SOLID STATE PHYSICS

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DEDICATION

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"We would like to express our heartfelt gratitude to the Almighty God for giving us the wonderful opportunity to write this book. Without His blessings and guidance, this achievement would not have been possible.

We would also like to extend our sincere thanks and appreciation to our honourable President Er. A. C. S. Arun Kumar, Dr. M. G. R. Educational Research Institute, Chennai, for his unyielding support, encouragement, and motivation throughout the writing process. His vision and leadership have been instrumental in our success.

Our deepest thanks go to the Management, Executives, Staff, and Students of Dr. M.G.R Educational Research Institute, whose valuable support and encouragement were instrumental in the completion of this work. Without their contributions, this book would not have been possible.

We would also like to acknowledge and thank our parents and family members, whose unwavering support and love have been our pillars of strength throughout our lives. Their unending encouragement and belief in us have been critical in making this work a success.

Finally, we dedicate this book to all those who strive to make this world a better place through their dedication and hard work. May it inspire and motivate them to continue their noble efforts for the betterment of humanity."

Authors

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Preface

Solid state physics is an exciting field of study that has revolutionized the world of modern electronics and advanced technology. This book is intended for graduate engineers who seek to deepen their understanding of the fundamental concepts and principles of solid-state physics.

The book is divided into five chapters, each covering a different aspect of solid-state physics. **Chapter 1** introduces the basic concepts of crystal structures, including lattice structures, symmetry operations, and crystallographic planes and directions.

Chapter 2 focuses on conductors and superconductors, including the electrical and thermal properties of metals, the Meissner effect, and the BCS theory of superconductivity.

Chapter 3 delves into semiconductor physics, including band theory, carrier transport, and the physics of p-n junctions.

Chapter 4 explores magnetic and dielectric physics, including the behavior of magnetic materials, ferroelectricity, and the physics of dielectric materials.

Chapter 5 discusses the principles of optoelectronics, including the physics of light emission, absorption, and detection in semiconductors. Throughout the book, we strive to provide a clear and concise presentation of the key concepts of solid-state physics, with numerous examples and illustrations to aid in understanding. We also include a number of problems at the end of each chapter to help reinforce the concepts and encourage active learning.

This book is intended to serve as a comprehensive resource for graduate engineers seeking to gain a deep understanding of the fundamental principles of solid-state physics. It is our hope that this book will be a valuable reference for students, researchers, and professionals working in the fields of materials science, electronics, and engineering.

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Foreword

Solid state physics is a fascinating field of study that has captivated the minds of physicists and materials scientists for many decades. It is a discipline that explores the fundamental properties of matter in solid form, and has given rise to some of the most transformative technological advances of the modern era.

This book, titled "Solid State Physics", provides a comprehensive overview of the key concepts and theories that underpin this important field of physics. Written by experts in the field, it is designed to be accessible to both students and researchers, with a focus on the fundamental principles that govern the behavior of solid-state materials. The book covers a wide range of topics, including crystal structures, lattice vibrations, electronic properties, magnetic properties, and transport phenomena in solids. It also delves into more advanced topics such as superconductivity, topological materials, and quantum computing.

The authors have done an excellent job of presenting the material in a clear and concise manner, making it easy for readers to follow along and understand even the most complex concepts. The text is accompanied by numerous figures and illustrations, which help to bring the material to life and provide visual aids for understanding.

In short, "Solid State Physics" is an outstanding resource for anyone interested in learning about this important field of study. Whether you are a student, researcher, or simply someone with a passion for physics, this book will provide you with a solid foundation in the principles of solid-state physics and equip you with the tools you need to explore this fascinating area of science.

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Prologue

The study of solid-state physics is the exploration of the mysteries that lie at the heart of the material world. From the solid crystals that form the foundation of our buildings, to the semiconductors that power our electronics, to the exotic materials that challenge our understanding of matter, solid state physics offers a glimpse into the fundamental nature of the universe.

This book is an introduction to the principles and concepts of solid-state physics, intended for students and researchers in physics, materials science, and engineering. It covers the essential topics of crystal structure, electronic properties, lattice vibrations, and thermal properties of solids, as well as the principles of semiconductor physics and the physics of magnetism.

Throughout the book, we strive to convey the beauty and elegance of solid-state physics, as well as its relevance to modern technology and society. We present the key ideas and theories in a clear and concise manner, using illustrative examples and diagrams to help readers develop a visual understanding of the concepts.

At the same time, we acknowledge the challenges and complexities of the subject, and we encourage readers to grapple with the open questions and puzzles that remain at the forefront of solid-state research. We hope that this book will inspire readers to pursue further study and research in this exciting and important field of physics.

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Chapter 1

CRYSTAL STRUCTURE

1.1 Introduction

There are three general states of matter: solid, liquid, and gaseous state. When there is a transition from solid state to gaseous state, the space between the neighbouring atoms increases and their structures also change. Conductors, semiconductors, and insulators are the categories used to describe the properties of solids according to their electrical behaviour. Materials containing a significant quantity of unpaired electrons (free electrons) are called conductors. These available electrons are mainly responsible for the flow of electricity. Examples for conductors are copper, iron metals etc.,

On the other hand, insulators cannot contain free electrons and there is no flow of electricity. Sometimes it rarely contains any free electrons that may potentially carry electric current. Examples are wood, glass, dielectric materials etc., the semiconductors are located in the middle of the conductors and the insulators. When temperatures are below absolute zero, semiconductors behave like insulators, but semiconductors become more conductive as temperature rise. Examples are Germanium, silicon etc..You will learn about the many states of solids as you go through this subject. In addition, you will learn about lattices, bases, many kinds of lattices, and crystal formations.

1.2 Crystalline and Amorphous Formations

The ability of the component atoms of a great many solids to organise themselves in an orderly periodic pattern is one of the most striking characteristics of matter in its solid form. Many different types of solids exhibit this property. Based on the arrangement of the components that make up solids, solids can be classified as crystalline polycrystalline and amorphous. A solid substance with such a regular arrangement of atoms is known as a crystalline solid, more frequently referred to as a crystal. Crystalline matter is produced when a specific pattern of similar building blocks is repeated in three dimensions regularly and periodically. The atoms that make up these fundamental units may be single atoms or they may be made up of a collection of atoms. The term "motif" refers to these recurrently occurring building pieces. Semi crystalline or partly crystalline solids are crystals that only contain uniformity and periodicity in the arrangement of their atoms or molecules in one or two dimensions. These crystals are also known as polycrystalline solids. Crystalline structures may be found in the natural state of most metals. These things, when melted, lose their crystalline structure, yet their electrical characteristics nearly completely retain their original state. In a crystal, each of the bonds has the same strength as the others. Therefore, organic and inorganic crystalline materials melt (and solidify) at a fixed temperature. Crystalline solids include things like diamonds, rock salt, and sugar, amongst other things.

The arrangement of atoms in amorphous materials does not follow any regular or periodic pattern. Hence these substances are not classified as crystalline. The strength of the bonds that make up an amorphous solid is not uniform across the board. When it is heated, the bonds that are not very strong are the ones that break apart first. As a result, an amorphous solid will gradually become a liquid when heated. As a result, it is impossible to determine the exact temperature at which they will melt or freeze. Because of its high viscosity or the rapid pace at which it is cooling, the molten state of the amorphous solid progressively transforms into a solid at temperature that range from room temperature to a much lower temperature as it is cooled. Therefore, the disordered shape is maintained even in the solid state of an amorphous matter. Glass perfectly illustrates an amorphous solid.

Therefore, long-range order is the characteristic that distinguishes a crystal from an amorphous solid, even though both types of solids display order in their structures.

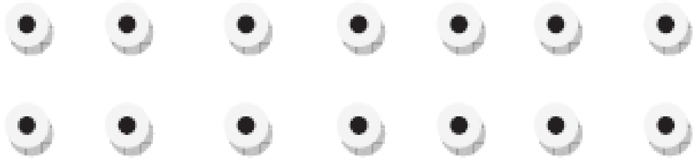
1.2.1 Space or Crystal Lattice

The crystal structure is generally described by various terms such as lattice, indexing systems of planes and directions. The endless repeating term accomplishes the formation of a crystal in the space of similar structural elements (atoms, molecules or ions). One may substitute a geometric point for each unit. The result is a pattern of dots that share the crystal's geometrical characteristics. This particular geometrical arrangement is known as the crystal lattice, or lattice for short. Lattice points are the name given to each point. The crystal lattice is another name for space lattice. **A crystal structure is a regular pattern of points representing the three-dimensional arrangement of a crystal's particles, atoms, molecules, or ions.**

In order to create a crystal structure, a lattice must first have a basis attached to each point of the lattice. This gives rise to the equation

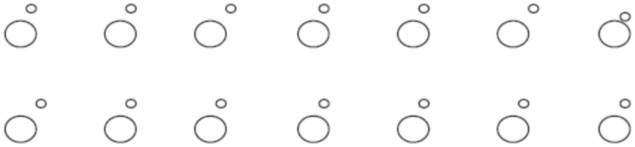
"**Lattice + Basis = Crystal Structure**."

In contrast to the lattice, the crystal structure exists in the physical world. The direct causal connection that can be drawn between lattice, basis, and the crystal structure is shown graphically in fig. 1. The crystalline structure is produced when the basis, denoted by b, is added to each lattice point that make up the lattice (a). Using that information, you can identify the basis by looking at (c) and abstracting the space lattice.



a) Space Lattice

b) Bases containing two different ions



c) Crystal Structure

Fig. 1 Crystal Structure

Qualities and Traits of Crystal Lattices

The following is a list of some of the qualities that a crystal lattice possesses:

- Each point in the crystal lattice represents a component particle, an atom, a molecule, or an ion. These constituent particles can be found everywhere in the crystal.
- Each point that makes up the lattice is referred to as a lattice point or a lattice site.
- To illustrate the geometry of the lattice, the points are connected by lines.

The formation of crystal lattice in unit cell is shown in fig. 2 and 3.

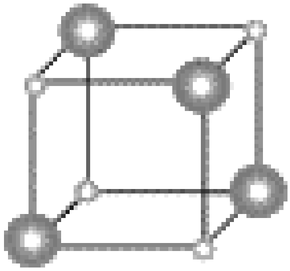


Fig. 2 Unit Cell

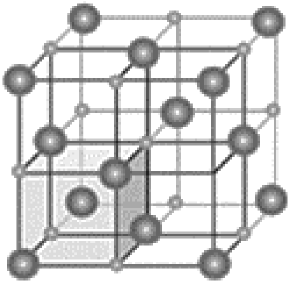


Fig. 3 Crystal Lattice

1.3 Unit Cell

The term "unit cell" refers to the smallest piece of a space lattice capable of producing a whole crystal by repeatedly reproducing its dimensions in several different orientations.

Unit cells are characterized by the length of their edges and the angles formed by those edges. Fig. 4 illustrates the dimensions of the unit cells as OA = a, OB = b, and OC = c, respectively. ϒ, α and β, in that order, are used to depict the angles that exist between a and b, b and c, a and c respectively. These kinds of angles are referred to as interfacial angles. The axes of the crystal are denoted by the vectors $\vec{a},\vec{b},\vec{c}$ respectively.

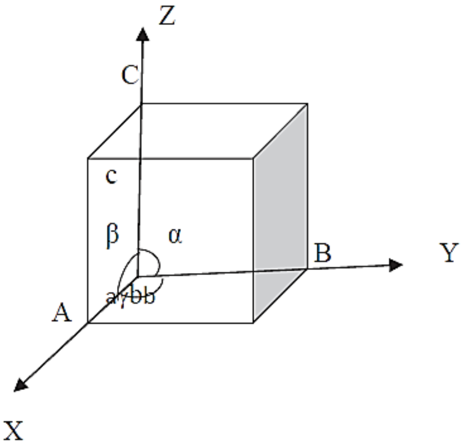


Fig. 4 lattice parameters of Unit Cell

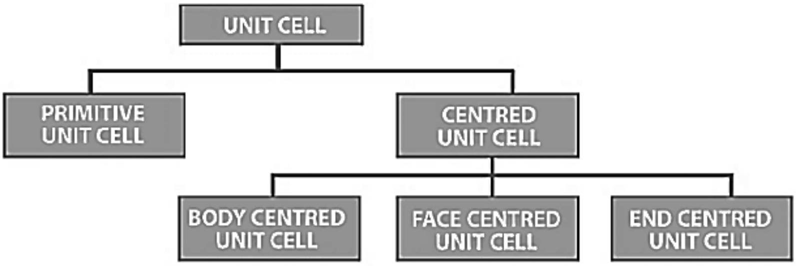
Despite this, selecting a unit cell with the smallest volume is customary. Therefore, a unit cell has the smallest possible volume that, when repeated methodically in each of the three dimensions, may reveal the whole structure of the atoms that make up the crystal.

The Unit cell dimensions, OA = a, OB = b, and OC = c are called inter atomic distances. The distance between the two nearest neighbouring atoms is called inter atomic distance.

The angles that exist between a and b, b and c, a and c respectively are ϒ, α and β and these angles are called as interfacial angles.

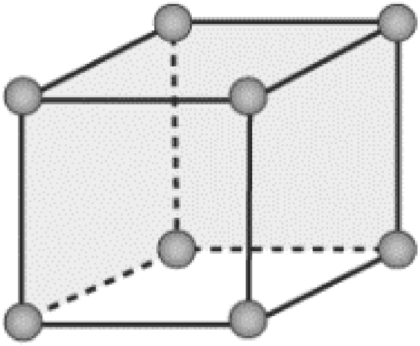
1.3.1 Different kinds of unit cells

The assumption was made that the particles could only be found at the four corners of the unit cell. However, it has been discovered that the particles may be present at the corners and certain other particular spots in addition to those at the corners. This is in addition to the fact that the particles may be present at the corners. As a result, the unit cell may be broken down into the following groups in a general sense:



(a) Primitive Unit Cells

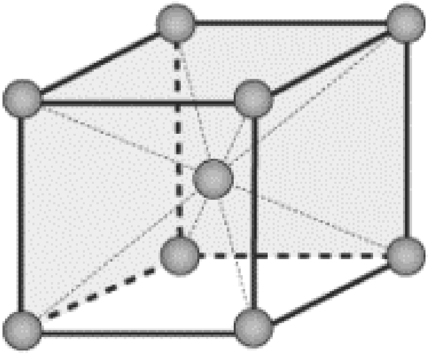
The unit cell formed by the primitives a, b and c is called primitive cell, In a primitive cell, there is only one lattice point. Simple unit cells, also known as primitive unit cells, are cells in which the component particles are only present at the cell's corners. According to the table that follows, there are thus seven distinct kinds of primitive unit cells.



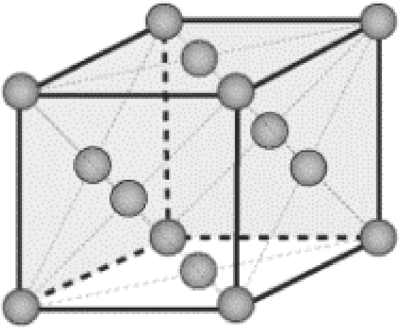
(b) Non-Primitive or Centred Unit Cells

Non-primitive unit cells, also known as centred unit cells, are the same as primitive unit cells except that the component particles may also be found in other areas inside the unit cell, such as the corners. The following is a list of the three kinds of centred unit cells that may be found:

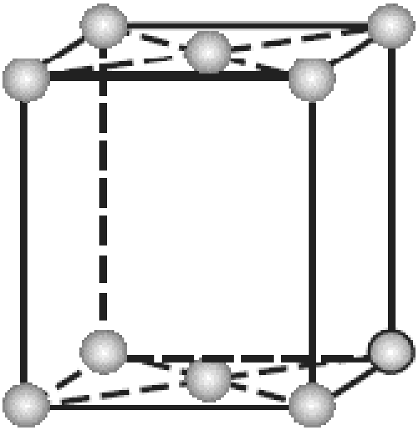
i. Unit cells with a centre of mass: In addition to particles located at the four corners of the unit cell, one particle is also located in the centre of its body. This kind of cell is referred to as a body-centred unit cell.



ii. Face-centred unit cells: Face-cantered unit cells have particles in each face's corners and middle. A face-centred unit cell is one such type of unit cell.



iii. End-centred unit cell: This unit cell consists of particles located at the corners and particles in the middle of any two opposite sides.



There are four distinct kinds of unit cells; however, not all are present in every crystal lattice. As a result, only 14 different kinds of space lattices correspond to seven different crystal systems.

1.4 Bravais Lattice

The idea of crystals naturally leads to the notion of a lattice. Crystalline solids have particular patterns, which develop owing to the exact patterns in which the various atoms that make up the crystals are arranged. These patterns give the crystalline solids their distinctive appearance. The construction of a lattice, in which a succession of atoms is grouped in a

Switching) technology are the most common. It offers a very large viewing angle, an excellent image picture quality, a quick reaction, an excellent contrast, minimal burn-in faults, and other features. LCD monitors, LCD televisions, smartphones, tablets, and other electronic devices often make use of IPS LCDs. Even the LED backlighting has been upgraded by Samsung to be QLED (quantum dot), which automatically turns off LEDs in areas where it is not necessary for light to be present in order to achieve deeper blacks.

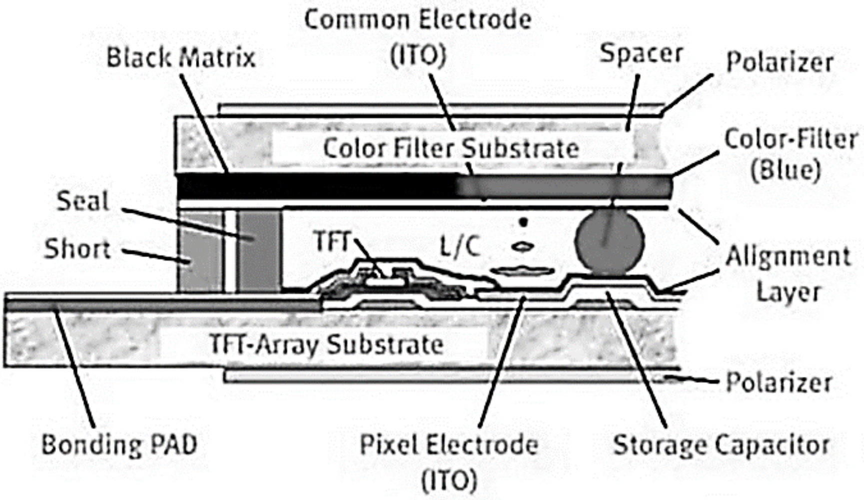


Fig.11 LCD Technology

5.13.2 Different Types of LCD

Twisted Nematic Display: The TN (Twisted Nematic) LCDs manufacture may be done most regularly and employed diverse sorts of displays all over the industries. When compared to other displays, the ones with this particular combination of low cost and fast reaction time are the ones that gamers use the most often. The biggest problem of these displays is that they have inferior quality as well as partial contrast ratios, viewing angles & reproduction of colour. But, these gadgets are adequate for everyday operations.

In-Plane Switching Display: IPS displays are believed to be the best LCD because they give excellent picture quality, greater viewing angles, brilliant colour accuracy and difference. The majority of people who use these displays are graphic designers; but, LCDs are also utilised in various other applications where the highest possible picture and colour reproduction requirements are required.

Vertical Alignment Panel: The vertical alignment (VA) panels drop anywhere in the middle amid Twisted Nematic and in-plane switching panel technologies. When compared to displays of the TN type, these panels offer superior viewing angles and superior colour reproduction, as well as other characteristics of greater quality. These panels have a minimal reaction time. On the other hand, they are much more practical and suitable for usage on a regular basis. In comparison to the twisted nematic display, the structure of this panel is capable of producing deeper blacks and more accurate colour reproduction. And numerous crystal orientations may provide for higher viewing angles as compared with TN type displays. These displays come with a tradeoff in the form of a higher price tag when compared to other screens of comparable size and quality. In addition to this, their reaction times are poor, and their refresh rates are low.

Advanced Fringe Field Switching (AFFS): When compared with IPS displays, AFFS LCDs provide the greatest performance and a broad spectrum of colour reproduction. AFFS LCDs are also known as advanced fringe field switching. The applications of AFFS are considered to be quite sophisticated since they are able to lessen the amount of colour distortion without sacrificing the wide viewing angle. This display is often used in settings that are both highly sophisticated and professional, such as those seen in the cockpits of functioning aeroplanes.

Passive and Active-Matrix Displays: LCDs that are of the passive-matrix kind function by using a straightforward grid to facilitate the delivery of charge to individual pixels on the display. The use of a transparent conductive substance such as indium-tin oxide is what allows one glass layer to produce columns while the other glass layer is responsible for producing rows. There are a number of significant problems associated with the passive-matrix technology, the most notable of which are the poor reaction time and imprecise voltage regulation. The capacity of the display to update the picture being presented is primarily what is meant when reaction time is discussed in relation to displays.

TFTs are the primary reliance of active-matrix types of LCDs (thin-film transistors). These transistors are miniature switching transistors and capacitors that are arranged in a matrix on top of a glass substrate. Because all of the additional rows that the column intersects are turned off, only the capacitor next to the designated pixel receives a charge when the appropriate row is activated. This allows a specific pixel to be addressed. When the appropriate row is activated, then a charge can be transmitted down the exact column.

5.14 Laser Diodes

Laser diodes have the ability to generate a concentrated beam of laser light in which all of the individual light waves have the same wavelength. Because of this quality, laser beams may produce very brilliant light and be concentrated across an extremely narrow region of space. In a broad variety of devices, including barcode scanners, laser printers, security systems, fibre optic communications, and many more, laser diodes are a common component. We are going to discuss the many kinds of laser diodes, their properties, and the various uses for them in this post.

A laser diode is a kind of semiconductor that generates coherent light in the visible or infrared spectrum by using a p-n junction to do so. This radiation has the same frequency and phase over its entire range. Injection laser diode is another name for this component, and the technology behind it is comparable to that of an LED.

Laser’s diodes are used to convert the electrical signal to light signal. In direct bandgap materials where high recombination velocities exist, optical gain can be achieved by creating population inversion of carriers through high-level current injection and by forming a resonant cavity. This cavity is usually produced by the high Fresnel reflectivity obtained from cleaving the material along faces perpendicular to the junction plane.

The structure of a typical laser diode is shown in fig.12. In this diode, opposite ends of the junction are polished to get mirror like surfaces. When free electrons recombine with holes, the emitted photons reflect back and forth, they induce more recombinations and hence an Avalanche effect that causes all newly created photons to be emitted with the same phase. One of the mirror surfaces is semi transparent. From this surface a fine thread like beam of photons emerge out. All the photons of laser light have same frequency and phase and hence coherent.

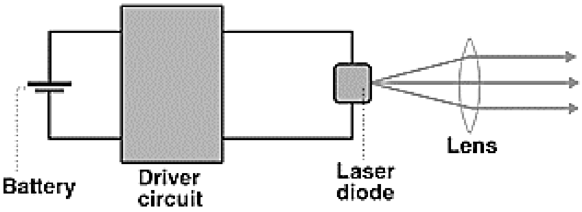


Fig.12 Function of Laser diode

It has a well-defined current threshold as seen from the power output vs. drive current characteristic. Below this threshold the device exhibits low levels of spontaneous emission. At the limiting current density stimulated emission occurs and the emitted radiation increases linearly with drive current.

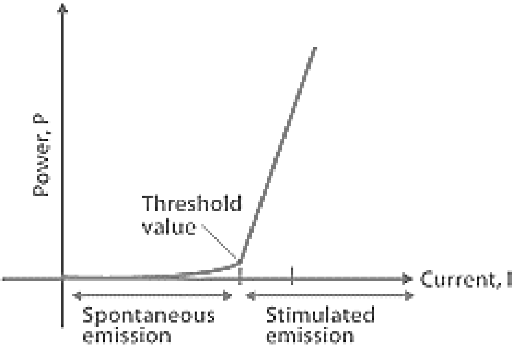
5.14.1 Types of laser diodes

Double heterostructure laser diode: A material is said to have a heterostructure if it is composed of two n-type materials and two p-type materials. This kind of laser diode is known as a double heterostructure (DH) laser diode because it contains material that has a heterostructure. The fact that the active area may be used for improved optical amplification is the primary benefit offered by this diode. Quantum well laser diode: A extremely thin layer in the centre of the diode is known as the quantum well. Quantum energy is put to use in the process of lowering the energy level of electrons, which ultimately results in increased productivity and productivity.

Separate confinement heterostructure laser diode: In addition to the three layers, there are an extra pair of layers. These layers have a reduced refractive index, and the emission of light is also enhanced thanks to these layer's improvements. Vertical cavity surface-emitting laser diode: The optical cavity of this particular kind of laser diode is positioned along the axis of the current flow. Discover more about the many kinds of diodes available here.

Monochromatic laser diodes have the following characteristics: A tiny band of emitted light that solely contains one hue and has a width that is insignificant. In this kind, the light will be focused into a small beam since it has been carefully guided. Launching anything across an optical fibre is a simple process.

A light that is coherent has just one wavelength and is produced by an LED that has a broad wavelength range. The approach, sometimes known as the threshold, of a laser diode is the most significant of its characteristics. After a certain amount of power has been delivered, the laser diode will begin to function. If the light's energy is less than what it normally is, then the emission will be less powerful than the threshold in comparison to the light's energy at its normal level.



5.14.2 Applications of Laser Diode

- Consumer electronics, such as CD and DVD players, laser printers, and fibre optic communication systems are included in this category.
- Industrial uses: The laser diode is the device of choice when it comes to industrial applications since it is a source of a laser beam with a high intensity and is used for a variety of tasks including cutting, drilling, and welding.
- Laser diodes have a number of uses in medicine, including the removal of abnormal tissues and tumours, as well as their usage in dental medicines.
- Scientific instrumentation: With the assistance of laser diodes, scientific instruments such as spectrometers, range finders, and contact-less measuring devices may be constructed.
- The laser diode and its role in the telecommunications industry Laser diodes with 1.3 m and 1.55 m bands are utilised as the primary source of light in the telecommunications industry. As the band changes, laser diodes find employment in optical amplification.

Advantages of Laser Diode

The operational power of a laser diode is lower when compared to the operational power of other light-emitting devices. These diodes are simple to handle because of their tiny size. The light that is created by these diodes has a high efficiency.

Disadvantages of Laser Diode

Laser diodes are more costly than other devices that produce light, and the light created by these diodes has a negative impact on the eyes.

5.15 Photodetectors

Photodetectors are devices that are used in the process of detecting light, more specifically the optical power of the light. To be more specific, photodetectors are typically understood to be photon detectors, which in some way utilise the photo-excitation of electric carriers; thermal detectors are not included in this definition of the term. Photodetectors typically deliver an electronic output signal, such as a voltage or electric current that is proportional to the incident optical power. They are thus considered to be a part of the field of optoelectronics.

5.15.1 Different types of photodetectors

There are many different kinds of photodetectors, each of which may be suitable for a certain situation, due to the fact that the criteria for applications might vary quite a little (see below for more information on this topic):

- Photodiodes are semiconductor devices that have either a p–n junction or a p–i–n structure I = intrinsic material) (p–i–n photodiodes), and they work by generating a photocurrent when light is absorbed in a depletion zone of the device. If they are used in conjunction with the appropriate electronics, such devices can have a very small footprint, be very quick, have a high linearity, have a high quantum efficiency (i.e., generate nearly one electron for every incident photon), and have a wide dynamic range. All of these characteristics can be achieved. Avalanche photodiodes are an extremely sensitive sort of photodiode, to the point that they are even sometimes employed for counting photons.
- Metal–semiconductor–metal (MSM) photodetectors are distinguished from traditional photodetectors by the presence of two Schottky contacts rather than a p–n junction. They have bandwidths that can go up to hundreds of gigahertz, making them theoretically faster than photodiodes.
- Phototransistors are electronic components that, unlike photodiodes, use an inbuilt amplifier to boost the strength of the photocurrent. In comparison to photodiodes, they are not used nearly as often.
- Photoconductive detectors rely on certain semiconductors like cadmium sulphide in order to function properly (CdS). They are less expensive than photodiodes, but they have a nonlinear response, are rather sluggish, and do not have a high level of sensitivity. On the other

hand, they have the ability to react to infrared light with a long wavelength.

- Phototubes are devices that use the photoelectric effect and may either be vacuum tubes or gas-filled tubes (also known as photo emissive detectors).
- Photomultipliers are a specialised kind of phototubes that take use of electron multiplication processes in order to achieve a much higher level of responsivity. They also have the potential to move at a rapid pace and cover a big active area.
- Research is being done on innovative photodetectors based on carbon nanotubes (CNT) or graphene, which may provide a very wide wavelength range and a very quick response. Some of them are based on multichannel plates, and they can be much more compact than classic photomultipliers.
- Investigations are being carried out to find methods of incorporating such devices onto optoelectronic chips.
- Each of these devices relies on either an internal or an exterior photoelectric effect; photo emissive detectors are classified as falling into the second group.
- Photodetectors come in a wide variety of types, and they may be included into a variety of different types of devices, including power metres and optical power monitors. Others may be fabricated in the shape of enormous two-dimensional arrays, which is useful for imaging applications among other things. They are sometimes referred to as focal plane arrays. For instance, there are sensors known as CCD and CMOS, and the majority of their applications are in cameras.

Important Qualities and Characteristics of Photodetectors

- Depending on the use, a photodetector has to meet a variety of criteria, including the following:
- It has to have sensitivity in a certain area of the electromagnetic spectrum (range of optical wavelengths). Within a certain wavelength

range, the responsivity needs to be constant, or at the very least, clearly defined, under certain circumstances.

- The responsivity indicates how much electrical signal is obtained per unit of optical power.
- It can be important to have zero response in some other wavelength range. One example of this is solar-blind photodetectors, which are sensitive to short-wavelength ultraviolet light but not to visible light from the sun.
- In some circumstances, not only a high responsivity but also a high quantum efficiency is required, since otherwise extra quantum noise is produced. This is because the optical wavelength plays a role in this. This impacts not just the photon detection probability of photon counting detectors but also the detection of compressed states of light, for example.
- The detector has to have the ability to work with a variety of optical powers. The lowest detectable power is often controlled by noise, but the maximum power might be restricted in a number of ways, for as by concerns related to damage or by a nonlinear response. Often, the most essential factor is the size of the dynamic range, which is often stated as the ratio of the greatest detectable power to the least detectable power, for example in dB. It is possible for some detectors, such as photodiodes, to display strong linearity throughout a dynamic range that is more than 70 dB.
- When dealing with significantly divergent beams from laser diodes, for example, the active area of a detector might be an essential factor to consider. It's possible that having a high enough regularity of the responsiveness is significant. If the light source has a very large and/or non-constant beam divergence, it is almost impossible to get all of the light onto the active region. In this case, an integrating sphere may be used to measure the total power (with the proper calibration).
- The detection bandwidth may start at 0 Hz or at a certain finite frequency (for AC-coupled detectors), and it may end at some

maximum frequency, which may be limited by internal processes (for example, the speed of electric carriers in a semiconductor material) or by the electronics that are involved (e.g. introducing some RC time constants). Some resonant detectors function just within a specific frequency range, making them well-suited for applications such as lock-in detection.

- The detection capabilities of some detectors, such as pyroelectric detectors, are limited to the detection of discrete light pulses and not continuous light waves.
- The timing accuracy may be of relevance for the purpose of detecting light pulses (perhaps on a level of just a few photons). Some detectors have what's called a "dead time," which is a period of time after they detect a pulse during which they are insensitive to other pulses.
- Depending on the kind of detector, the associated electronics may be more or less complicated. The demand to apply a high voltage or the requirement to detect very tiny voltages, for example, might result in size and cost penalties.
- It is necessary to bring the temperature of certain mid-infrared detectors, in particular, down to a rather low level. Because of this, using them in a variety of settings would be unfeasible.
- One-dimensional or two-dimensional photodetector arrays are often required for the applications that call for them, with photodiode arrays being the most common kind. When it comes to detector arrays, there are a few distinct factors that come into play, including cross-pixel interference, read-out methodologies, and detector uniformity.
- Finally, the cost, size, and durability are all crucial considerations for a wide variety of applications.
- The many kinds of detectors, which are enumerated above, vary greatly from one another in many of these characteristics. In the majority of application settings, some constraints completely exclude the utilisation of certain kinds of detectors, which swiftly results in a choice that is substantially constrained. Take into account the fact that

there are also certain common compromises. For instance, it is usually challenging to combine a large detection bandwidth with a high sensitivity. This is only one example.

5.15.3 Construction and Working

Photodetectors or Photosensors are sensors of light or other Electromagnetic energy.Photodetectors has a PN junction that converts light photons into current.The absorbed photons make electron hole pair in the depletion region. When an electron-hole pair is generated due to the incident radiation, the pair separated at the junctions as a result of the existence of electric field.As a result, it generates open circuit voltage or short circuit current. This is the principle applied in the photodiodes to produce both voltage and current in an external circuit.

The geometry of the slab of a photo conducting material is shown in fig.13. Let L W and D be respectively the length, width and thickness of the conducting material. It consists of two electrodes on opposite faces. The incident radiation falls on the opposite surfaces of the materials. The detector are the terminal devices and are used as light dependent resistors. The commonly used symbol for a photo conductive detector consists of a resistance symbol with incident arrows representing the radiations, as shown in figure. The detectors are available in the form of photodiodes and photo transistors.

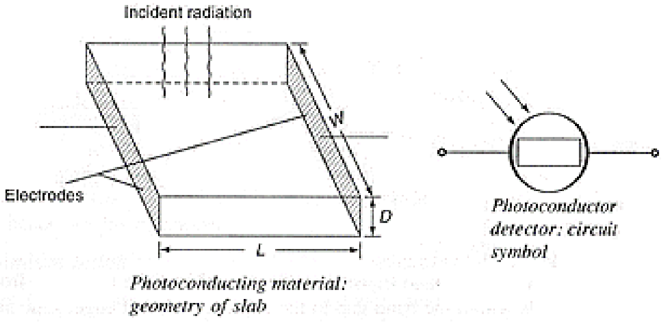


Fig.13 Photodetector

5.15.4 Photodetector Bias Circuit

The photodetector (P) is connected in series with a voltage source and a load resistor R_L as shown in fig.14.When a light radiation is incident on the photodetector, Whose energy is greater than E_g,the increase in conductivity of the detector takes place. As a result, the flow of current in the circuit leads to an increase in potential across the load resistor R_L. The same can be measured using a high impedance Volt meter. A blocking capacitor C is introduced in the output line to remove any dc components while measuring the current in the circuit, due to time variations of the incident light.'

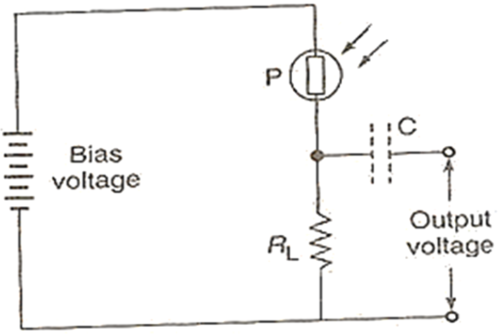


Fig.14 Photodetector Bias circuit

The Sensitivity and linearity of the detector depends on R_L. One can obtain the optimum value of R_L by a fractional change in the resistance of the photo detector when it is under illumination. When the change in the fractional resistance is less than 5 %.The sensitivity shows a large value at R_L=R_D, where R_D is the resistance of the photodetector. On the other hand, if the change in the resistance is large, I.e, R_L<< R_D, which is required for output voltage measurements.

Let I_0 and I be the intensities of the incident and transmitted radiations, respectively, on the semiconductors detector materials. Therefore, the average generations of charge carries, i.e, electron-hole pairs per unit volume is

$$r_g = \eta / \nu$$

Where is the quantum efficiency of the absorption process, and v is the frequency of radiation (=c/λ).

5.15.5 Applications of Photodetectors

Photodetectors may be used in an extremely extensive variety of contexts. Some examples:

- In radiometry and photometry, they can be utilised for the measurement of properties such as optical power, luminous flux, optical intensity, and irradiance, in conjunction with additional means for properties such as the radiance. Additionally, they can be utilised for the measurement of radiance.
- They are used to measure optical powers in devices such as spectrometers, light barriers, optical data storage devices, autocorrelators, beam profilers, fluorescence microscopes, interferometers, and various types of optical sensors.
- Laser rangefinders, LIDAR, quantum optics experiments, and night vision devices require photodetectors with a particularly high level of sensitivity.
- Optical fibre communications, optical frequency metrology, and the characterization of pulsed lasers or laser noise all make use of photodetectors that are very quick. These applications include:
- Focal plane arrays are typically two-dimensional and include a large number of photodetectors that are similar to one another. These arrays are often used for imaging applications. The vast majority of cameras, for instance, include components that are known as image sensors.

5.16 Tunneling

An ordinary Pn junction diode has an impurity concentration of about 1 part in 10^8.With this amount of doping the width of the depletion layer is of the order of 5 microns. This potential barrier restrains the flow of carries from the majority carrier side to the minority carrier side. If the concentration of impurity atoms is greatly increased to the level of one part in 1000, the device characteristics are completely changed. The width of the junction barrier varies inversely as the square root of the impurity concentration and therefore is reduced from 5 microns to less than 100A.This thickness is only about 1/50th of the wave length of visible light. For such thin potential energy barriers, the electrons will penetrate through the junction rather than surrounding them. This quantum mechanical behaviour is referred to as tunnelling.

5.17 Resonant tunneling diode

A **tunnel diode** or Esaki **diode** is a type of semiconductor that is capable of very fast operation, made possible by the use of the quantum mechanical effect called **tunneling**. A particularly useful form of a tunnelling diode is the Resonant Tunnelling Diode (RTD).

5.18 Resonant tunneling

A quantum well is a potential structure which spatially confines the electron. According to quantum mechanics, an electron subjected to potential confinement has its energy quantized and a discrete energy spectrum would be expected for the electron system. Resonant tunneling refers to tunneling in which the electron transmission coefficient through a structure is sharply peaked about certain energies.

A resonant tunneling diode is a diode with a resonant tunneling structure in which the electrons can tunnel through some resonant states at certain energy levels. Resonances are simply energies at which the cross section of a particle reaches a maximum.

An RTD can be fabricated using many different types of materials (such as III–V, type IV, II–VI semiconductor) and different types of resonant tunneling structures, such as the heavily doped p–n junction in Esaki diodes,

5.18.1 Advantages

Resonant tunneling diodes can be very compact and are also capable of ultra-high-speed operation because the quantum tunneling effect through the very thin layers is a very fast process.

RTDs have been shown to achieve a maximum frequency of up to 2.2 THz as opposed to 215 GHz in conventional Complementary Metal Oxide Semiconductor (CMOS) transistors. The very high switching speeds provided by RTDs have allowed for a variety of applications in wide-band secure communications systems and high-resolution radar and imaging systems

5.19 Carbon nanotubes

A carbon nanotube is a tube-shaped material, made of carbon, having a diameter measuring on the nanometer scale. A nanometer is one-billionth of a meter, or about 10,000 times smaller than a human hair.

These incredible structures have an array of fascinating electronic, magnetic and mechanical properties. CNT are at least 100 times stronger than steel, but only one-sixth as heavy, so nanotube fibers could strengthen almost any material. Nanotubes can conduct heat and electricity far better than copper.

5.19.1 Structure of carbon nanotubes

Carbon nanotubes have many structures, differing in length, thickness, and number of layers. The characteristics of nanotubes can be different depending on how the graphene sheet has rolled up to form the tube causing it to act either metallic or as a semiconductor. The graphite layer that makes up the nanotube looks like rolled-up chicken wire with a continuous unbroken hexagonal mesh and carbon molecules at the apexes of the hexagons. The different formation of carbon nanotubes are shown in fig.15.

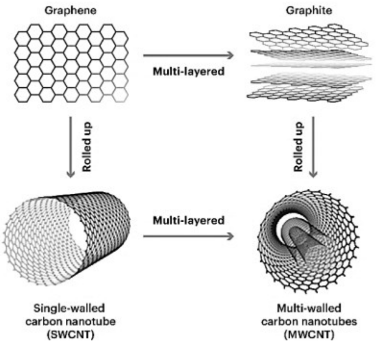


Fig.15 Carbon Nanotubes

5.19.2 Types of Carbon nanotubes:

There are many different types of carbon nanotubes, but they are normally categorized as either single-walled (SWNT) or multi-walled nanotubes (MWNT). A single-walled carbon nanotube is just like a regular straw. It has only one layer, or wall. Multi-walled carbon nanotubes are a collection of nested tubes of continuously increasing diameters. They can range from one outer and one inner tube (a double-walled nanotube) to as many as 100 tubes (walls) or more. Each tube is held at a certain distance from either of its neighboring tubes by interatomic forces.

5.19.3 Properties:

- CNTs have High Electrical Conductivity.
- CNTs show a unique combination of stiffness, strength, and tenacity(firmness)
- CNTs are Highly Flexible- can be bent considerably without damage.
- CNTs are Elastic in nature
- CNTs have High Thermal Conductivity.
- CNTs have a Low Thermal Expansion Coefficient.

5.19.4 Applications:

Carbon nanotube technology can be used for a wide range of new and existing applications:

- Micro- and nano-electronics

- Structural composite materials
- Flat-panel displays
- Power applications (e.g. batteries with improved lifetime, photovoltaic applications)
- Sensors and Biosensors

5.20 Various Types of Optical Materials with Properties

When it comes to the construction of optical elements, a wide variety of materials are used. Optical materials are often thought to be transparent materials. This refers to materials that have strong light transmission in certain spectral bands and show negligible light absorption as well as light scattering. Nevertheless, absorption may be put to use in the creation of optical filters, and light scattering is even put to use in certain applications. In addition, some materials may be beneficial for the fabrication of optical components that do not allow light to pass through them. For instance, the substrates for laser mirrors can be made from specific materials that have complete transparency.

Inorganic Glasses

Optical glasses, which are comprised of inorganic compounds and include chemical species such as silicon, oxygen, sodium, aluminium, germanium, boron, and lead, make up the majority of the materials used in the optical industry. Pure materials are those that have no or extremely few traces of any chemical elements. The most common example of this kind of material is fused silica glass (silicon dioxide, SiO2), which is used extensively in the field of bulk optics. It is also used in the form of silica fibres; however, in this application, the core of the fibre is often infused with some other substance, such as germanium.

There are also several types of glasses known as silicate glasses, which are produced by combining silica with a variety of other mineral components to produce glasses with altered characteristics.

- Soda-lime glasses, which are often used for windows, may have additional ingredients like sodium carbonate, calcium oxide, magnesium oxide, and aluminium oxide added to them, for instance.

They are referred to as crown glasses as long as they have relatively low reflective indices and low dispersion.

- Increased refractive indexes can be obtained by adding heavier materials such as barium, lead, thorium, zirconium, titanium, or lanthanum. This usually comes together with increased dispersion (usually as oxides). These kinds of glasses are referred to as flint glasses.
- Borosilicate glasses have a much lower thermal expansion and are therefore much more resistant against thermal shocks.
- Aluminosilicate glasses are extensively used for glass fibres, including rare-earth-doped fibres for use in fibre amplifiers and lasers. In the past, the majority of them were made with lead, which is a toxic metal. However, this has largely been replaced with other metals, such as titanium or zirconium. They can withstand moderate amounts of heat without too much damage.
- Germanosilicate glasses are also often used for optical fibres, notably for telecom fibres. These glasses display extremely low propagation losses and are hence commonly used.
- Fluoride glasses and fluorophosphate glasses have the potential to be used as high-index low-dispersion glasses, for example in the building of achromatic optics.
- Phosphate glasses are used, for example, in the production of some rare-earth-doped fibres, in particular where high doping concentrations are needed.
- Additional elements such as iron, which absorb infrared light (for example, in heat-absorbing filters), or cerium, which absorbs ultraviolet light, may be employed to provide the desired effect.

The fields of optics and photonics make use of a variety of glasses, some of which include toxic elements like lead and cadmium. It is difficult to ensure that these materials are properly handled after use so that they do not get into the environment. Despite the fact that this hardly creates any hazards during use because the substances are tightly bound in the glass, there are serious attempts being made to ban their use wherever it is possible to do so.

Crystalline Materials

Insulators

Crystalline substances, in contrast to glasses, which are considered to be amorphous, have a microscopic order that extends across a longer range. Because the scattering of light at the interfaces between grain boundaries might be deleterious, the vast majority of crystalline optical materials are monocrystalline, also known as single crystal materials. Materials used in optical crystals are almost usually generated in an artificial environment. The rate of development is often quite slow because, if it were much faster, it would be impossible to produce a single crystal. Crystalline optical materials are often more costly than glass or ceramic alternatives due to their inherent properties. Crystals may be used instead of glasses in order to gain a broader spectral transmission range, which is one rationale to employ crystals. This is especially true in the middle and far infrared, where there is a restricted selection of materials that have a fair degree of transparency.

In some circumstances, optical anisotropy is necessary. One example of this is in the form of birefringence, which may be created from crystalline materials that do not have too high levels of crystal symmetry. Calcite crystals are used, for instance, in the production of polarizers as well as other forms of polarisation optics. Crystalline substances are the only ones capable of exhibiting the Pockels effect, which is used in the production of electro-optical modulators. In acousto-optic devices, several types of crystal materials, in addition to glasses, are used.

In addition, there are many different kinds of laser crystals, which are crystalline insulators that have been doped with laser-active ions (also known as doped insulator lasers). In this case, we are interested in more than just the optical qualities. It is especially significant how the laser-active ions interact with the host glass, since the characteristics of the pump and the laser transitions may be highly dependent on the kind of glass.

Other types of doped crystals are used as saturable absorbers in applications such as laser Q switching.

Last but not least, the (2) nonlinearity of a variety of different crystal materials with poor crystal symmetry is used in the process of nonlinear frequency conversion. In contrast to glasses, the exact composition of the raw materials that are used to make optical crystals can somewhat vary, and there are certain fluctuations in the local chemical composition. Optical crystals, particularly those that do not contain any special dopants, are extremely pure materials that possess very consistent optical properties.

Semiconductors

Due to the fact that the energy of their band gaps is lower than the energy of the photons that make up visible light, semiconductors do not transmit light via the visible spectral area. On the other hand, they have a high degree of transparency when seen in the infrared. For infrared optics, for instance, silicon, germanium, and gallium arsenide are common materials used. In most cases, the refractive index will be rather high. When it comes to infrared optical windows, semiconductor materials are sometimes employed in certain applications. Nevertheless, there are applications in which the unique optical features of semiconductors are used to their full potential. For instance, there are nonlinear frequency conversion devices that use gallium arsenide with quasi-phase matching. There is also the larger field of study known as silicon photonics, which focuses on integrating optics using silicon as the primary material.

Polycrystalline Ceramics

Optics makes use of some of the properties that polycrystalline materials possess. The primary obstacle they face is the dispersion of light caused by grain boundaries. However, certain transparent ceramic materials such as alumina (Al2O3) and yttrium aluminium garnet (YAG = Y3Al5O12) have been developed with good optical quality including low scattering losses; this can be achieved if the used materials are very pure and the particles of the raw material have very small dimensions, so that the grains also become very small. Other transparent ceramic materials such as yttrium aluminium garnet (YAG = Y3Al5O12) have (with nanometer dimensions). Given that scattering is far more pronounced at shorter wavelengths, lengthy operating wavelengths (i.e. for infrared optics) constitute an additional consideration that should not be overlooked.

Ceramics may have optical qualities that are comparable to those of glasses in certain cases. As a result, ceramic materials are suitable for use in the production of a wide variety of optical components, including lenses, prisms, optical windows, and many others. Ceramic windows, for instance, are a viable option for use in thermal imaging and night vision equipment. Ceramics called YAG (yttrium aluminium garnet) have been created specifically for use in lasers. These ceramics may also be doped with elements like neodymium. The laser gain medium that is achieved is quite comparable to that of Nd:YAG single crystals, but it may be more cost-effective, especially when big dimensions are required. For more information, please refer to the page on ceramic laser gain medium. Ceramics have many advantages over single crystals, one of which is that (much like glasses), they may be manufactured with extremely large dimensions without the need for a time-consuming method known as crystal formation.

Organic Polymers

The majority of polymeric materials (plastics) have high transparency in the visible spectral region, and some have some degree of transparency in the infrared spectrum as well. Because of their amorphous nature, they are also referred to as organic glasses. They have a lot of appealing features that make them useful in a variety of contexts, including the following:

- They may typically be manufactured at a cheap cost, for example by using moulding and embossing techniques, which can also be used to generate aspheric surface forms. This is because these procedures are versatile. There are instances in which they might be produced concurrently with their mounts.
- They are lighter and less delicate than glasses.
- It is simple to equip them with dyes in order to generate optical filters.

- Certain applications demand particularly soft materials, such as optical silicone.

On the other hand, the optical quality that may be achieved is often poorer than that achieved with glasses. Additionally, things made of plastic are particularly sensitive to variations in temperature. In most cases, they are not acceptable for use in applications using lasers. Ophthalmology, small picture cameras, and optical data storage are only a few examples of typical uses.

Liquids

Although using liquid in optical applications is not very prevalent, there have been some fascinating breakthroughs in the field of liquid micro-optics. For instance, there are fluidic microlenses that can be tuned to a certain wavelength. When the dimensions of a liquid droplet are extremely tiny, it is very easy to regulate the shape of the droplet, and when the dimensions are very small, the danger of losing the liquid, for example because the device moved, is also quite modest. It's possible that additional safety measures may need to be done to protect against evaporation and contamination.

Materials for Optical Coatings

For the production of dielectric coatings, such as anti-reflection coatings, mirror coatings, and others for thin-film polarizers, a wide variety of transparent materials are used. If the refractive index of the coating material is approximately the square root of the refractive index of the substrate material, then a thin layer of just one material may be adequate in the simplest of situations, for example as an AR coating. In certain instances, multilayer coatings are constructed from scratch. The vast majority of the time, amorphous dielectric materials are used; nevertheless, there are also crystalline mirrors with semiconductor multilayer structures. These crystalline mirrors are manufactured using entirely distinct processes.

In addition to the optical qualities, it is essential that the materials be appropriate for usage in the particular deposition methods that are being used. They should be able to generate high-quality layers with ease and consistency, characterised by excellent thickness uniformity, high optical homogeneity, minimal scattering and absorption losses, and strong adherence to the substrate. Certain typical coating materials are not optimal in all areas, yet they are nonetheless widely used. For instance, titanium dioxide (TiO2) is often employed as a high-index material in multilayer coatings; however, the deposition process might result in the material having a density that is either higher or lower than what was originally intended. Low-density variations not only have a lower refractive index, but they are also more susceptible to external conditions. In particular, water vapour may be absorbed, and this causes a modification in the optical characteristics of the coating. Other types of materials, such as silica, are significantly less susceptible to these kinds of reactions. Even when using TiO2, there are deposition processes (such as IAD, which stands for ion-assisted deposition) that may yield coatings that are quite thick. In any event, one had to be aware that the refractive indices might vary to some degree, based not only on the type of deposition that was used but also on the ambient circumstances that prevailed when the process was being carried out.

Metals

Reflectors are almost always made up of metal (mirrors). Most of the time, they are only used in the form of thin films that are placed on dielectric materials (also known as metal-coated mirrors). In some circumstances, such as in certain high-power lasers, particularly strong reflectors are constructed using components made of solid metal that have their surfaces polished. Gold and silver, aluminium, chrome, and a variety of nickel-chrome alloys are some of the metals that are used often in the production of reflectors. Most of the time, they are used as mirrors for the initial surface. There are protected silver coatings, for instance, which are significantly less sensitive when it comes to contacting the surface with anything like a finger. In certain instances, the surfaces of metals are covered with extra coatings that are transparent.

Photonic Metamaterials

There are certain man-made photonic metamaterials, and some of these materials may exhibit quite peculiar optical characteristics. One example is that some of them have a refractive index that is negative.

Questions

Part A

1. List out the properties of optical materials
2. Illustrate how nanophase materials are incorporated in day today life.
3. List out some metals and alloys used as biomaterials
4. Interpret biocompatibility
5. Write short note on MEMS
6. Give the advantages of MEMS materials
7. Give the applications of NEMS materials
8. Compare MEMS and NEMS
9. Write the principle used in LED materials
10. Write short note on Resonant Tunnelling Diode
11. Give the advantages of Resonant Tunneling Diode
12. Definet the principle used in photodetector circuit

Part B

1. Explain the classification of optical materials
2. Describe about the properties, types and applications of composite materials
3. Describe about nano phase materials, its production, types, properties and applications.
4. Explain biomaterials. How they interact with human tissues? Give the classifications of biomaterials. Also give the applications of biomaterials in medical.
5. Define LED. Explain the construction and working of LED materials

6. Explain with neat diagram about the construction and working of LCD materials
7. Describe about laser diode with neat its characterization. Give its properties and applications.
8. Explain the construction and working of photodetector with neat diagram.
9. Explain the structure, type and applications of carbon nano tube.

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