses will be large.

9.1. General optics

In most areas of optics, and especially in microscopy, the numerical aperture of an optical system such as an objective lens is defined by

$$NA = n\, sin\theta$$

where is the half-angle of the largest cone of light that can enter or exit the lens, and n is the index of refraction of the medium in which the lens is operating (1.00 for air, 1.33 for pure water, and commonly 1.52 for immersion oil). Generally speaking, this is the angle of the system's actual marginal ray. The NA of a pencil of rays is an invariant as it moves from one material to another through a flat surface because the index of refraction is taken into account. By rearranging Snell's law to discover that n sin is constant across an interface, this is simply demonstrated.

Within the paraxial approximation, the lens's angular aperture in air is around double this amount. The NA will change as an item or picture point is moved, and is often measured with regard to that point. Unless otherwise stated, NA in microscopy normally refers to object space NA.

NA is significant in microscopy since it represents a lens's capacity for resolution. The resolution has a proportional relationship with the size of the smallest detail that can be resolved.

$$\frac{\lambda}{2NA}$$

Where, the light's wavelength is. Finer details can be seen using a lens with a higher numerical aperture than one with a smaller one. Given good (diffraction limited) optics,

lenses with higher numerical apertures will typically produce brighter images, but at the expense of a shorter depth of field.

In optical disc formats, the term "pit size" refers to a numerical aperture.

The working distance, or the distance between the front lens and the specimen, is reduced by decreasing the objective's numerical aperture and magnification.

9.2. Laser physics

Numerical aperture is defined slightly differently in laser physics. Slowly propagating laser beams spread out as they travel. The dispersion of the laser beam in the "far field" creates a cone of light when it is distant from the narrowest point of the beam, where it is roughly linear with distance. The relationship utilised to describe an optical system's NA is also used to define the NA of a laser beam.

$$NA = n\,sin\theta$$

However, the definition of varies. Unlike the cone of light that passes through the aperture of a lens, laser beams often do not have sharp edges. Instead, the irradiance progressively decreases as one moves away from the beam's centre. A Gaussian profile for the beam is extremely typical. The divergence of the beam is commonly defined by laser physicists as the far-field angle between the beam axis and the location away from the axis where the irradiance is reduced to e^{-2} times the on axis irradiance. The NA of a Gaussian laser beam is then related to its minimum spot size ("beam waist") by $NA \approx \frac{\lambda_0}{\pi wo}$

Where, λ_0 is the vacuum wavelength of the light, and 2wo is the diameter of the beam at its narrowest spot, measured between the e^{-2} irradiance points ("Full width at e^{-2} maximum of the intensity"). This means that a laser beam that is focused to a small spot will spread out quickly as it moves away from the focus, while a large-diameter laser beam can stay roughly the same size over a very long distance.

9.3. Fiber optics

The acceptance cone of a multi-mode optical fibre is the range of angles at which light will enter the fibre and only propagate there. The acceptance angle, max, of this cone is its half angle. The indices of refraction of the core, cladding, and medium alone determine the acceptance angle for step-index multimode fibre in a particular medium: see figure 6.

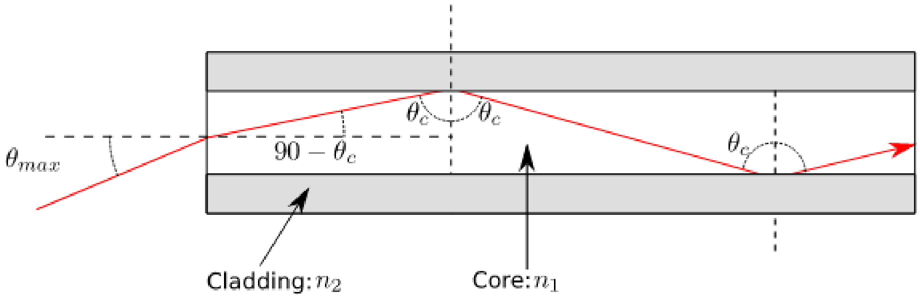


Figure: 6: A multi-mode fiber of index n_1 with cladding of index n_2

$$n.\, sin\theta_{max} = \sqrt{n_{core}^2 - n_{clad}^2}$$

n_{core}, n_{clad}, are the refractive indices of the fiber's core and cladding, respectively, while n is the refractive index of the medium surrounding the fibre. Higher angle light will pass through the core, but because it won't completely reflect off the core cladding interface, it won't reach the fiber's other end. The following is the formula's derivation.

Snell's law at the medium-core contact provides the following when a light beam is incident from a medium of refractive index n to the core of index n_{core}at the maximum acceptance angle.

$$n.\, sin\theta_{max} = n_{core}.\, sin\theta_r$$

From the geometry of the above figure, we have:

$$sin\theta_r = \sin(90^o - \theta_c) = cos\theta_c$$

Where

$$\theta_c = arcsin\frac{n_{clad}}{n_{core}}$$

In the critical angle for total internal reflection, Substituting $cos\theta_c$ for $sin\theta_r$ in Snell's law we get:

$$\frac{n}{n_{core}} sin\theta_{max} = cos\theta_c$$

By squaring both sides

$$\left(\frac{n}{n_{core}}\right)^2 (sin\theta_{max})^2 = (cos\theta_c)^2 = 1 - sin^2\theta_c = 1 - \frac{n_{clad}^2}{n_{core}^2}$$

Solving, we find the formula stated above:

$$n.\, sin\theta_{max} = \sqrt{n_{core}^2 - n_{clad}^2}$$

It has become common to define the numerical aperture (NA) of any type of fibre to be since this has the same shape as the NA in other optical systems.

$$NA = \sqrt{n_{core}^2 - n_{clad}^2}$$

Where, n_{core} is the fiber's centre axis' refractive index. It should be noted that when this definition is applied, the relationship between the NA and the fiber's acceptance angle is reduced to an approximation. Although the acceptance angle for single-mode fibre is very different and cannot be derived from the indices of refraction alone, manufacturers frequently cite "NA" for single-mode fibre based on this calculation.

The volume of bound modes, or the NA, is correlated with the normalised frequency.

Equilibrium numerical aperture is a phrase occasionally used in relation to multimode fibres. This is the numerical aperture of a ray leaving a fibre with a stable equilibrium mode distribution with regard to its extreme exit angle.

10 Pulse broadening optical fiber

155 Mbp and 622 Mbps are the operating speeds of GRIN fibre local area networks (LANs) for broadband multimedia applications using asynchronous transfer mode (ATM). Already, speeds greater than 1 Gbps were being used without compensating for differential mode delay (DMD). An enhanced route to gigabit Ethernet is provided by the interconnect technology of Ethernet LAN 10 Mbps and 100 Mbps. Modal dispersion, which transforms digitised square signal pulses into widened Gaussian pulses, limits the bandwidth of multimode fibres. Delay distortion is a result of this signal distortion. If the discrepancy is significant and the pulse no longer appears to be Gaussian, the pulse may occasionally disintegrate.

Intramodal and intermodal dispersion are the two main pulse-broadening mechanisms in an optical fibre. Because group velocity is wavelength dependent, intramodal dispersion results. Additionally, it grows as the optical source's spectral width grows. A laser diode's spectral breadth is just about 1 or 2 nm, but an LED's is roughly 40 nm for a spectrum of 830-870 nm with a peak emission wavelength of 850 nm. As a result, utilising a single-mode laser diode as an optical source helps lower intramodal dispersion in optical fibres. The dispersive characteristics of the optical fibre material (material dispersion) and the guidance effects of the optical fibre (waveguide dispersion) both contribute to intramodal dispersion.

The fluctuation of group velocity for each mode at a single frequency led to intermodal dispersion. Due to the massive multi-mode dispersion that results in the maximum pulse broadening, multimode step index fibres exhibit a high value of dispersion. The overall dispersion of GRIN fibre is 100 times less than that of multi-mode step-index fibre as a result of the parabolic shape of the refractive index profile. Multi-mode fibres can be used in GRIN optical fibre networks to lessen the intermodal dispersion. A quick and precise measurement method that enables the identification of intrinsic profile dispersion effects on transmission bandwidths in graded index fibres is required as the intermodal dispersion reduces.

Numerous writers have investigated intramodal dispersion in optical fibres. Investigations have been done on both the step-index and graded-index profiles. It has been investigated how intramodal dispersion behaves in multimode graded index profiles with the core profile parameter. On the other hand, there have been a number of reports of attempts to detect intermodal dispersion in optical fibres. A parabola like graded refractive index profile throughout the fibre core and optical mode coupling, in which energy is transferred between the modes by means of random perturbations along the fiber's propagation direction, are the two main methods employed to account for the dispersion.

Although fabrication techniques may provide a central index dip in the core refractive index profile, UV treatment, which is used to increase the overall refractive index difference, causes a very faint index dip in the fibre to become very noticeable. Additionally, it is possible to deliberately broaden the fundamental mode field profile in the direction of a plateau like distribution, which has benefits for fibre amplifiers, fibre connections, and self-imaging.

The light rays go through the fibre as skew rays or helical rays because the core refractive index has a parabolic shape. As a result, with graded-index fibre, the refractive index profile determines the fiber's bandwidth. The index profile of optical fibres has been characterised using a number of methods, including the far-field pattern technique, quantitative phase microscopy, non-interferometric transverse phase gradients method based on bright field microscopy, a laser lens fibre interferometer, a diffraction method, digital holographic interferometry, light scattering method, and propagating-beam method, in order to reduce dispersion in optical fibre communications.

In the study of fibres, a potent method is the multiple-beam Fizeau fringe. The refractive index, birefringence, and dispersion of natural, synthetic, and optical fibres have all been calculated using this method. It has also been used to study the creation and identify the fibre characteristics of GRIN optical fibres, omitting the optical fibre dip. The fibre dip is taken into account in the current work. The optical phase shift difference is investigated using multiple-beam Fizeau fringes in transmission along the optic axis of GRIN optical fibre while submerged in matching liquid. It is investigated how GRIN optical fibres with a central index dip affect the pulse broadening, intermodal and intramodal dispersion, and maximum transmission rate across the fibre cross section.

11 Advantages of fiber optics

Extremely high bandwidth - Fibre offers a bandwidth that is unmatched by any other cable-based data transmission medium.

1. E**asily accommodate growing bandwidth** - New equipment may be added to inert fibre cables using several of the most recent kinds of fibre optic cabling to offer significantly increased capacity over the fibre that was originally laid. Dense Wavelength Division Multiplexing, or DWDM, allows fibre optic cabling to switch on and off different light wavelengths as they pass through the fibre at will. These two features of fibre cable make it possible to dynamically provision network bandwidth to accommodate spikes and lulls in data traffic.

2. **Resistance to electromagnetic interference** - Because fibre is so resistant to electromagnetic interference, it has an extremely low bit error rate. Transmission over fibre optics is essentially noise free.

3. **Early cable damage detection and secure transmissions** - Fibre transmissions are

much more secure than conventional electron-based ones because no data can be intercepted by "listening in" to electromagnetic energy that is "leaking" through the cable. Splices in the cable can be easily found by continuously monitoring an optical network and precisely measuring the amount of time it takes for light to reflect down the fibre.

12 Disadvantages of fibre optics

1. Despite a decline, installation expenses are still substantial. Even if the cost of installing fibre is decreasing by as much as 60% a year, fibre optic cabling installation is still quite expensive. Fibre is moving into the local loop and enabling subscriber and end user broadband access through technologies like FTTx (Fibre To The Home, Premises, etc.) and PONs (Passive Optical Networks) as installation costs fall. Fiber's original domain and primary application in the carrier backbone is still where it primarily exists today.

2. Special test equipment is frequently needed - A fibre optic network cannot be used with the test equipment that is generally and customarily used for conventional electron- based networking. In order to effectively test optical fibre, expensive, specialised optical test equipment like optical probes and an OTDR (Optical Time Domain Reflectometer) are needed at the majority of fibre endpoints and connection nexuses.

3. Physical damage susceptibility - Fibre is a small, compact wire that is very prone to being cut or harmed during construction or installation work. Railroad car derailments represent a serious threat to cable damage since railroads frequently provide rights of way for fibre optic installation, and these incidents can disrupt service to large populations as fibre optic cables have incredible data transmission capacities. As a result, when fibre optic cabling is selected as the transmission medium, restoration, backup, and survivability issues must be addressed.

4. Damage of fibre optic cables caused by wildlife for instance, many birds gnaw at fibre cable jackets to use portions of the Kevlar reinforcement material because they find it particularly enticing as nesting material. Insects like ants like to eat the plastic shielding; therefore, they frequently may be seen nibbling at the fibre optic cable. Beavers and other rodents utilise exposed fibre wire to sharpen their teeth. Sharks have also been known to chew through underwater fibre optic cabling, particularly at the repeating spots, causing damage. A plant known as the Christmas tree plant wraps itself so tightly around fibre optic cable that light impulses moving down the fibre are choked off. This plant views the wire as a tree root.

13 Summary

In this unit, you have studied about optical fiber its principle and working. You learnt fabrication of optical fiber and their different types. Optical fibers have large application. Despite the fact that fibre optics have been there for a long time, our technology is only now able to fully utilise them. Researchers and scientists will keep looking for new methods to use fibre optics in our daily lives in the near future. There is little doubt that fibre optics will continue to advance and enable people to keep increasing their communication, medical care, and military capabilities thanks to their capacity to improve gadgets and communication.

14 Lexicon

ATM: Asynchronous Transfer Mode

DMD: Differential Mode Delay

LAN: Local Area Network

NA: Numerical Aperture

PON: Passive Optical Networks

OTDR: Optical Time Domain Reflectometer

15. References

1. "Optical Fiber". www.thefoa.org. The Fiber Optic Association. Retrieved 17 April 2015.

2. Senior, John M.; Jamro, M. Yousif (2009). Optical fiber communications: principles and practice. Pearson Education. pp. 7–9. ISBN 978-0130326812.

3. "Birth of Fiberscopes". www.olympus-global.com. Olympus Corporation. Retrieved 17 April 2015.

4. Lee, Byoungho (2003). "Review of the present status of optical fiber sensors". Optical Fiber Technology. 9 (2): 57–79. Bibcode:2003OptFT...9...57L. doi:10.1016/s1068-5200(02)00527-8.

5. Pearsall, Thomas (2010). Photonics Essentials, 2nd edition. McGraw-Hill. ISBN 978- 0-07-162935-5. Archived from the original on 2021-08-17. Retrieved 2021-02-24.

6. The Optical Industry & Systems Purchasing Directory. Optical Publishing Company. 1984.

7. Hunsperger (2017-10-19). Photonic Devices and Systems. Routledge. ISBN 9781351424844.

8. Fennelly, Lawrence J. (26 November 2012). Effective Physical Security (Fourth ed.). Elsevier Science. p. 355. ISBN 9780124159815.

9. "Narinder Singh Kapany Chair in Opto-electronics". ucsc.edu. Archived from the original on 2017-05-21. Retrieved 2016-11-01.

10. Colladon, Jean-Daniel (1842). "On the reflections of a ray of light inside a parabolic liquid stream". Comptes Rendus.

11. Bates, Regis J (2001). Optical Switching and Networking Handbook. New York: McGraw-Hill. p. 10. ISBN 978-0-07-137356-2.

12. Tyndall, John (1870). "Total Reflexion". Notes about Light.

16 Suggested readings

1. "Optical Fiber Communications" By: JOHN M. SENIOR

2. Introduction to Optical Electronics by Keneth E Jones 3. Open resources

17 Terminal questions

1. What is an optical communication system?

2. What are the components of an optical communication system? and What is the working principle of optical fiber?

3. What are the advantages and disadvantages of optical fiber communication?

4. What is the significance of the Numerical aperture of optical fiber cable?