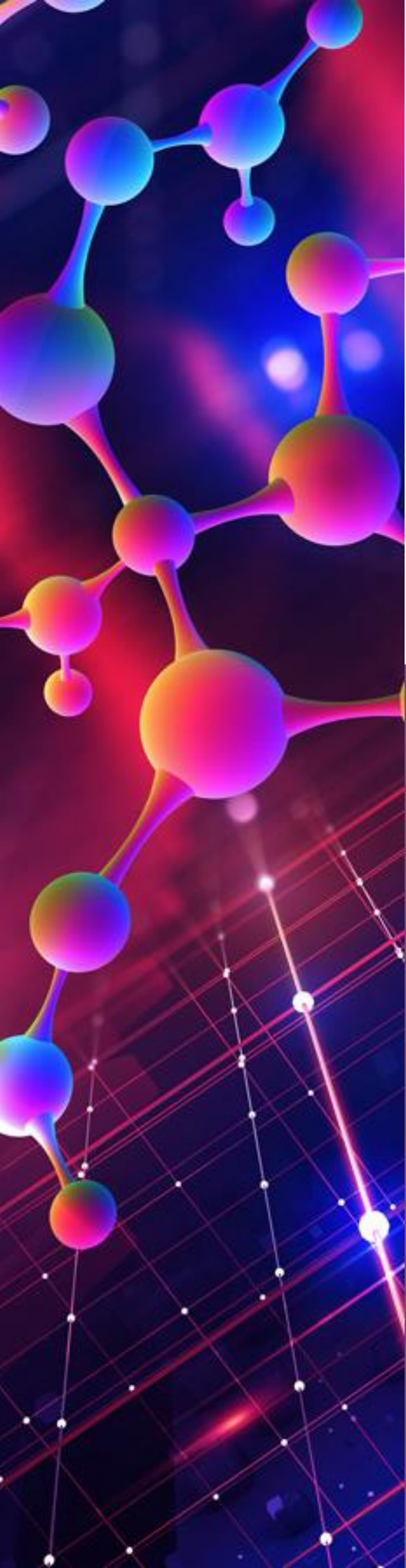

Optoelectronic

Devices &Applications

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ABSTRACT

This book covers knowledge with respect to quantum physics and mechanics. Starting with the basic units of matter and the basic structure of atoms. This knowledge is very important in understanding the properties of materials such as semiconductors which are important materials used for light emitters and detectors. Discussions regarding applications related to optoelectronics are also included to further explain their relevance and importance in daily life.

ACKNOWLEDGEMENT

First of all, Alhamdulillah, thanks Almighty for His guidance and blessing. We had succeeded in completing the Optoelectronic E-Book. We want to express our utmost gratitude to our Head Department of Electrical Engineering, Mr Shaffie Bin Husin, who supported us in grabbing this opportunity. Without his support, we would not be able to produce this E-Book. Not to forget the E-Learning team because it provides us with this opportunity and guides us in making this E-Book.

Besides, we also extend our gratitude to all friends and our lovely families for their kindness and sincere assistance in adding us to finish up this E-Book. Indeed, we have appreciated them. Again, thanks for everything.

Our hopes are may this E-Book helps students out there, especially engineering students in polytechnic, ease to understand and implements in their Optoelectronic course. Nevertheless, we also need any comments from reads to help us improve our next debut. We hope this E-Book could ease everyone to understand and implement the knowledge and could fulfill everybody needs.

Thank you.

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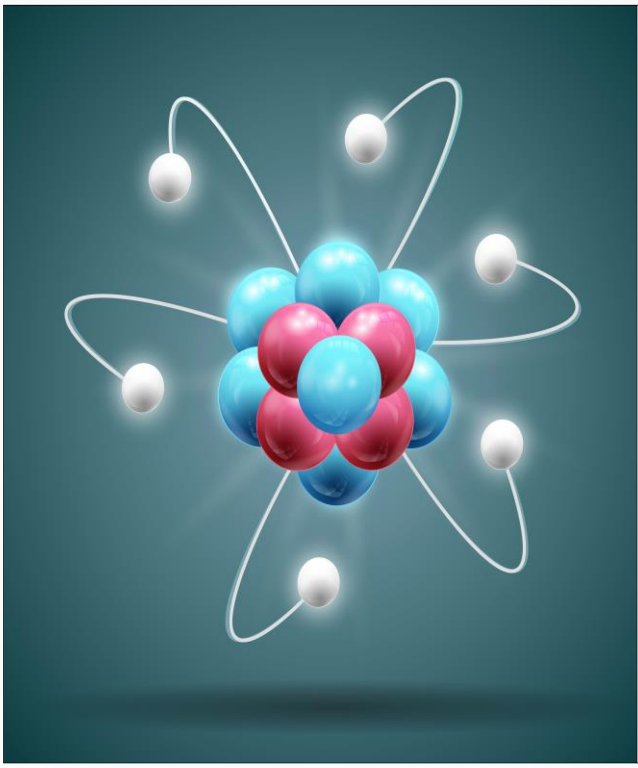
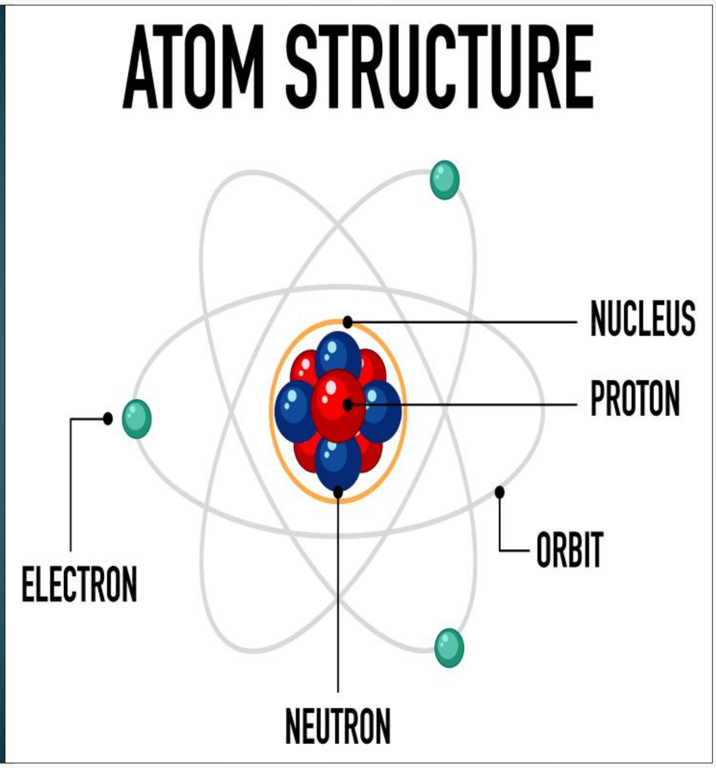
Element Of Solid State Physics

Chapter 1

ELEMENT OF SOLID STATE PHYSICS

ATOM





The atom is the building block of all matter. The atom is the smallest unit of matter that is incapable of being divided chemically and the building block with special abilities. In other words, each element's atom is distinct from those of other elements. But even the atom can be divided into smaller parts known as quarks.

The smallest component of an element is an atom. An atom is composed of three parts which are proton, neutron and electron. Proton is a positive electrical charge that can be found in the atom's nucleus. The atom's nucleus contains neutrons, which are neutral or electrically uncharged. A negative electrical charge called an electron is observed revolving around the nucleus.

The size (mass) of the electron is enormously smaller than that of the neutron and proton. Proton and electron electrical charges are exactly equal and just the opposite of one another. Electrons and protons are attracted to one another. The neutron does not attract or repel either the proton or the electron.

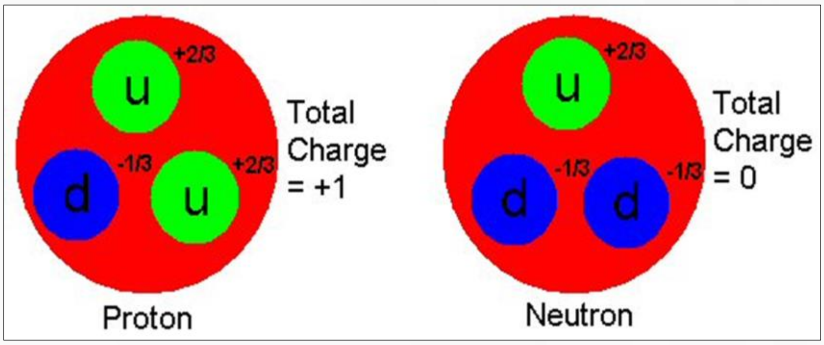
ELEMENT OF SOLID STATE PHYSICS

QUARKS

Quarks is believed to be one of the basic building blocks of matter. Composite particles are created by the combination of these quarks. There are three recognised quark families. Each family contains two quarks

1. **1st Family.**

The quarks that combine to produce protons and neutrons belong to the first family, which also includes up and down quarks.



2. **2nd Family.**

The second family, which only exists at high energies, is made up of Strange and Charm quarks.

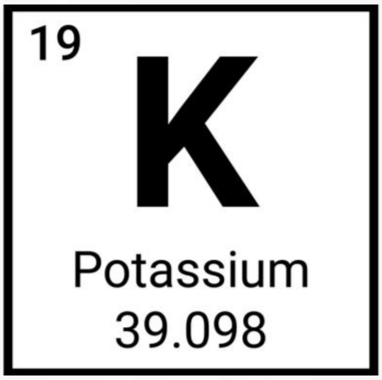
3. **3rd family.**

The third family, which only exists at very high energies, is made up of Top and Bottom quarks.

Generation		1	2	3
Quarks	+2/3	u UP	c CHARM	t TOP
	-1/3	d DOWN	s STRANGE	b BOTTOM

ELEMENT OF SOLID STATE PHYSICS

ELEMENT



Atomic number (Z)

the number of protons in an atom

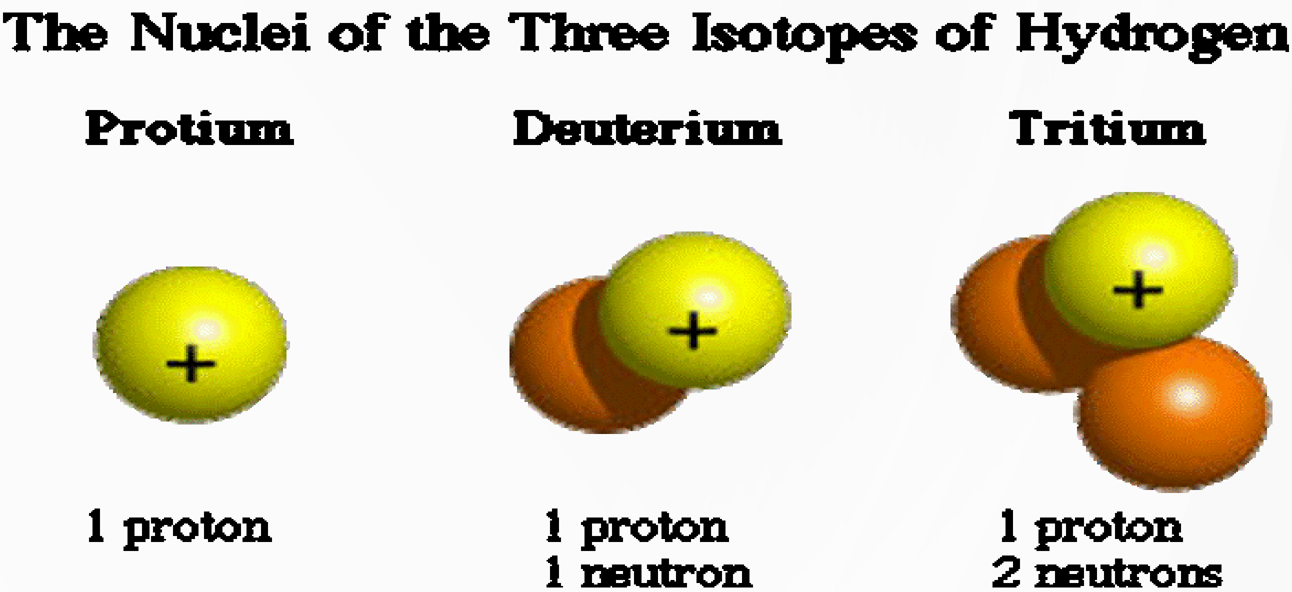
Atomic mass (A)

the number of protons and neutrons in an atom

The element is the basic material with just one kind of atom in it. Smaller particles make up elements, which might be synthetic or man-made. Based on the quantity of protons, they are arranged in the periodic table in ascending order. Z stands for the element's atomic number. You obtain distinct forms of an element when atoms are positioned differently in an element with the same number of protons.

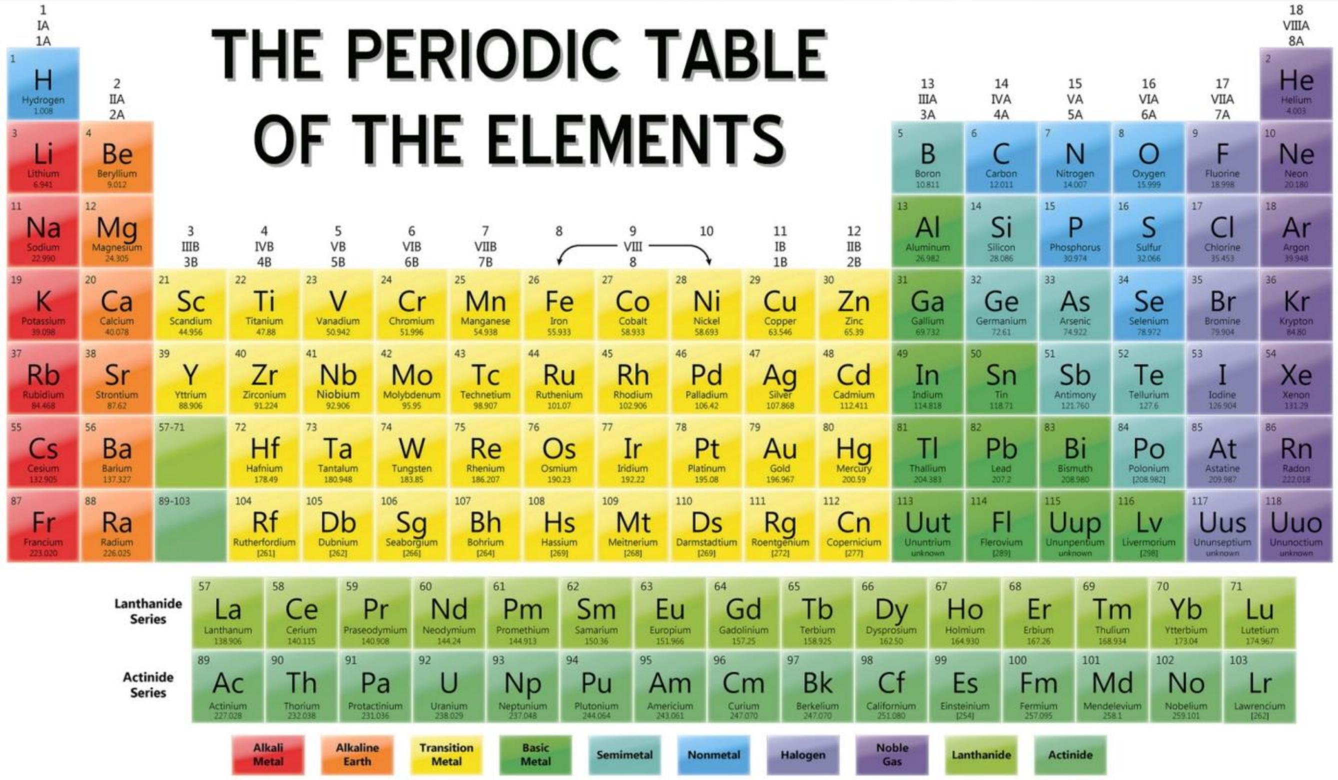
For instance, although both graphite and diamond are composed of the element carbon, they have completely distinct appearances. The mass number A of an atom is determined by adding the atomic number Z and the number of neutrons N.

Isotopes is an atoms with various numbers of neutrons but the same amount of protons, example is Hydrogen isotope:



ELEMENT OF SOLID STATE PHYSICS

ELEMENT



PERIODIC TABLE.

The chemical elements are shown in tabular form on the periodic table, commonly referred to as the periodic table of the (chemical) elements. It is frequently used in physics, chemistry, and other disciplines and is frequently regarded as a symbol of chemistry.

It is a visual representation of the periodic law, which claims that the atomic numbers of chemical elements have a periodic influence on those elements' attributes. The table is split into four blocks that are about rectangular in shape. The table's columns are referred to as groups and its rows are known as periods. Chemical properties of elements in the same column group of the periodic table are comparable.

Trends may be seen across the periodic table, with metallic characteristics (surrendering electrons to other atoms) increasing in the opposite way from left to right throughout a period and from down to up across a group. The fundamental cause of these patterns is atoms' electron configurations.

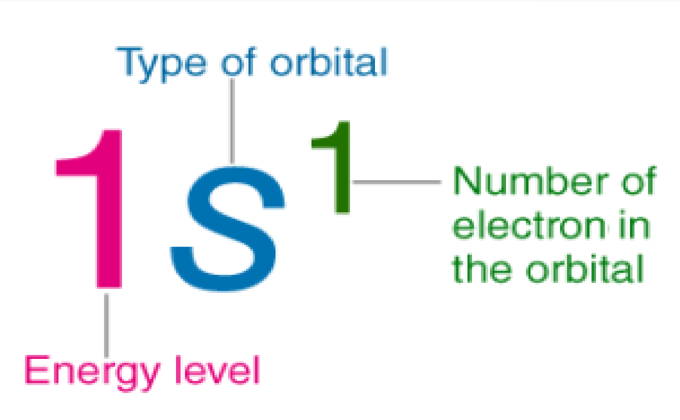
The periodic table is a visual representation of the periodic law, according to which an element's atomic number determines its attributes and atomic structure. The periodic table categorises elements according to the electron configurations of those elements, which exhibit periodic recurrences that explain the patterns in the periodic table's features.

ELEMENT OF SOLID STATE PHYSICS

ELECTRON CONFIGURATION

The arrangement of an atom's, molecule's, or other physical structure's electrons is referred to as its electron configuration in atomic physics and quantum chemistry. It focuses on how electrons can be distributed throughout the system's orbitals (atomic or molecular for instance).

The distribution of electrons in an element's atomic orbitals is described by the element's electron configuration. Atomic electron configurations are written using a standard notation that arranges all atomic subshells that contain electrons in a sequential order.

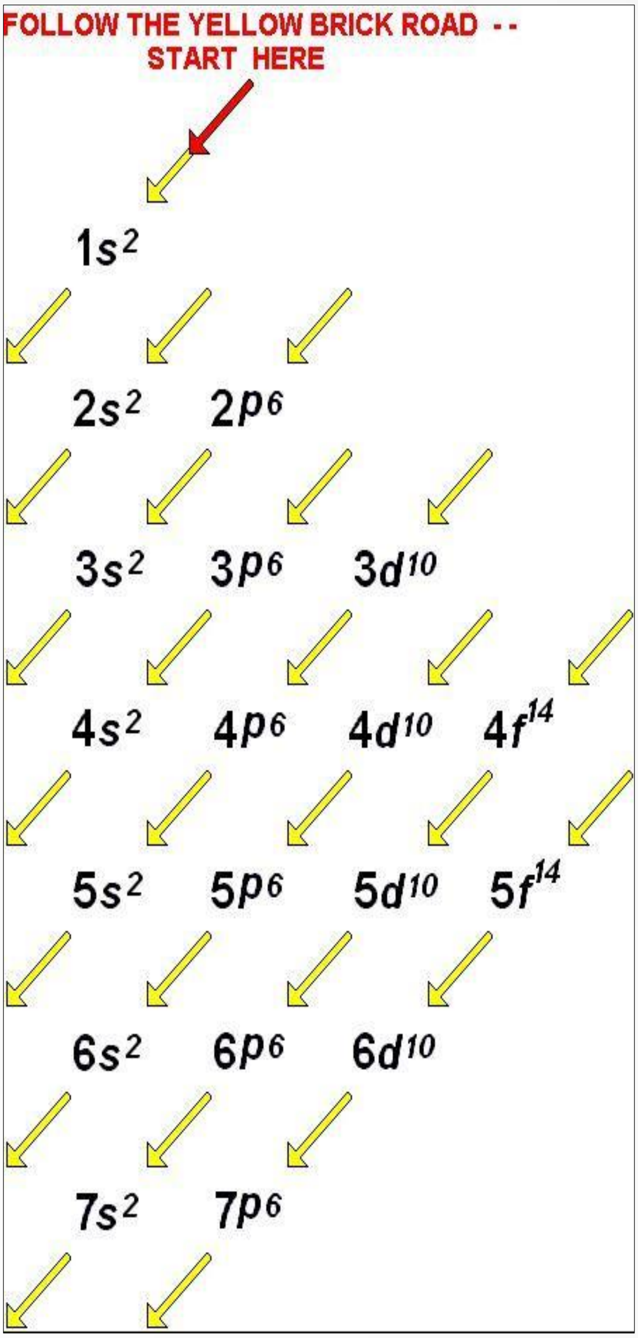


The chemical bonds that hold atoms together can also be described using this. This same concept explains the peculiar characteristics of semiconductors and lasers in bulk materials.

Despite advances in knowledge of the quantum-mechanical nature of electrons, the Bohr model of the atom is still commonly used when discussing electron configuration, and the terms shells and subshells are still frequently used.

An electron shell is the set of allowed states that share the same principal quantum number whereas A subshell is the set of states defined by a common azimuthal number.

The numbers of electrons that can occupy each shell and each subshell arise from the equations of quantum mechanics.



SHELL

Based on the primary quantum number, the maximum number of electrons that can fit in a shell may be calculated. The formula for it is $2n^2$, where n is the shell number. The tables below list the shells, 'n' values, and the total number of electrons that can fit.

Shell and 'n' value	Maximum electrons present in the shell
K shell, n=1	$2*1^2 = 2$
L shell, n=2	$2*2^2 = 8$
M shell, n=3	$2*3^2 = 18$
N shell, n=4	$2*4^2 = 32$

SUBSHELLS

The azimuthal quantum number, represented by the letter 'l', determines the subshells into which electrons are distributed. The value of the primary quantum number, n, determines the value of this quantum number. Therefore, when n has a value of 4, four different subshells are possible. When n=4, the subshells correspond to l=0, l=1, l=2, and l=3 and are named the **s**, **p**, **d**, and **f** subshells, respectively. The maximum number of electrons that can be accommodated by a subshell is given by the formula 2*(2l + 1). Therefore, the maximum number of electrons that can fit into the **s**, **p**, **d**, and **f** subshells are 2, 6, 10, and 14 correspondingly. Below is a table listing every conceivable subshell for n values up to 4.

Principle Quantum Number Value	Value of Azimuthal Quantum Number	Resulting Subshell in the Electron Configuration
n=1	l=0	1s
n=2	l=0	2s
	l=1	2p
n=3	l=0	3s
	l=1	3p
	l=2	3d
n=4	l=0	4s
	l=1	4p
	l=2	4d
	l=3	4f

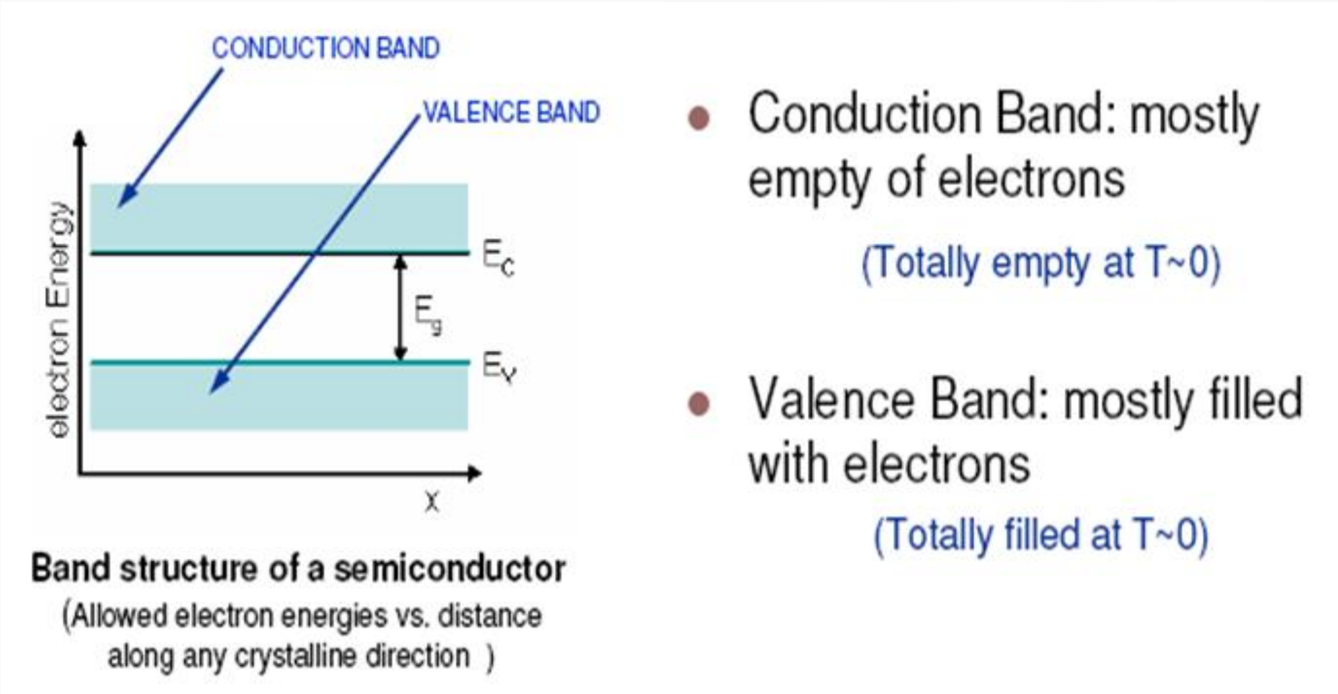
NOTATION

The electron configuration of an atom is written with the help of subshell labels. These labels include the subshell name (determined by the azimuthal quantum number), the shell number (determined by the main quantum number) and the total number of electrons in the subshell, which is shown in superscript. For instance, the notation would be "$1s^2$" if two electrons were added to the first shell's "s" subshell. These subshell labels make it possible to write the electron configuration of magnesium (atomic number 12) as $1s^2\ 2s^2\ 2p^6\ 3s^2$.

ELEMENT OF SOLID STATE PHYSICS

BAND STRUCTURE

The electronic band structure (or simply band structure) of a solid in solid state physics describes the range of energies that an electron within the solid may have (referred to as energy bands, allowed bands, or simply bands) and the ranges of energies that it may not have (referred to as band gaps or forbidden bands).

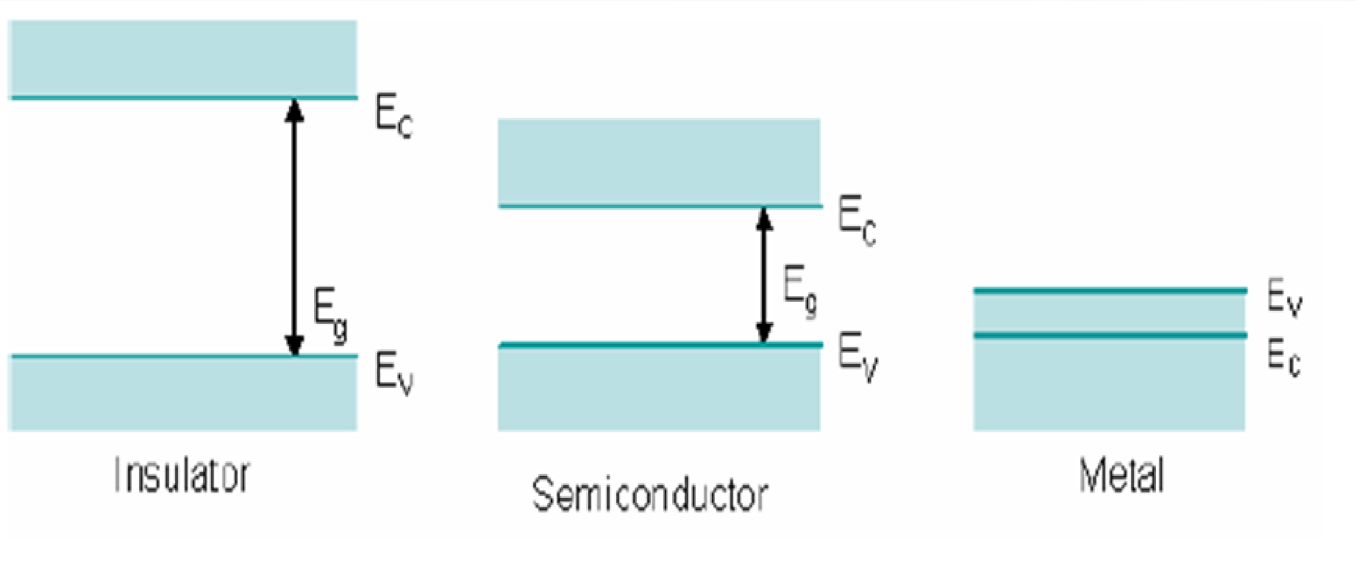


Band structure of a semiconductor
(Allowed electron energies vs. distance along any crystalline direction)

A band gap, also known as an energy gap or bandgap, in solid state physics refers to an energy range in a material where no electron states may exist. The band gap is often defined as the energy difference (in electron volts) between the top of the valence band and the bottom of the conduction band in insulators and semiconductors in graphs of the electronic band structure of solids. It is the ENERGY needed to encourage a valence electron attached to an atom to change into a conduction electron, which is free to travel about the crystal lattice and function as a charge carrier to carry out electrical current.

BAND STRUCTURE

Different types of material such as insulator, semiconductor and metal will have different band structure diagram. A substance that acts as an insulator at absolute zero but permits thermal excitation of electrons into its conduction band at temperatures below its melting point is referred to as a semiconductor because it has a tiny but nonzero band gap. A substance having a wide band gap, on the other hand, is an insulator. Conductors may not have a band gap because the valence and conduction bands may overlap.



Semiconductor Physics

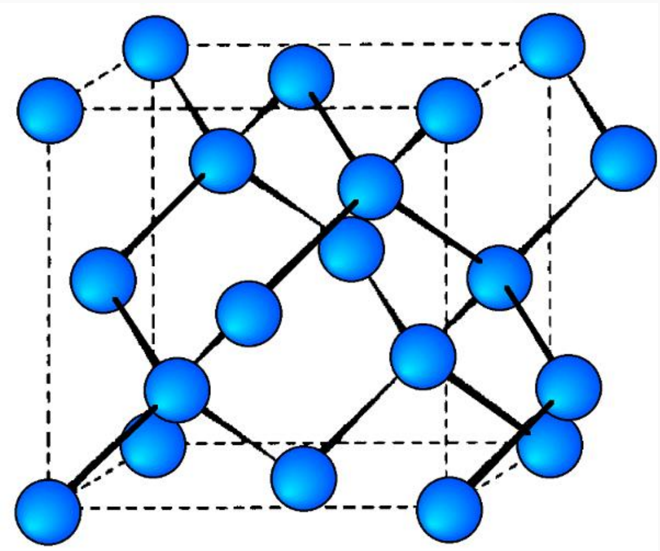
Chapter 2

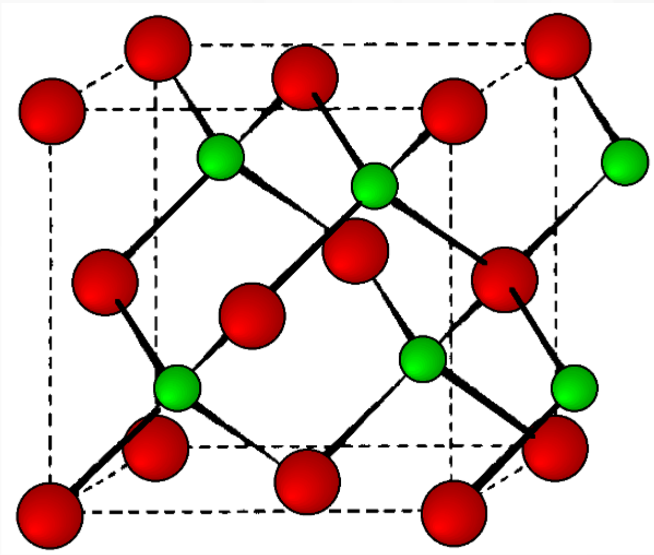
SEMICONDUCTOR PHYSICS

SEMICONDUCTOR CRYSTAL STRUCTURE

For better understanding on propagation of light, it can be consider as a wave. We turn now to a study of devices in which light is generated or detected. The interaction of light with matter, enabling generation and detection of light and it is here that the particle nature of light (quantum viewpoint) becomes relevant. Semiconductors are the key materials use in light emitters and detectors. Properties of matter such as semiconductors can be understand easily through Quantum mechanics. In this chapter, we briefly review those aspects of semiconductors that are essential for an understanding of light generation and detection.

The knowledge on semiconductor crystal lattice arrangement are very important and critical. In order to fully comprehend the material properties of various semiconductors and how to engineer them, it is essential to understand how these atoms are structured.





Semiconductors is made of an atoms which are placed in an ordered form which is called a crystal. Lattice structure is used to identify crystals. For instance, the diamond lattice, which is used to describe silicon's crystal structure, is similar to that of a diamond. In the diamond lattice, a tetrahedron is formed when four neighboring atoms make covalent bonds with one another. Compound semiconductors such as GaAs and InP have a lattice structure which is similar to that of diamond. However the lattice contains two different types of atoms. There are still four covalent links between each atom, but they are now bonds with different type of atoms. This structure is referred to as the zinc-blende lattice as shown above.

ELEMENT OF SOLID STATE PHYSICS

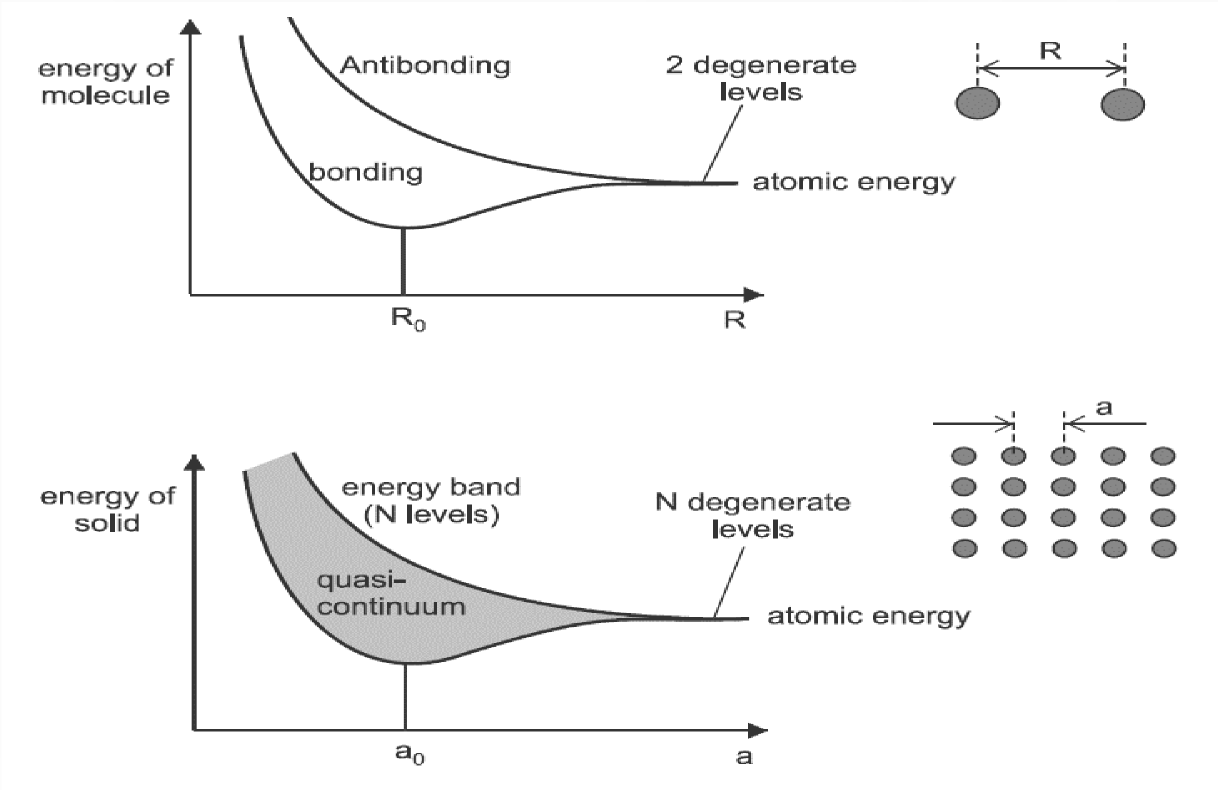
UNIFORM SEMICONDUCTOR

Consider a semiconductor that is limitless in scope and has attributes that are constant throughout the material as we begin by disregarding the borders between various materials (i.e., a uniform material). The simplest explanation of semiconductor physics just takes into account the electron energies that are permitted in the substance. The effects of electron momentum are included in a more sophisticated approach. Both perspectives are helpful for comprehending semiconductors' optical characteristics.

ENERGY BANDS

The energy of a system cannot take on random values but must instead be quantized, according to a fundamental principle of quantum mechanics. Each level can only contain two electrons (Pauli Exclusion Principle). By absorbing or producing photons, electrons can move from one vacant energy level to another.

When two atoms are in close proximity, the interaction of their nuclei and electrons changes the energy level. There are two energy levels with the same value when there is a great distance between the atoms (Degeneration level). As R falls, the two levels separate, with the "bonding" level moving toward lower energy and the "antibonding" level moving toward greater energy.



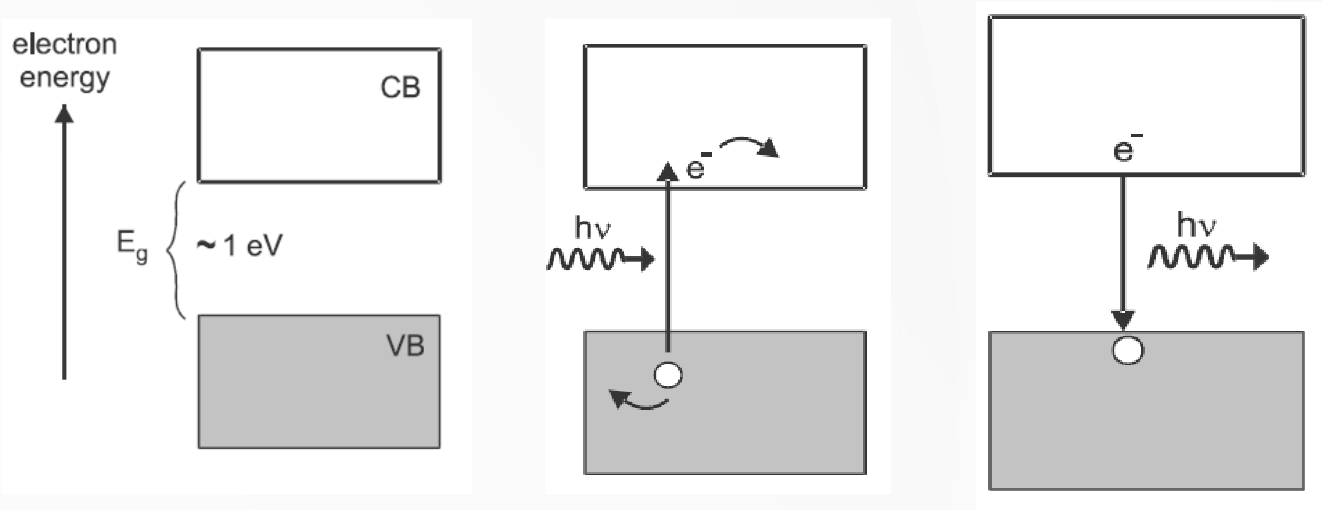
ELEMENT OF SOLID STATE PHYSICS

UNIFORM SEMICONDUCTOR

GENERATION & RECOMBINATION PROCESS

It is simple to understand how light is absorbed by a semiconductor using the band diagram of solids. Consider of light that is incident on a semiconductor with bandgap energy Eg and has photon energy hv, the photon's energy is sufficient to move an electron from the valence band to the conduction band if hv ≥ Eg. When this happens, there is a deficiency of one electron in the valence band in addition to an additional electron in the conduction band.

This hole, that had less electron than normal, behaves in many ways like a positive particle. The net result of this process is the formation of an electron-hole (e-h) pair and the absorption of a photon (the photon vanishes) or known as generation process.



The electron and hole get some kinetic energy from the surplus energy h - Eg in the conduction and valence bands during an absorption process, but this energy is soon dissipated through inelastic collisions. The hole settles at the top of the valence band as the electron moves toward the bottom of the conduction band as it loses kinetic energy. Once the electron and hole (together referred to as charge carriers) are produced by photon absorption, they are each free to travel in the conduction and valence bands, respectively.

The operation of the LED (light emitting diode) and laser diode can also understood by using the energy band diagram to explain the emission of light by a semiconductor. It is possible for electrons to join with holes in the valence band again if they are somehow promoted into the conduction band. This process known as recombination process which is the fundamental of light emission in photonics devices.

SEMICONDUCTOR ENERGY BAND DIAGRAM

Material	Eg	Type of Gap
Si	1.12	Indirect
Ge	0.66	Indirect
GaAs	1.42	Direct
AlAs	2.15	Indirect
InAs	0.33	Direct
InP	1.35	Direct
GaP	2.27	Indirect

Above table show the value of Eg and gap's type for different semiconductor materials. The energy separation between the top of the valence band and the bottom of the conduction band is known as the bandgap energy Eg. As conclusion:

- ❑ Each atom contains additional energy levels that divide into bands.
- ❑ At absolute zero, the valence band is largely filled with electrons.
- ❑ Conduction band is largely empty at absolute zero.
- ❑ Energy gap: the difference between allowed and prohibited energy levels.
- ❑ The photon has enough energy to move an electron from the valence band to the conduction band if hv is larger than Eg. developed EHP.
- ❑ If hv is smaller than Eg, photon absorption is impossible.

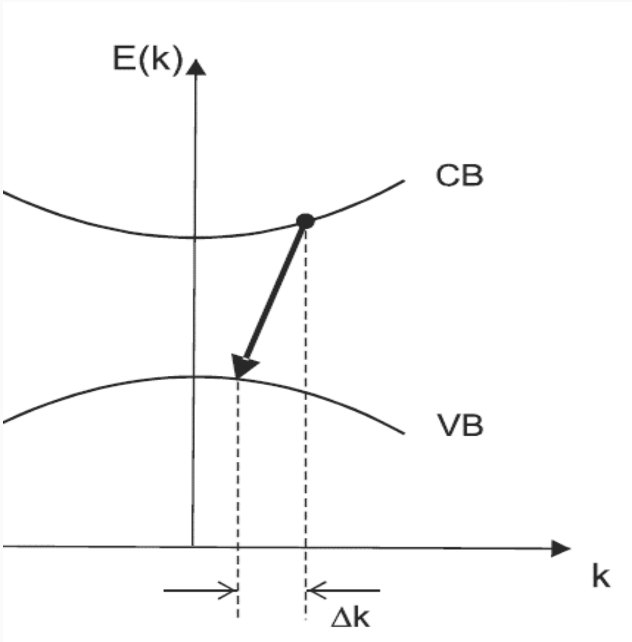
ELEMENT OF SOLID STATE PHYSICS

UNIFORM SEMICONDUCTOR

ENERGY AND MOMENTUM

Electron has momentum as well as energy. The interaction of the electrons with the atoms and the solid prevents them from freely spreading while they are within a solid.

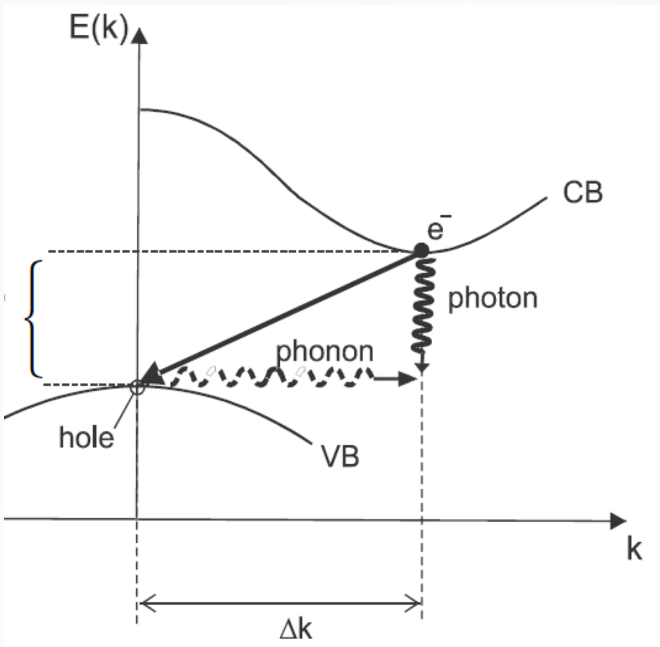
Direct Radiative Transition



- The conduction band minimum and valance band maximum for a direct-band gap material are located at the same momentum, k, values.
- There won't be any change in the momentum values when an electron at the bottom of the CB recombines with a hole at the top of the VB.
- By emitting a photon, energy is preserved; these transitions are referred to as radiative transitions.

Direct Radiative Transition

- Minimum of CB and maximum of VB lies at different k-values for indirect band-gap materials.
- Because the states in the valence band just beneath the electron in the conduction band are already full, a vertical transition is not possible in this situation.
- Phonons is involved to conserve momentum, when electron recombine with holes in indirect band-gap materials.
- **Phonons** is a vibrational waves inside atomic crystal structure at a finite temperature.

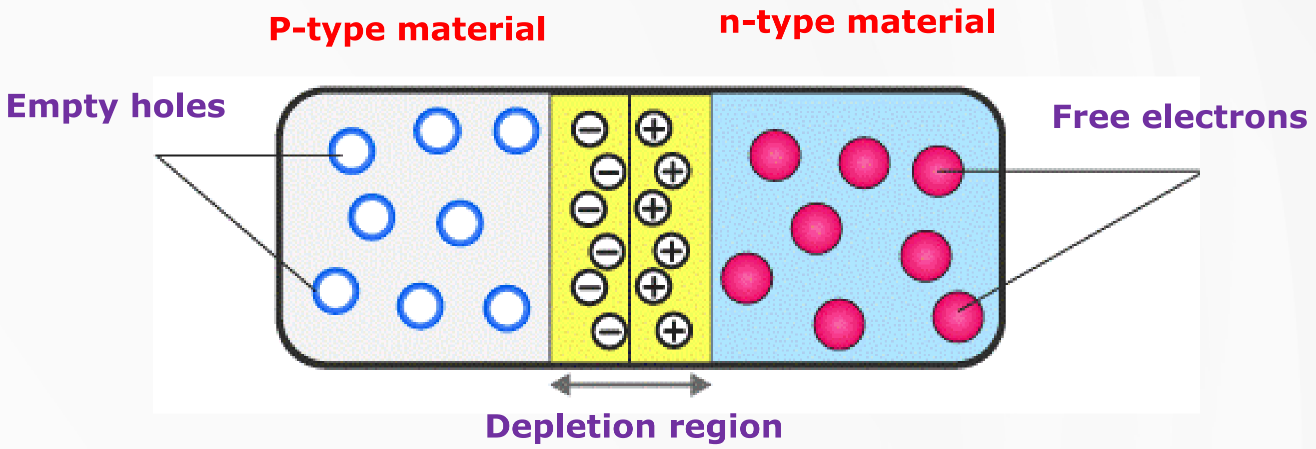


ELEMENT OF SOLID STATE PHYSICS

LAYERED SEMICONDUCTOR

A lot of photonic devices operate in a way that is fundamentally dependent on the border between several semiconductor layers. Junctions can form between metals and semiconductors as well as between semiconductors with similar or different compositions. We consider here these different types of junctions and their important applications.

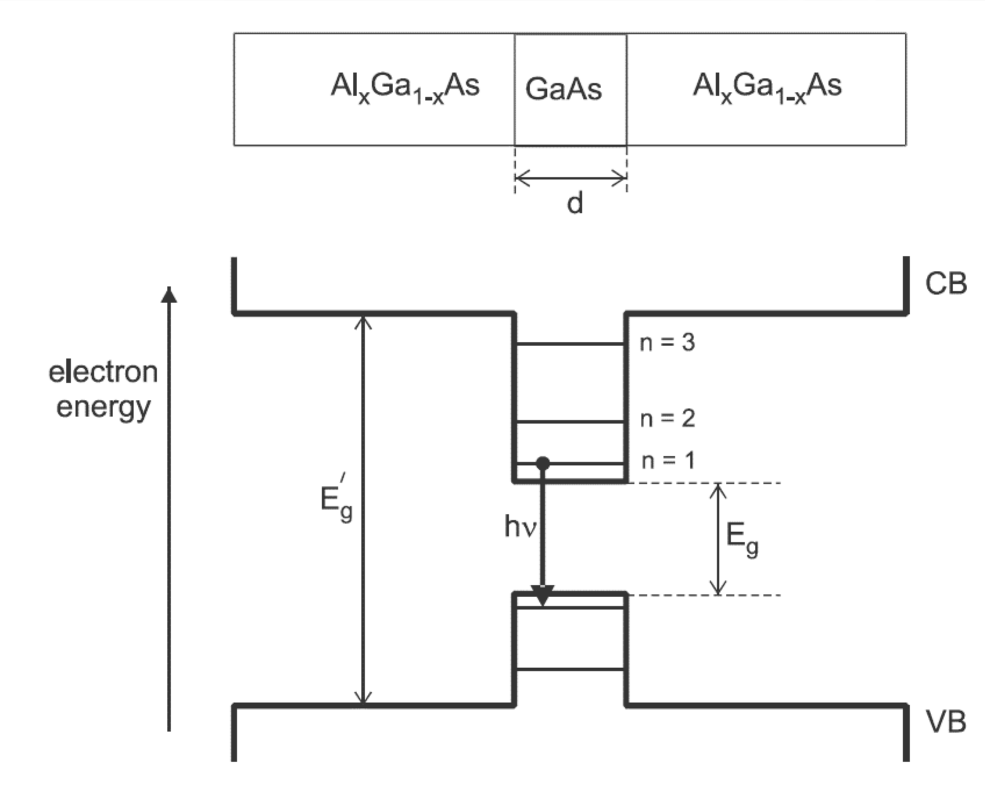
P-N JUNCTION



An intrinsic semiconductor is a pure semiconductor material, such as Si that naturally contains electrons in the conduction band as a result of the thermal excitation of e-h pairs. The essential characteristics of the p-n junction may be understood by assuming that the p and n type materials were developed independently and then brought into physical contact. When the materials come into contact, the free electrons and holes have a natural tendency (known as diffusion) to migrate across such that the entire substance is filled uniformly.

A area close to the barrier known as the depletion region, which is depleted of free charge carriers, is created when the electrons and holes cross the boundary and begin to recombine there. The positive and negative ion cores that remain after the electrons and holes recombine provide a net charge density inside the depletion area. This charge density produces an electric field that is directed in a way that prevents free holes from diffusing into n-type material and free electrons from diffusing into p-type material. The recombination process is thus self-limiting, and results in a depletion region of finite width.

SEMICONDUCTOR HETEROJUNCTIONS: THE QUANTUM WELL



A homojunction is a border between two sections of the same semiconductor material, one doped with donor impurities and the other with acceptors. It is a form of p-n junction similar to the one explained in the previous section. The band gap on either side of the p-n junction is the same, and the electric potential change across the junction causes an equal shift in the energies of the valence and conduction bands. Another type of boundary is a heterojunction, where the semiconductor composition and equivalent band gap are different on either side.

GaAs and AlxGa1-xAs, for instance, have differing band gap energies and are lattice-matched for all values of x. They may be developed in a layered form with a thin layer of GaAs sandwiched between two thick layers of AlxGa1-xAs, and the conduction and valence band energies will change depending on the layer's arrangement. Any charge carriers that end up in the GaAs material will experience a high potential energy barrier upon reaching the boundary on either side and will be "confined" to the GaAs layer as a result. The structure is known as a quantum well when the GaAs layer's thickness d is sufficiently thin to emphasize quantum mechanical processes.

Light Source

Chapter 3

Light Source

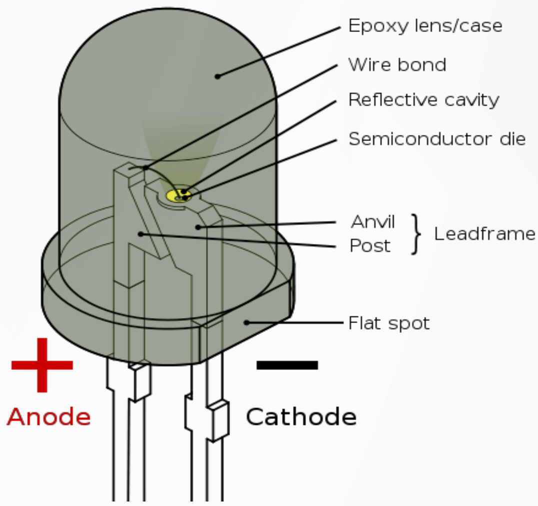
LED vs LASER

HISTORY OF LED

Early in the 20th century, Henry Round from Marconi's Labs made the first observation that a semiconductor junction might create light. The first LED was independently developed by Russian scientist Oleg Vladimirovich Losev in the middle of the 1920s, but his research publications were turned down at the time by British, German, and Russian scientific journals.

In 1955, Rubin Braunstein of the Radio Corporation of America published a research on the infrared emission of semiconductor alloys such as gallium arsenide (GaAs). In 1961, Bob Biard and Gary Pittman of Texas Instruments discovered that Gallium Arsenide emits infrared light when a potential difference is introduced. In order to secure the infrared light-emitting diode patent, Biard and Pittman had to prove the prioritisation of their effort. The first usable visible-spectrum LED was created in 1962 by Nick Holonyak Jr., a former employee of General Electric and later a researcher at the University of Illinois at Urbana-Champaign [8]. He is known as the "father of the light-emitting diode" [9]. M. George Craford, a former graduate student of Holonyak, created the first yellow LED and 10x brighter red and red-orange LEDs in 1972.

InGaN-based high-brightness blue LEDs were originally demonstrated by Shuji Nakamura of the Nichia Corporation of Japan, building on important advances in GaN nucleation on sapphire substrates and the demonstration of p-type doping in GaN made in Nagoya. The effectiveness and dependability of high-brightness LEDs were studied in 1995 by Alberto Brbieri at the Cardiff University Laboratory. He produced extremely high results by employing a transparent contact formed of indium tin oxide (ITO) on (AlGaInP/GaAs) LED. The first white LED, sometimes known as a "YAG" phosphor, used a $Y_3Al_5O_{12}$:Ce coating to combine yellow (down-converted) light with blue light to create light that appears white. This technique was widely adopted with the development of the high efficiency blue LED. The Millennium Technology Prize was given to Nakamura in 2006 for his creation.



LED structure. Retrieved from (SANGUINIS2015, 2016)

Light Source

LED vs LASER

There are several types of light sources available, including LED, halogen, and laser. LED and laser light sources are two examples of semiconductor light sources.

1. LED: A General Overview

LED lighting stands for light-emitting diodes (LEDs). LEDs are semiconductor p-n junctions which can generate electromagnetic radiation by electroluminescence in the UV, visible, or infrared spectrums when subjected to forward bias conditions. The semiconductor's band gap and the amount of light energy produced are roughly inversely related.

As they are semi-conductor solid-state devices, this technology has progressed from use in numerical displays and indicator lights to a variety of novel applications such as exit signs, traffic lights, signage, outdoor lighting, accent lighting, down lighting, and so on. LED illumination is achieved by directly producing visible light in a desired wavelength range by excitating a semiconductor crystal.

2. Important traits of LED

1. When a power supply activates an LED, it converts the AC voltage into enough DC voltage to be delivered across the diode semiconductor crystal, where excess energy is turned to light.

2. The brightest LEDs and white LEDs have been developed thanks to the usage of indium gallium nitride (InGaN) as a semiconductor material.

3. LEDs have higher efficacies in terms of lumen output than incandescent bulbs, and they operate with low voltage and low current.

4. Color can be produced by LEDs depending on the chemical makeup of the material being activated. It can generate colours including white, deep blue, yellow, green, orange, red, bright red, and deep red.

Light Source

LED vs LASER

3. Mechanism behind photon emission in LEDs

LEDs use a technique known as injection electroluminescence, which is the recombination of the majority carrier in a p-n junction, to generate light. By injecting majority carriers from both the p and n materials across the junction when the p-n junction is forward biased, visible light is produced when the majority carriers recombine on the opposite side of the junction as shown in Figure 3.1 below.

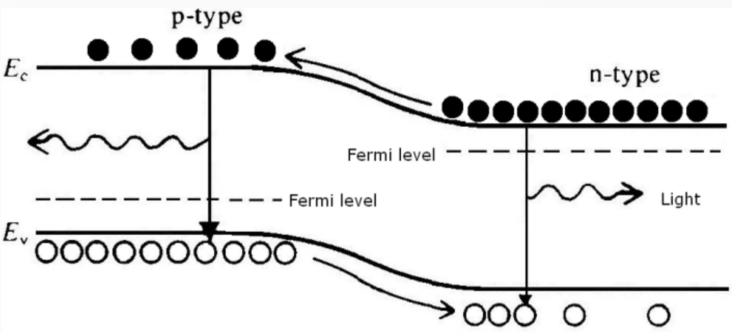


Figure 3.1: Radiative recombination with the majority carrier and minority carrier injection in a forward bias p-n junction.

When the electron falls down from conduction band and fills in a hole in valence band, there is an obvious loss of energy. Therefore, for a material with a direct band gap, the excess energy from the electron-hole recombination can either be removed as heat or, most commonly, as a light photon. Then, whenever an electron and hole unite again, this radiative transition emits light, conserving energy and momentum. The illustration is shown in Figure 3.2.

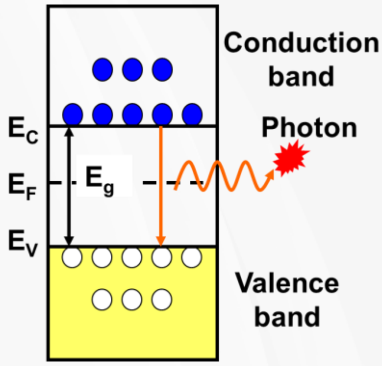


Figure 3.2: Photon emission in semiconductor

When an electron collides with a hole, it loses energy in the form of a photon and falls into a lower energy level. The band gap of the semiconductor material determines the wavelength of the light.

DID YOU KNOW?

i. Electro part tells us that the photons are being produced by an electric current.

ii. Injection tells us that photon production is by the injection of current carriers.

iii. Electroluminescence (EL) is an optical phenomenon and electrical phenomenon in which a material emits light in response to the passage of an electric current or to a strong electric field.

Light Source

LED vs LASER

Higher carrier densities and enhanced carrier confinement can be accomplished in the double heterojunction LED, such as pAlGaAs-iGaAs-nAlGaAs, by sandwiching a narrow energy band-gap material like iGaAs between two wide energy band-gap materials like AlGaAs, as shown in Fig. 3.3. Furthermore, the shorter radiative recombination lifetime results in more effective radiative recombination. Minority carriers would be increased on both sides of the p and n materials by the injected carrier across the junction.

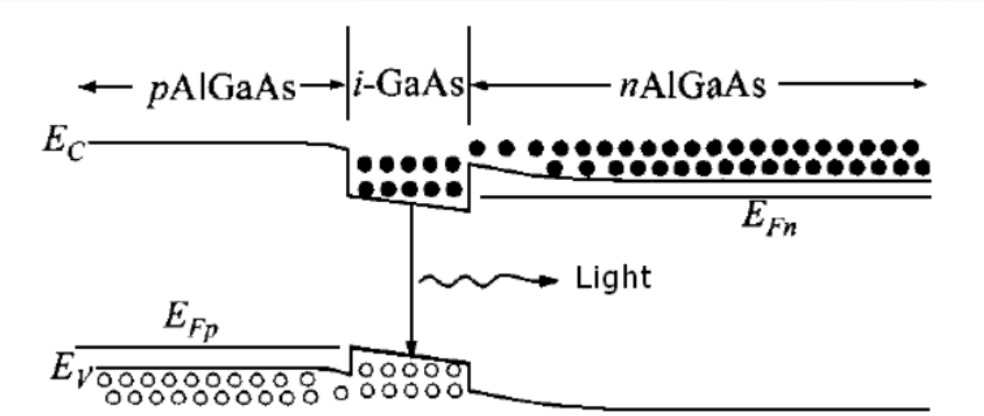


Figure 3.3 Double heterojunction pAlGaAs-iGaAs-nAlGaAs LEDs provide a higher injection density and improved carrier confinement.

Due to lattice interaction mostly caused by phonon and other scattering agents that cause poor radiative transition, indirect semiconductors like silicon and germanium have very low probabilities of radiative transition. The idea of complete wavevector conservation will be used to explain the cause. Indirect semiconductors can now, however, be doped or diffused with elements like bismuth (Bi) and nitrogen (N), which create a capturing centre in the forbidden gap.

A photon with an energy equal to the transition energy is produced when a direct semiconductor, such as gallium arsenide, gallium arsenide phosphide $GaAs_{1-x}P_x$, or gallium indium arsenide phosphide, recombines very effectively. LEDs may create visible light ranging from infrared to violet by properly combining the compound semiconductor gallium indium arsenide and phosphide.

Electron Hole Pair Recombination

In optoelectronic devices, the extra electrons and holes (in pair-form) are produced by adequate light absorption. The rate of carrier generation and device efficiency are both determined by the degree of light absorption. The simplest method of light absorption involves the collision of semiconductor electrons with optical radiation energy units, or photons. The valence band electron is stimulated into the conduction band by optical absorption if the incoming photon has a specific minimum energy (h≥Eg), which results in the formation of a hole in the valence band, as shown in Figure 3.3. The most frequent process in optical detectors is the conversion of optical energy into electron-hole pairs (via an absorption process).

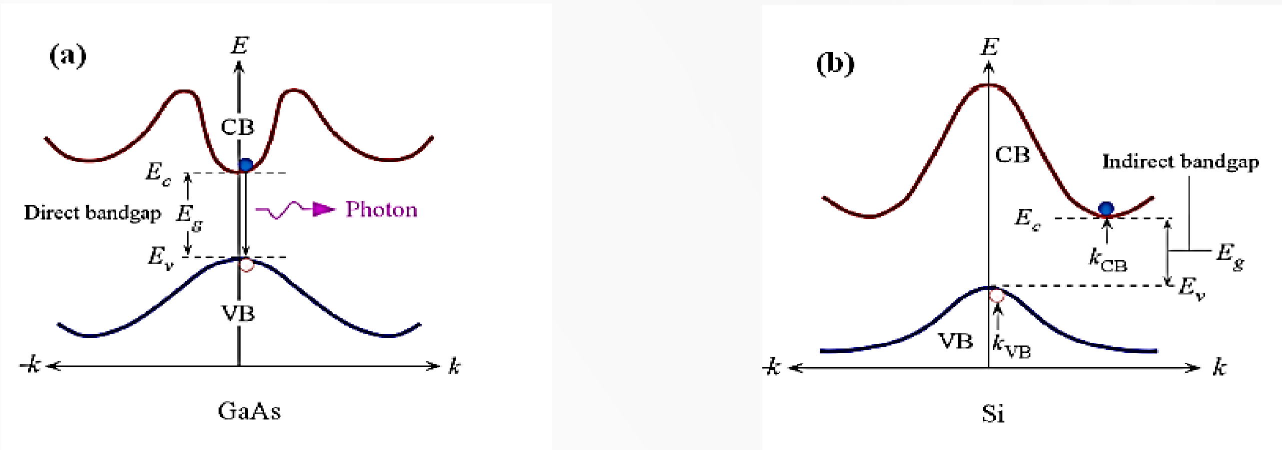


Figure 3: Carriers generation in semiconductors with (a) direct bandgap and (b) indirect bandgap.

When light is absorbed, the incoming photons provide the filled valence band electrons the energy they need to transition into the higher energy states in the conduction band, leaving holes in the valence band behind (at least energy equivalent to bandgap energy). In the opposite process, the excited electrons release the extra energy as light radiation when they recombine with holes using radiative or non-radiative mechanisms. The fundamental operation of numerous light sources, including light emitting diodes, lasers, and various display systems, etc., is the transfer of excited electrons from the conduction band to the valence band through the release of light.

QUICK INFO

- The recombination of an electron from the conduction band with the a hole from the valence band can be either:
  - **a)** **Radiative** (releases photon / light). It is this radiative process which is very much wanted to produce an efficient LED.
  - **b)** **Nonradiative** (do not emit light but emit heat). This should be avoided in a LED.
- In general, the recombination process in a material has to satisfy the **energy and momentum conservation** rule.

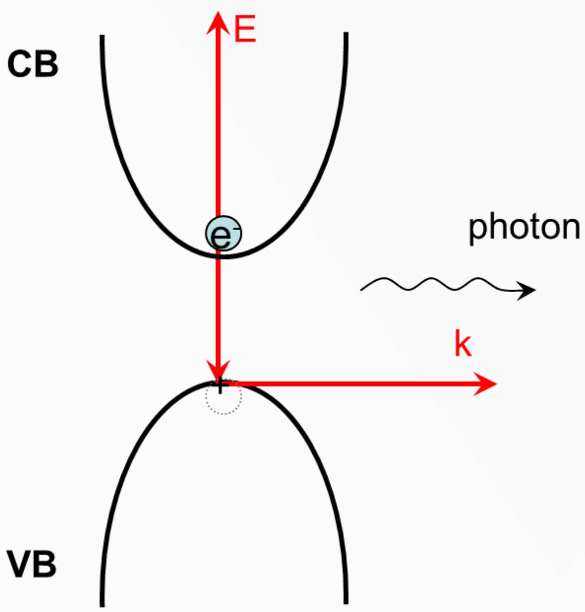
Direct and Indirect-Band Gap Materials

INDIRECT BAND GAP MATERIAL

For a direct-band gap material, the minimum of the conduction band and maximum of the valance band lies at the same momentum, k, values.

When an electron sitting at the bottom of the CB recombines with a hole sitting at the top of the VB, there will be no change in momentum values.

Energy is conserved by means of emitting a photon, such transitions are called as radiative transitions.

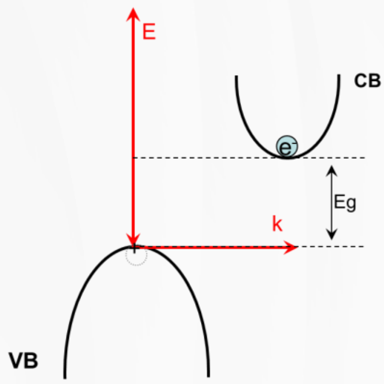


Direct-band gap s/c's , e.g. GaAs (Gallium arsenide), InP (Indium phosphide), AlGaAs (Aluminum Gallium Arsenide)

INDIRECT BAND GAP MATERIAL

For an indirect-band gap material; the minimum of the CB and maximum of the VB lie at different k-values.

When an e- and hole recombine in an indirect-band gap s/c, phonons must be involved to conserve momentum.

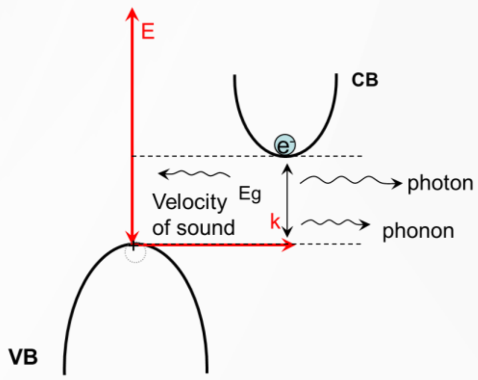


Indirect-band gap s/c's (e.g. Si and Ge)

Atoms vibrate about their mean position at a finite temperature. These vibrations produce vibrational waves inside the crystal.

Phonons are the quanta of these vibrational waves. Phonons travel with a velocity of sound .

Their wavelength is determined by the crystal lattice constant. Phonons can only exist inside the crystal.



Light Source

LED vs LASER

Various semiconductors' energy bandgaps in relation to the optical spectrum. The visible light spectrum ranges in wavelength from 380 to 750 nm.

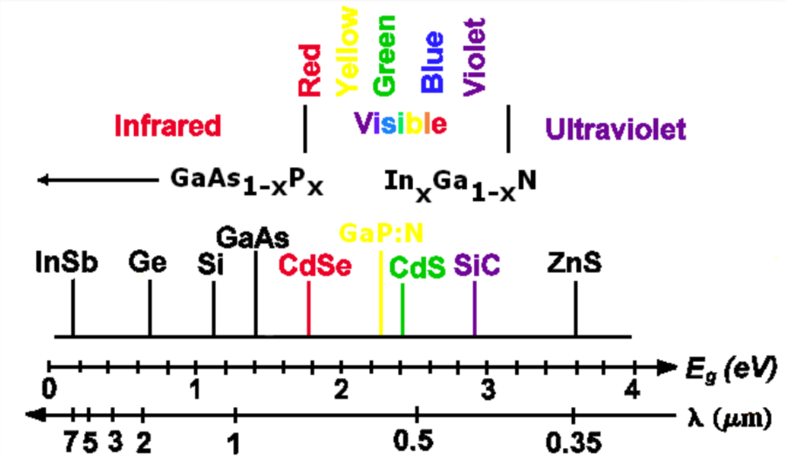


Figure 3.3 displays the optical spectrum and energy band-gap of a few semiconductors. The photon energy ranges from 0.18eV infrared (InSb) to 3.6eV ultraviolet (ZnS) energy..

Due to lattice interaction mostly caused by phonon and other scattering agents that cause poor radiative transition, indirect semiconductors like silicon and germanium have very low probabilities of radiative transition. The idea of complete wavevector conservation will be used to explain the cause. Indirect semiconductors can now, however, be doped or diffused with elements like bismuth (Bi) and nitrogen (N), which create a capturing centre in the forbidden gap.

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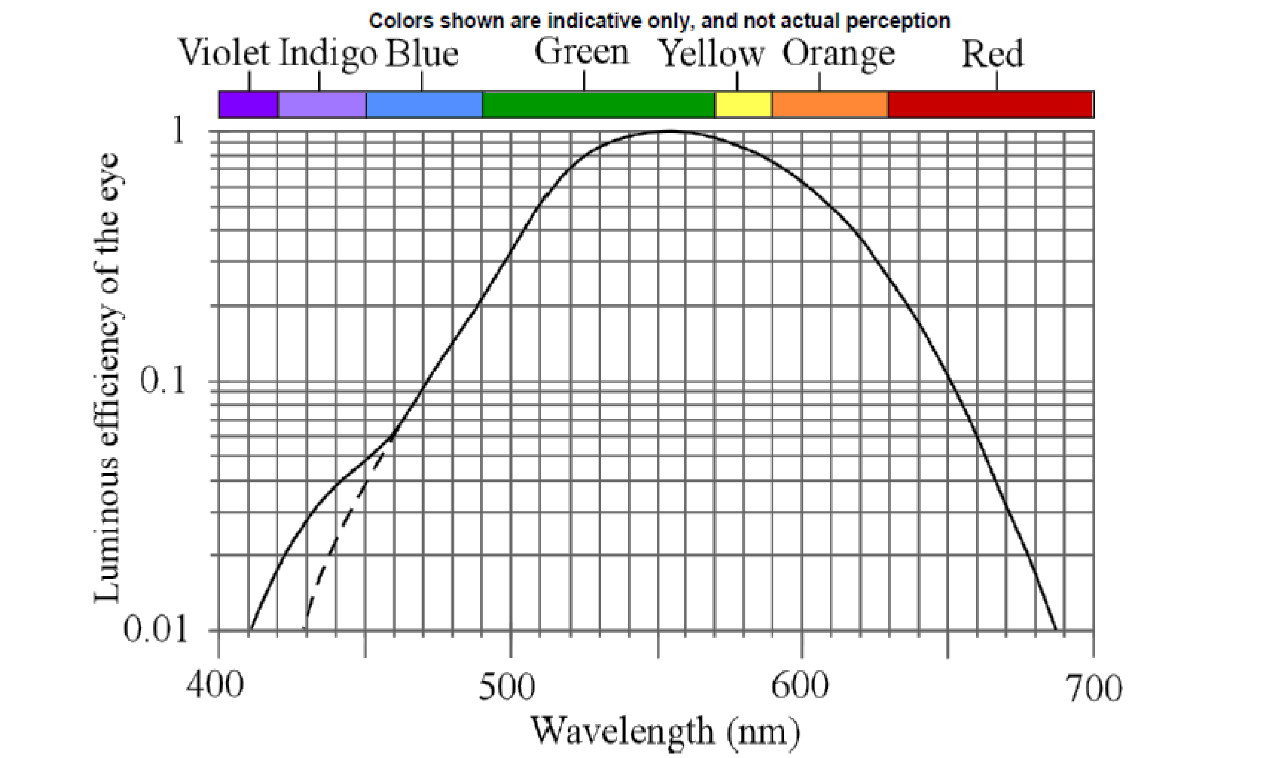
Light Source

LED vs LASER

LED Brightness (photopic vision)



The luminous efficiency $V(\lambda)$ of the light-adapted (photopic) eye as a function of wavelength. The solid curve is the Judd-Vos modification of the CIE 1924 photopic photosensitivity curve of the eye. The dashed line shows the modified region of the original CIE 1924 curve to account for its deficiency in the blue-violet region. (The vertical axis is logarithmic)

The brightness of a source as seen by the human eyes depends on the:

a) radiation (optical) power emitted by the source, P_o(□).

b) relative luminous efficiency of the human eye, V(□), to detect the spectrum

The total luminous flux, Φv , is measure of visual brightness, in unit lumens (lm). and is defined by

$$\Phi_v = P_o \times (633 \text{ lm W}^{-1}) \times V(\lambda)$$

Radiant power emitted   Luminosity function

This means that the higher the lumens, the brighter the human will perceive the object.

From the "luminous efficiency of the eye versus wavelength" curve in the previous slide, green the highest value compared to blue and red wavelengths. This is why a green laser pointer looks much brighter compared with blue or red laser pointers of the same optical power.

LED EFFICIENCIES

LEDs are semiconductor devices that produce light when electrons and holes recombine in the active zone, which is made up of a series of layers with unique design. Because the majority of these recombination events produce a photon of light, they are classified as "radiative" recombination events.

The bandgap of the active region controls the wavelength of the light that is emitted; a bigger bandgap causes higher energy output, which corresponds to a shorter wavelength.

The chemical makeup and arrangement of the semiconductor layers within the active region, in turn, control the bandgap.

Internal quantum efficiency (IQE) – what fraction of EHP recombination in the forward biased pn junction are radiative and therefore lead to photon emission

$$\eta_{IQE} = \frac{\text{Rate of radiative recombination}}{\text{Total rate of recombination (radiative and nonradiative)}} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r}+\frac{1}{\tau_{nr}}} \times 100\%$$

Where;

tr is the mean lifetime of a minority carrier before it recombines radiatively

tnr is the mean lifetime before it recombines via a recombination center

without emitting a photon

External quantum efficiency (EQE)– efficiency of conversion of electrical energy into an emitted external optical energy – incorporates efficiency of radiative recombination process and subsequent photon extraction from the device

$$\eta_{EQE} = \frac{\text{number of emitted photon per second}}{\text{number of electron flowing into LED}} = \frac{P_o/hv}{I/e}$$

i. Use EQE to compare different LED efficiencies direct bandgap : ηEQE : 30 – 40% indirect bandgap : ηEQE : < 1%
ii. Use IQE to compare different LED material.

Light Source

LED vs LASER

Diode lasers are semiconductor devices that generate coherent light that is typically of a single wavelength using the p-n junction of a semiconductor diode. Diode lasers are now the most widely used lasers in the world, employed in a wide range of components and disciplines, including electronics, communications, and medical procedures. This is because of the compact size, low power consumption, and economical fabrication of these devices. Diode laser performance is influenced by a number of factors, including the characteristic temperature, slope efficiency, and threshold current.

The term "LASER" is an acronym for:

- Light
- Amplification by
- Stimulated
- Emission of
- Radiation

The laser is a device that emits a collimated (pencil-like) beam of either visible or invisible electromagnetic radiation (light).

All lasers are comprised of these essential elements:

i. Active medium
ii. Excitation
iii. High reflectance mirror and the partially transmissive mirror (output coupler).

Lasers are categorized for safety considerations based on their ability to cause eye and skin harm in humans.

The Class of most laser products is required by law to be labelled. It will be listed in Arabic numbers (1, 2, 3R, 3B, 4) or Roman numerals (1, 2, 3R, 3B, 4). (I, II, IIIa, IIIb, IV). For the sake of simplicity, we predominantly utilize Arabic numbers on this ebook.

There are four basic types of visible-beam consumer lasers. Class 2, Class 3R, Class 3B, and Class 4 are each discussed in next page. The first two classes are quite safe for ocular exposure, however the last two are dangerous.

Classification of Laser

ANSI and IEC laser classification	Class 1		Class 2		Class 3		Class 4
Sub-class	Class 1	Class 1M	Class 2	Class 2M	Class 3R	Class 3B	Class 4
U.S. FDA laser classification	Class I	No special FDA class	Class II	No special FDA class	Class IIIa (definition is different but results are similar)	Class IIIb	Class IV
Human-accessible laser power (for visible light)	For visible light, emits beam less than 0.39 milliwatts, or beam of any power is inside device and is not accessible during operation.		Emits visible beam of less than 1 milliwatt.		For visible light, emits beam between 1 and 4.99 milliwatts.	For visible light, emits beam between Class 3R limit (e.g. 5 milliwatts) and 499.9 milliwatts	For visible light, emits beam of 500 milliwatts (1/2 Watt) or more
Caution/warning indication	No special caution/ warning indication		No special caution/ warning indication		CAUTION	WARNING	DANGER
Label descriptive text		DO NOT VIEW DIRECTLY WITH OPTICAL INSTRUMENTS	DO NOT STARE INTO BEAM	DO NOT STARE INTO BEAM OR EXPOSE USERS OF TELESCOPIC OPTICS	AVOID DIRECT EYE EXPOSURE	AVOID EXPOSURE TO BEAM	AVOID EYE OR SKIN EXPOSURE TO DIRECT OR SCATTERED RADIATION
EYE AND SKIN HAZARDS							
Eye hazard for intraocular exposure (having a direct or reflected beam enter the eye)	Safe, even for long-term intentional viewing. For visible light, usually applies when the laser is enclosed inside a device (ex: CD or DVD player) with no human access to laser light.	Safe for unaided eye exposure. May be hazardous if viewed with optical instruments such as binoculars or eye loupe.	Safe for unintentional exposure less than 1/4 second. Do not stare into beam.	Safe for unintentional (< 1/4 sec) unaided eye exposure. May be hazardous if viewed with optical instruments such as binoculars or eye loupe.	Unintentional or accidental exposure to direct or reflected beam has a low risk. Avoid intentional exposure to direct or reflected beam.	Eye hazard; avoid exposure to direct or reflected beam.	Severe eye hazard; avoid exposure to direct or reflected beam.
Maximum or typical Nominal Ocular Hazard Distance (for 1 milliradian beam, exposure time less than 1/4 second)	Not an eye hazard -- does not apply	Consult an LSO as described in the Technical Note below	**NOHD of 0.99 mW beam:** 23 ft (7 m)	Consult an LSO as described in the Technical Note below	**NOHD of 4.99 mW beam:** 52 ft (16 m)	**NOHD of 499.9 mW beam:** 520 ft (160 m)	**NOHD of 1000 mW (1 Watt) beam:** 733 ft (224 m). **NOHD of 10 W beam:** 2320 ft (710 m)
Eye hazard for diffuse reflection exposure (looking at the laser "dot" scattered off a surface)	None	Consult an LSO	None	Consult an LSO	None	Generally safe. Avoid staring at the laser "dot" on a surface for many seconds at close range.	To avoid injury, do not stare at laser "dot" on a surface. The light is too bright if you see a sustained afterimage, lasting more than about 10 seconds.
Skin burn hazard	None	Consult an LSO	None	Consult an LSO	None	Can heat skin if beam is held long enough on skin at close range	Can instantly burn skin. Avoid direct exposure to the beam.
Materials burn hazard	None	Consult an LSO	None	Consult an LSO	None	Can burn materials if beam is held long enough on substance at close range	Can instantly burn materials. Avoid direct exposure to the beam, for materials susceptible to burning.
VISUAL INTERFERENCE DISTANCES							
Maximum or typical flashblindness distance (FAA 100 $\mu W/cm^2$, for 1 milliradian beam, 555 nm green light)	Not applicable; beam is usually contained inside a device such as a CD or DVD player	Consult an LSO	**For a 0.99 mW beam:** 117 ft 36 m	Consult an LSO	**For a 4.99 mW beam:** 261 ft 80 m	**For a 499 mW beam:** 2,614 ft (1/2 mile) 797 m (0.8 km)	**For a 1 Watt beam:** 3,696 ft (0.7 mile) 1,127 m (1.1 km) **For a 10 W beam:** 11,689 ft (2.2 miles) 3,563 m (3.5 km)
Maximum or typical glare distance (FAA 5 $\mu W/cm^2$, for 1 milliradian beam, 555 nm green light)	See above	Consult an LSO	523 ft 159 m	Consult an LSO	1,169 ft 356 m	11,689 ft (2.2 miles) 3,563 m (3.5 km)	**For a 1 Watt beam:** 16,531 ft (3.1 miles) 5,039 m (5 km) **For a 10 W beam:** 52,275 ft (9.9 miles) 15,933 m (16 km)
Maximum or typical distraction distance (FAA 0.05 $\mu W/cm^2$ or 50 nanowatts/cm², for 1 milliradian beam, 555 nm green light)	See above	Consult an LSO	5,227 ft (1 mile) 1,593 m (1.6 km)	Consult an LSO	11,689 ft (2.2 miles) 3,563 m (3.5 km)	116,890 ft (22 miles) 35,628 m (35.6 km)	**For a 1 Watt beam:** 165,307 ft (31 miles) 50,386 m (50 km) **For a 10 W beam:** 522,746 ft (99 miles) 159,333 m (160 km)
Technical Notes	For a 1/4 second exposure to accessible visible-light beams, Class 1 limits are the same as Class 2, and such lasers are usually labeled as Class 2.	We are unaware of any Class 1M laser devices intended for consumer use. If you do have such a laser, consult a qualified Laser Safety Officer for more detailed analysis.	Class 2 (and 2M) only applies to visible lasers. Infrared and ultraviolet lasers cannot be Class 2 (or 2M).	We are unaware of any Class 2M laser devices intended for consumer use. If you do have such a laser, consult a qualified Laser Safety Officer for more detailed analysis.	Class 3R is either: (1) From 1 to 4.99 mW into a 7mm aperture (e.g., pupil of the eye) or (2) five times the Class 2 limit of 2.5 mW/cm², which works out to be 12.5 mW/cm². The second method is used by LaserSafetyFacts to determine NOHD.		
	Class 1	Class 1M	Class 2	Class 2M	Class 3R	Class 3B	Class 4
	Class 1		Class 2		Class 3		Class 4

Light Source

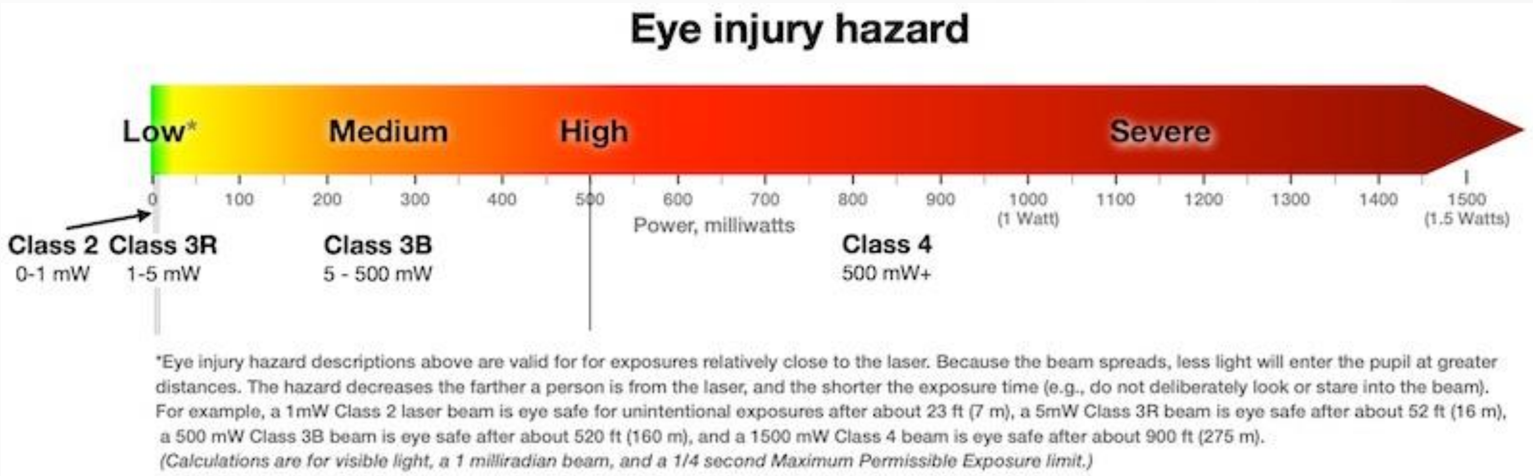
LED vs LASER

Lasers and laser systems are assigned one of the four broad classes (1 to 4) depending on the potential for causing potential damage.

Class 1: "safe" if not disassembled. Example: Laser printers, CD-ROM players/drives
Class 2: may exceed class 1 exposure limits if viewed more than 0.25 seconds [aversion respond time], but still not pose a significant eye hazards. Example: Supermarket scanners
Class 3a: eye hazard if viewed using collecting optics, e.g., telescopes, microscopes, or binoculars.
Class 3b: eye hazards if beams are viewed directly or specular reflections are viewed. Example: research
Class 4: eye hazards if beams are viewed directly or specular reflections and sometimes even from diffuse reflections are viewed. Also skin burns from direct beam exposure. Example: research, manufacturing.

Eye Injury Hazard

The chart below depicts how the risk of eye injury increases as laser strength increases.



Optical Detectors

Chapter 4

Optical Detectors

Thermal Detectors and Photon Detectors

Optical Detectors

An optical sensor is a device that allows a measurand to modulate an optical signal's characteristic in a repeatable and recoverable manner. Despite the optical transduction mechanism, an electrical signal must be generated in order to process and either record or display the optical signal.

A photodetector, which transforms optical energy into electrical energy, is used to carry out this function. Ordinarily, a basic photodetector only generates a weak electrical signal, which needs to be amplified right away in order to be processed further. A receiver is a device that combines a photodetector and its on-the-spot amplification.

Depending on how the electrical signal is generated, optical detectors can be classified as thermal detectors or photon detectors as shown in Figure 4.1.

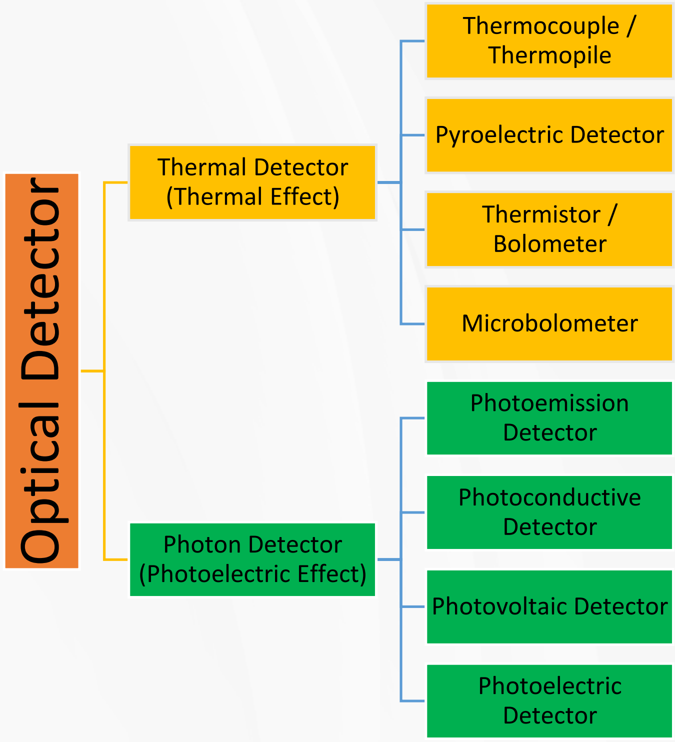


Figure 4.1: Optical detectors classification

Thermal Detectors

Thermal detectors work by using the thermal effect to heat the detection element and change some physical properties through heat so that the IR radiation energy can be detected.

Thermal detectors are relatively simple devices that function primarily at room temperature (see Fig. 4.2). Temperature fluctuations occur while it is in operation, and compared to photon detectors, it may respond slowly and have relatively low sensitivity.

Optical Detectors

Thermal Detectors and Photon Detectors

Infrared thermal detectors generally come in 4 different varieties: Thermistor / Bolometer, Pyroelectric Detector, Thermocouple / Thermopile, and Microbolometer.

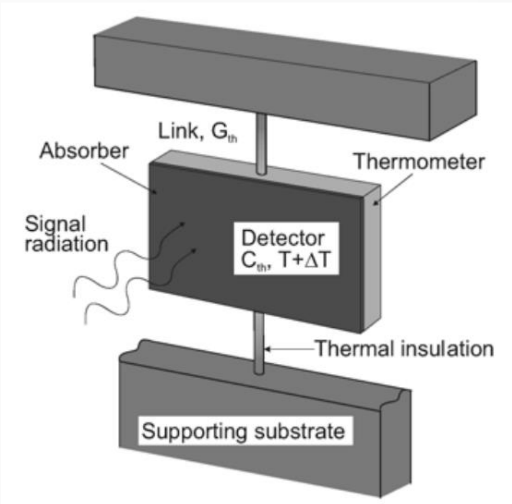


Figure 4.2: The thermal detector in its most basic form. The detector is represented by a thermal capacitance Cth coupled to a heat sink at a constant temperature via a thermal conductance Gth. The temperature difference caused by the optical signal is denoted by ΔT. Retrieved from (Jozef & Rogalski, 2007).

Thermal detector is typically suspended from lags that are linked to a heat sink. The photonic nature of the incident radiation has no bearing on the signal. Thermal effects are therefore typically wavelength independent; the signal depends on the radiant power (or its rate of change) but not on its spectral content, assuming that the mechanism causing the radiation to be absorbed is also wavelength independent (see Fig. 4.3).

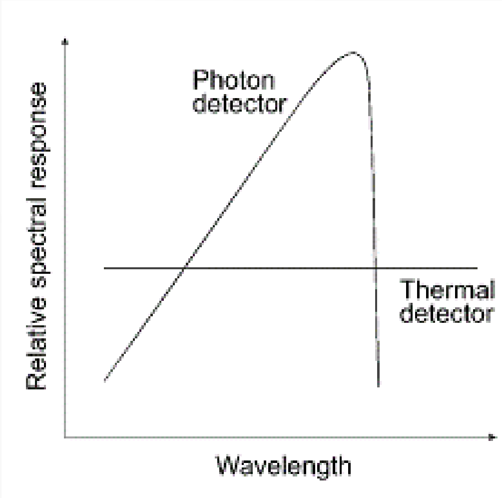


Figure 4.3: Thermal and photon detectors' respective spectral responses. Retrieved from (Jozef & Rogalski, 2007).

Example of Thermal Detectors:

1. Thermoelectric detectors

These rely on the thermocouple principle (the Seebeck effect), which states that when one junction between two dissimilar metals is heated in relation to the other, current flows around a circuit in a proportional manner to the difference in temperature between the junctions. Their simplicity and robust construction make them useful.

Optical Detectors

Thermal Detectors and Photon Detectors

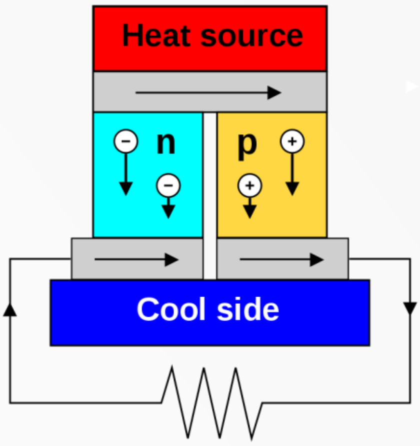


Figure 4.4: A thermoelectric circuit composed of materials of different Seebeck coefficients (p-doped and n-doped semiconductors), configured as a thermoelectric generator. If the load resistor at the bottom is replaced with a voltmeter, the circuit then functions as a temperature-sensing thermocouple.

2. Pyroelectric Detectors

In a ferroelectric material with molecules that have a permanent electric dipole moment, the incident radiation is absorbed. Temperature affects the amount of net electric polarisation at the moment (below the a critical temperature characteristic of the material). By monitoring the change in charge on the capacitor's plates when it is set up as a capacitor in a circuit, it is possible to identify polarisation changes brought on by material temperature changes.

It is possible to create pyroelectric detectors with response times in the nanosecond range and wavelength responses that go out to about 100 m. They have proven to be very effective as affordable, reliable IR detectors in applications like fire detection and intrusion alarms.

Figure 4.5: Pyroelectric detector

Photon Detectors

The basic idea behind a photon detector is to use the incident radiation's photon flow to interact with the electrons present in the detector material. This changes the electrons' energy state and results in a variety of electrical phenomena known as photon effects.

The four types of photon detectors are photoemission detectors, photoconductive detectors, photovoltaic detectors, and photoelectric detectors.

Optical Detectors

Thermal Detectors and Photon Detectors

Photoelectric Effect

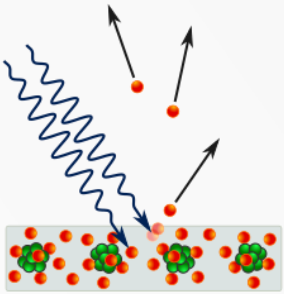


Figure 4.6: The emission of electrons from a metal plate caused by light quanta – photons.

The photoelectric effect was discovered to have a threshold wavelength that is determined by the relationship hv = hc/ E, where E is the energy necessary for the electron to exit the material, as first proposed by Einstein.

The excitation energy, E, in the case of a semiconductor is either the energy required to ionize a material impurity or the distance between the valence and conduction bands. The vacuum photodiode and its more practical adaptation, the vacuum photomultiplier, make up the first of the electronic detector family's two main branches. These are followed by photoconductor, photodiode, and semiconductor devices.

A photon's energy, E=hf, is absorbed by an electron to the point where it has enough energy to escape the cathode's metal surface, producing the photoelectric effect.

The amount of photon energy that enters the work function,Φ and contributes to its kinetic energy depends on the initial energy of the electron in the metal. Thus, the famous equation by Einstein is derived:

$$eV = \frac{1}{2} m_e v^2 = h f - \phi \, ,$$

where the electron's energy, which can also be expressed as an eV, is equal to the electron's charge times the electron's voltage. Figure 4.7 depicts how illumination produces photoelectrons.

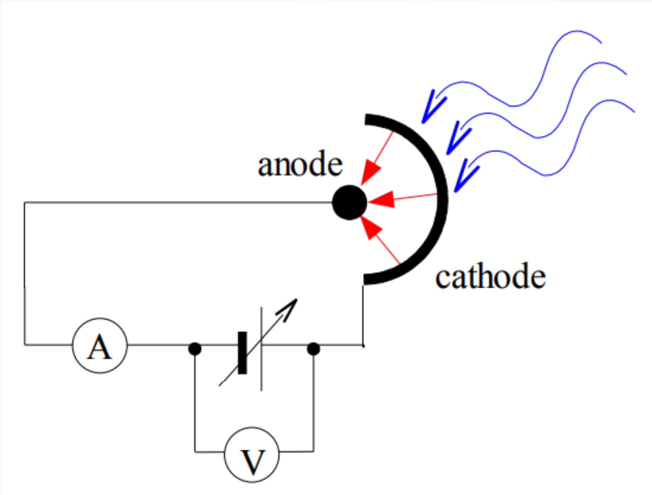


Figure 4.7: Circuit diagram of the device. Retrieved from (Lim & Mceuen, 2005)

Voltage can be used to calculate the maximum velocity of the escaping electrons. It is possible to stop the flow of photoelectrons by applying a potential difference across the cathode and anode, which is the opposite of the electron path.

Electrons are released when photons with wavelengths below a certain value are absorbed by a metal (the photoelectric or photoemissive effect). The energy of the electrons must be higher than the surface work function,Φ and they are released with kinetic energies.

If hv < eΦ (or λ_0 > hc/eΦ), then no electrons will be released. Figure 4.8 provides an illustration of this. Only a fraction of the electrons with this energy may escape if inelastic collisions are present. The quantum yield or quantum efficiency is the proportion of photons absorbed to electrons released in a system.

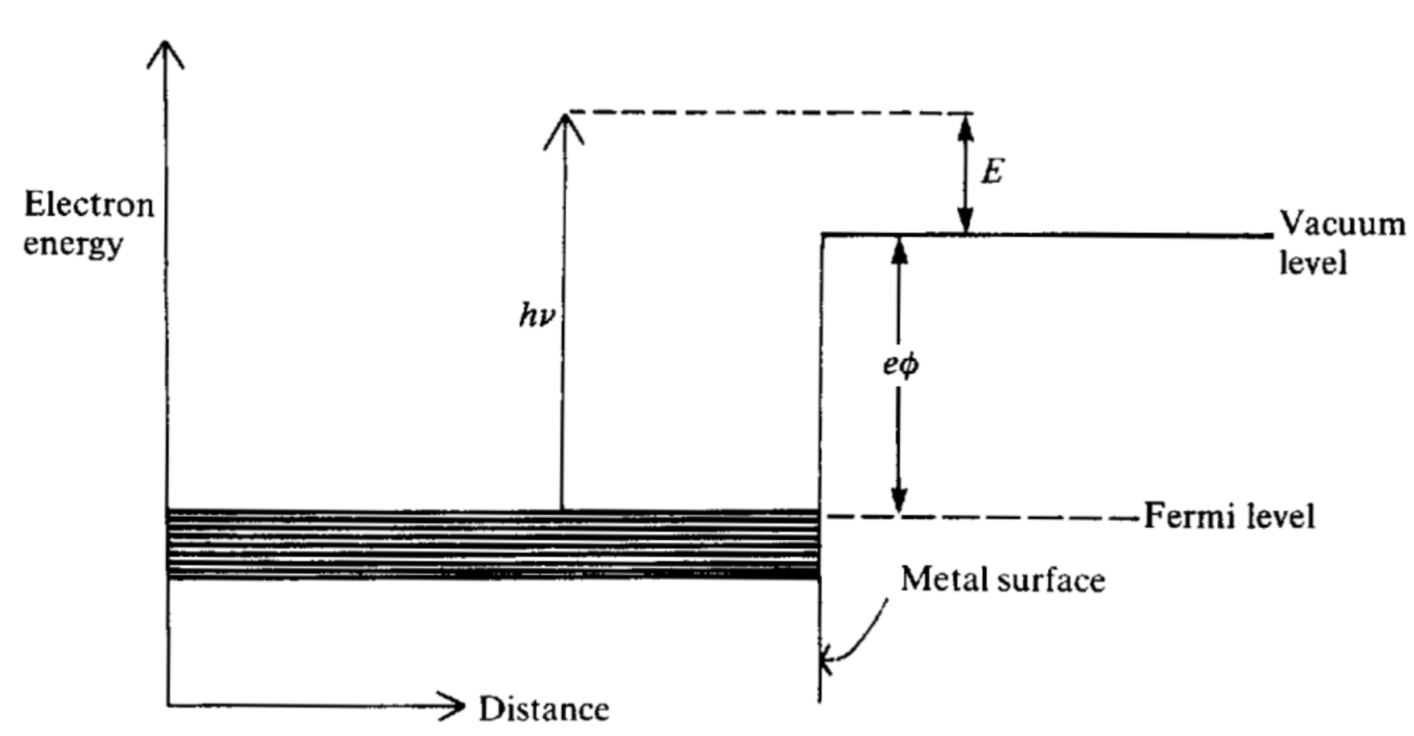


Figure 4.8: An illustration of the photoelectric effect showing the electron energy levels at the metal/vacuum interface. An electron needs to gain at least energy eΦ, in order to break free from the metal. Here, Φ is the work function. Retrieved from (Lecture 5 - Photodetectors and Noise Photon Devices - Photoemissive Detectors, n.d.)

Vacuum Photodiode

According to the photoelectric principle, vacuum photodiodes work by having sufficiently energy photons impact a metal plate known as the cathode and eject electrons that are subsequently gathered at the anode, as depicted in Figure 4.9. When the resultant current is measured, the incident photon flux can be estimated.

Due to the near-instantaneous nature of the photoelectric effect, vacuum photodiodes offer exceptional time response, enabling sub-nanosecond time resolution. Numerous detectors can be used in an experiment thanks to their ease of use and small size.

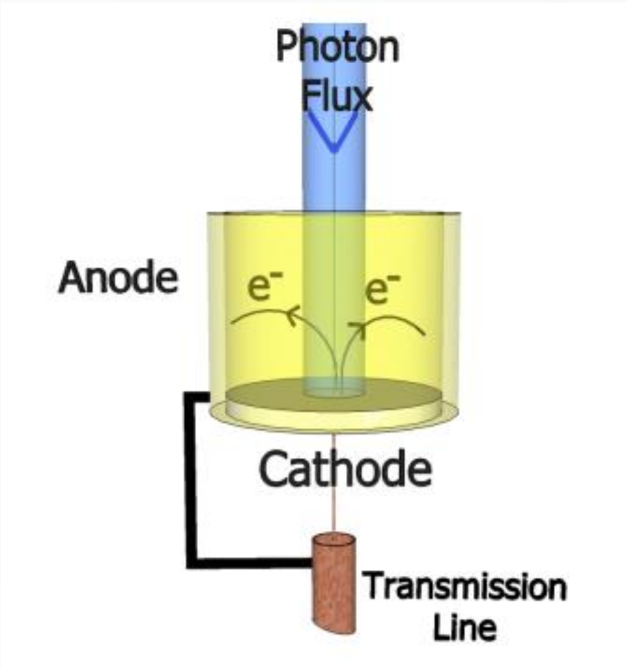


Figure 4.9: A vacuum photodiode consists of a cathode, in this example a metallic disc, that photoemits electrons when exposed to EUV photons, which are represented in this image by the blue incident column. The anode, a metallic cylinder positioned coaxially with the cathode, is where the released electrons are then collected. An estimate of the photon flux is obtained by measuring the photocurrent from the cathode to the anode. Retrieved from (Perkins, 2011)

Optical Detectors

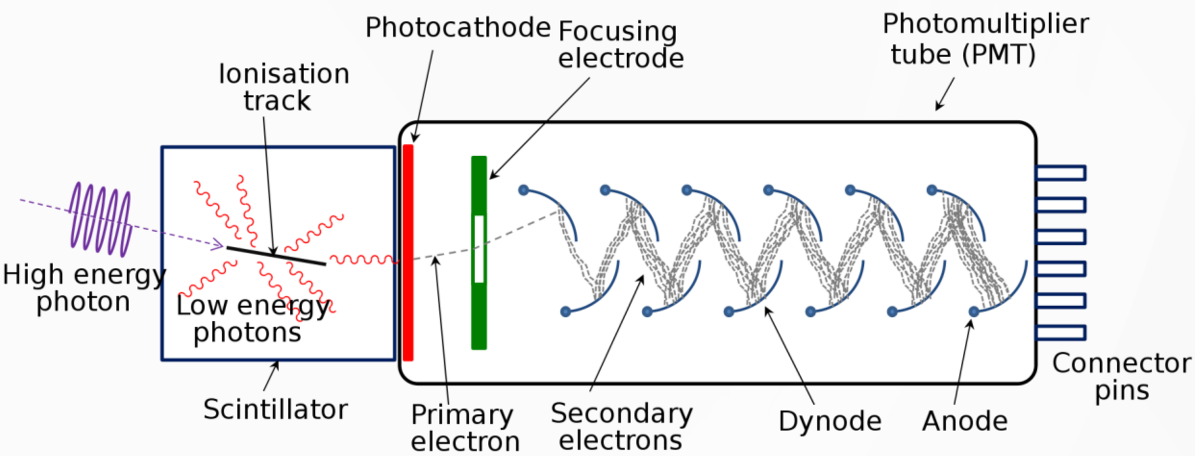
Thermal Detectors and Photon Detectors

QUICK INFO OF VACUUM PHOTODETECTOR

1. A photoemissive material's expelled electrons can be collected to provide a signal. Two electrodes are positioned in an evacuated tube to create a vacuum photodiode.
2. The photoemissive material (cathode) is at a lower potential as a result of a high voltage applied between the electrodes, while the collection electrode is at a higher potential (anode).
3. A photocathode is a cathode that emits electrons in response to light.
4. The electric field between the electrodes will accelerate photocathode electrons, resulting in a current in the external circuit.
5. This current causes a voltage across the series resistor RL, which is used to calculate the measured signal. The incident light power P_{in} determines the current I produced.

Photomultiplier

1. Vacuum photodiodes have the benefits of being straightforward and dependable for measuring power precisely, but one drawback is that they are not particularly sensitive to low light levels.
2. By placing an amplification section between the photocathode and anode, the sensitivity can be increased in one way.
3. This amplification device is called a photomultiplier.



Schematic of a photomultiplier tube coupled to a scintillator.
This arrangement is for detection of gamma rays.

Table 4.1 shows the advantages and disadvantages of thermal detectors and photon detectors.

Table 4.1: The advantages and disadvantages of thermal detectors and photon detectors

Performance	Thermal Detectors	Photon Detectors
Advantages	Detect light over a very wide wavelength range	Faster More sensitive
Disadvantages	Slow Not very sensitive	Restricted wavelength range

Meanwhile, the performance comparisons of thermal detectors and photon detectors in terms of sensitivity, response time, working temperature and their costs is shown in Table 4.2.

Table 4.2: Comparison of performance for thermal detectors and photon detectors

Performance	Thermal Detector	Photon Detectors
Sensitivity	Low	High
Response Time	Slow (Millisecond level)	Fast (Micro-seconds Level)
Working Temperature	Room Temperature	Cryogenic or Room Temperature
Cost	Low	High

NOISE IN PHOTODIODE RECEIVERS

Figure 4.10 depicts a receiver and the several kinds of noise sources that can occur. The so-called shot noise limit is a fundamental noise source imposed during the initial detection stage by the Poissonian statistics resulting from the quantized (photon) character of light. Previous research has shown that photodiodes can still produce current even when there is no light present.

The shot noise is a result of statistical changes in this dark current as well. As a result of the gain process in an APD, more noise is introduced. The detector signal is amplified externally, which introduces noise from the active amplifier components as well as thermal noise from the load resistor.

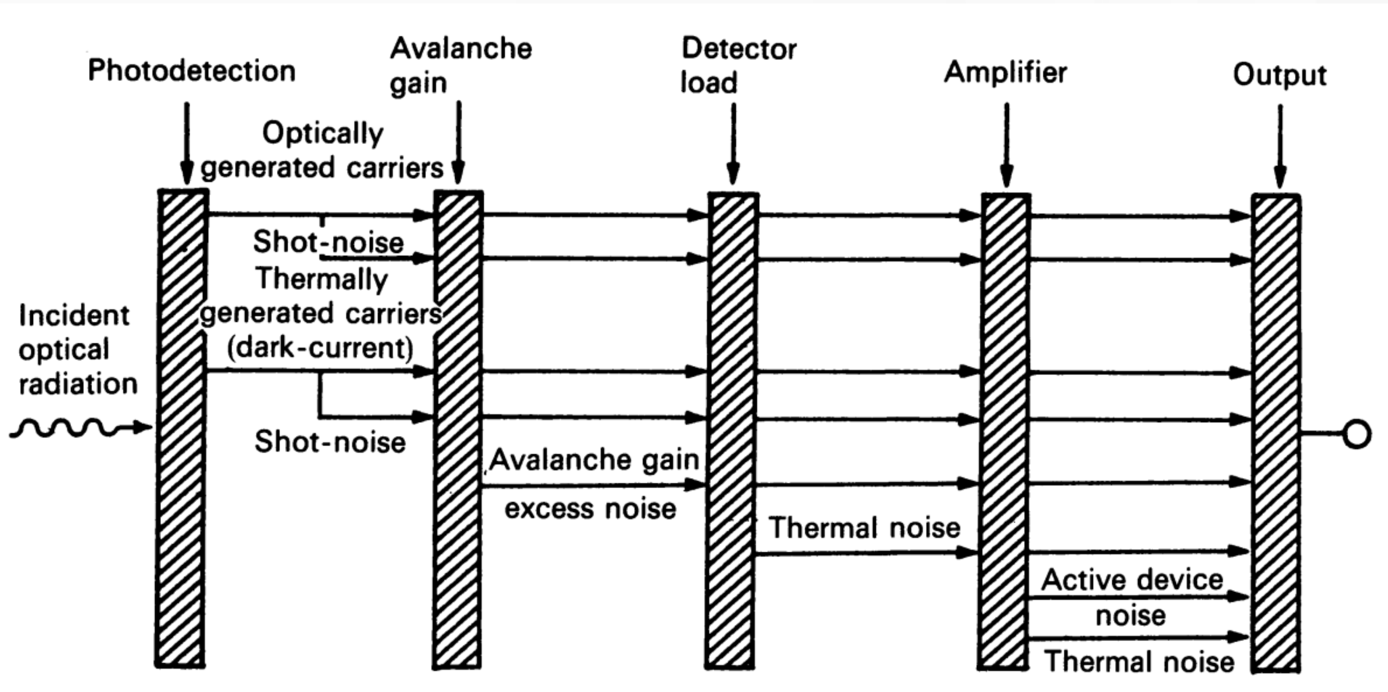


Figure 4.10: A list of the noise sources in an optical receiver. Retrieved from (Jones, 1995).

Photodiode Detector

Chapter 5

Photodiode Detector

Introduction

A photodiode is a semiconductor device with a P-N junction that converts photons (or light) into electrical current. The P layer has an abundance of holes (positive), and the N layer has an abundance of electrons (negative). Photodiodes can be manufactured from a variety of materials including, but not limited to, Silicon, Germanium, and Indium Gallium Arsenide. Each material uses different properties for cost benefits, increased sensitivity, wavelength range, low noise levels, or even response speed.

A photon can strike an atom within the device and release an electron if the photon has enough energy. This creates an electron-hole pair (e- and h+) where a hole is simply an "empty space" for an electron. If photons are absorbed in either the P or N layers, the electron hole pairs will be recombined in the materials as heat if they are far enough away (at least one diffusion length) from the depletion region. Photons absorbed in the depletion region (or close to it) will create electron hole pairs that will move to opposite ends due to the electric field. Electrons will move toward the positive potential on the Cathode, and the holes will move toward the negative potential on the Anode. These moving charge carriers form the current (photocurrent) in the photodiode.

Applications

Photodiodes as shown in **Figure 5.2** are used in consumer electronics devices such as compact disc players, smoke detectors, and the receivers for infrared remote-control devices used to control equipment from televisions to air conditioners. For many applications either photodiodes or photoconductors may be used. Either type of photosensor may be used for light measurement, as in camera light meters, or to respond to light levels, as in switching on street lighting after dark.

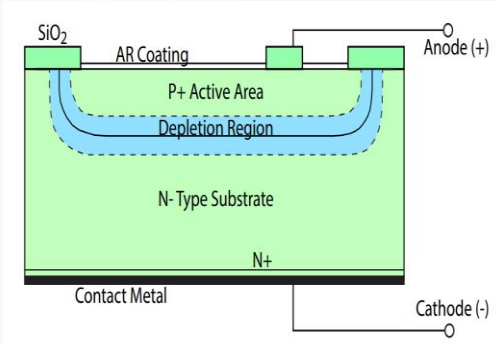


Figure 5.1 : P-N Photodiode Cross-section

Figure 5.1 shows cross section of a typical photodiode. A Depletion Region is formed from s diffusion of electrons from the N layer to the P layer and the diffusion of holes from the P layer to the N layer. This creates a region between the two layers where no free carriers exist. This develops a built-in voltage to create an electric field across the depletion region. This allows for current to flow only in one direction (Anode to Cathode). The photodiode can be forward biased, but current generated will flow in the opposite direction. Therefore, most photodiodes are reversed biased or not biased at all. Some photodiodes cannot be forward biased without damage.

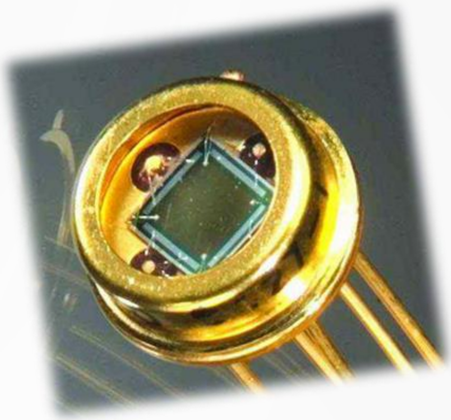


Figure 5.2 : Photodiode

Photodiode Detector
Photodiode Characteristics

I-V CHARACTERISTICS

The current-voltage characteristic as shown in **Figure 5.3** of a photodiode with no incident light is like a rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears. It is related to dark current as:

$$I_D = I_{SAT}\left(e^{\frac{qV_A}{k_B T}} - 1\right)$$ → **Equation1**

where I_D is the photodiode dark current, I_{SAT} is the reverse saturation current, q is the electron charge, V_A is the applied bias voltage, k_B=1.38 x 10^{-23} J / K, is the Boltzmann Constant and T is the absolute temperature (273 K= 0 °C).

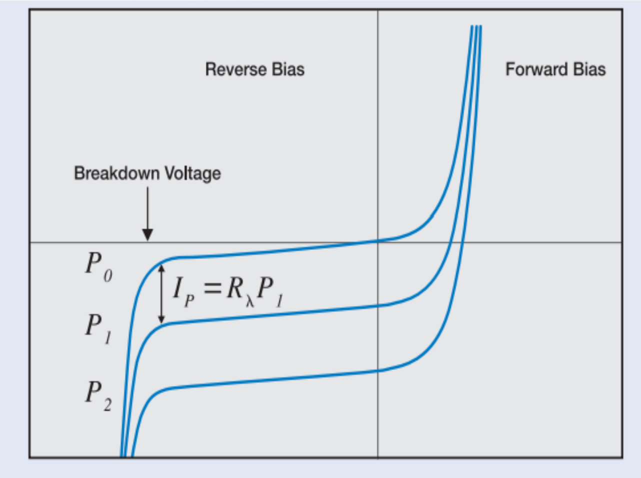


Figure 5.3: Characteristic I-V Curves of an OSI Optoelectronics photodiode for Photoconductive and Photovoltaic modes of operation. P0-P2 represent different light levels.

This relationship is shown in **Figure 5.3**. From **Equation 1**, three various states can be defined:

a) V = 0, In this state, the dark current I_P=0.
b) V = +V, In this state the current increases exponentially. This state is also known as forward bias mode.
c) V = -V, When a very large reverse bias is applied to the photodiode, the dark current becomes the reverse saturation current, I_{sat}.

Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent (I_P). Thus:

$$I_{TOTAL} = I_{SAT}\left(e^{\frac{qV_A}{k_B T}} - 1\right) - I_P$$ → **Equation 2**

As the applied reverse bias increases, there is a sharp increase in the photodiode current. The applied reverse bias at this point is referred to as breakdown voltage. This is the maximum applied reverse bias, below which, the photodiode should be operated (also known as maximum reverse voltage). Breakdown voltage, varies from one photodiode to another and is usually measured, for small active areas, at a dark current of 10 µA.

A photodiode signal can be measured as a voltage or a current. Current measurement demonstrates far better linearity, offset, and bandwidth performance. The generated photocurrent is proportional to the incident light power, and it must be converted to voltage using a transimpedance configuration. The photodiode can be operated with or without an applied reverse bias depending on the application specific requirements. They are referred to as "Photoconductive" (biased) and "Photovoltaic" (unbiased) modes.

Photodiode Detector

ELECTRICAL CHARACTERISTICS

A photodiode can be represented by a current source in parallel with an ideal diode as shown in **Figure 5.4**. The current source represents the current generated by the incident radiation, and the diode represents the p-n junction. In addition, a junction capacitance (C_j) and a shunt resistance (R_{SH}) are in parallel with the other components. Series resistance (R_S) is connected in series with all components in this model.

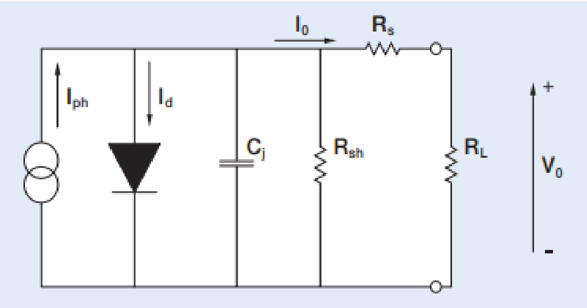


Figure 5.4: Equivalent circuit for photodiode

Shunt Resistance, R_{SH}

Shunt resistance is the slope of the current-voltage curve of the photodiode at the origin, i.e. V=0. Although an ideal photodiode should have an infinite shunt resistance, actual values range from 10's to 1000's of Mega ohms. Experimentally it is obtained by applying ±10 mV, measuring the current and calculating the resistance. Shunt resistance is used to determine the noise current in the photodiode with no bias (photovoltaic mode). For best photodiode performance the highest shunt resistance is desired.

Series Resistance, R_S

Series resistance of a photodiode arises from the resistance of the contacts and the resistance of the undepleted silicon as shown in **Figure 5.1**. It is given by:

$$R_S = \frac{(W_S - W_d)\rho}{A} + R_C$$

→ **Equation 3**

Where W_S is the thickness of the substrate, W_d is the width of the depleted region, A is the diffused area of the junction, is the resistivity of the substrate and R_C is the contact resistance. Series resistance is used to determine the linearity of the photodiode in photovoltaic mode (no bias, V=0). Although an ideal photodiode should have no series resistance, typical values ranging from 10 to 1000 Ω's are measured.

Junction Capacitance, C_J

The boundaries of the depletion region act as the plates of a parallel plate capacitor **Figure 5.1**. The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region. In addition, higher resistivity substrates have lower junction capacitance. Furthermore, the capacitance is dependent on the reverse bias as follows:

$$C_J = \frac{\epsilon_{Si}\epsilon_0 A}{\sqrt{2\mu\rho(V_A + V_{bi})}}$$

→ **Equation 4**

where 0= 8.854x10^{-14} F/cm, is the permittivity of free space, Si=11.9 is the silicon dielectric constant, μ = 1400 cm^2 /Vs is the mobility of the electrons at 300 K, is the resistivity of the silicon, V_{bi} is the built-in voltage of silicon and VA is the applied bias.

Photodiode Detector

ELECTRICAL CHARACTERISTICS

Biasing

A photodiode signal can be measured as a voltage or a current. Current measurement demonstrates far better linearity, offset, and bandwidth performance. The generated photocurrent is proportional to the incident light power, and it must be converted to voltage using a transimpedance configuration. The photodiode can be operated with or without an applied reverse bias depending on the application specific requirements. They are referred to as "***Photoconductive***" (biased) and "***Photovoltaic***" (unbiased) modes.

Photovoltaic mode

In the photovoltaic mode, the photodiode is unbiased. In other words, no external voltage is applied to the photodiode under photovoltaic mode. In photovoltaic mode, dark current is very low. Photodiodes operated in photovoltaic mode have low response speed. The photodiodes operated in photovoltaic mode are generally used for low speed applications or for detecting low light levels.

Photoconductive mode

In photoconductive mode, an external reverse bias voltage is applied to the photodiode. Applying a reverse bias voltage increases the width of depletion region and reduces the junction capacitance which results in increased response speed.
The reverse bias also increases the dark current.

Photodiodes operated in photoconductive mode has high noise current. This is due to the reverse saturation current flowing through the photodiode.

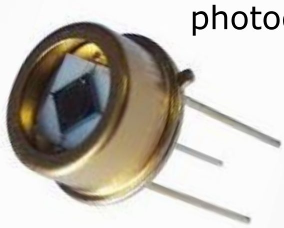
Dark current

Dark current is the leakage current that flows in the photodiode in the absence of light. The dark current in the photodiode increases when temperature increases. The material used to construct the photodiode also affects the dark current.

Types of Photodiodes

P-N JUNCTION

This is the most basic photodiode. The physics of how the P-N junction photodiode operates was reviewed earlier. The PIN and APD photodiode are variations from the P-N junction. The depletion region contains few free charge carriers, and the width of the depletion region can be manipulated by adding voltage bias. Current passing through the photodiode can only flow in one direction based on the P and N doped materials. If reverse-biased, current will not flow through a photodiode without incident light creating photocurrent.



pin photodetector

Photodiode Detector

The device structure consists of ***p and n*** semiconductor regions separated by a very lightly n-doped ***intrinsic (i)*** region. This layer is shown in **Figure 5.5**. This intrinsic layer is highly resistive and increases the electric field strength in the photodiode. There are many benefits to the added intrinsic layer because the depletion region is greatly increased. The capacitance of the junction is decreased, and so the speed of the photodiode increased. The increased layer also allows for a larger volume of photon to electron-hole conversion and higher Quantum Efficiency. In normal operation a reverse-bias voltage is applied across the device so that no free electrons or holes exist in the intrinsic region. Incident photon having energy greater than or equal to the bandgap energy of the semiconductor material, give up its energy and excite an electron from the valence band to the conduction band.

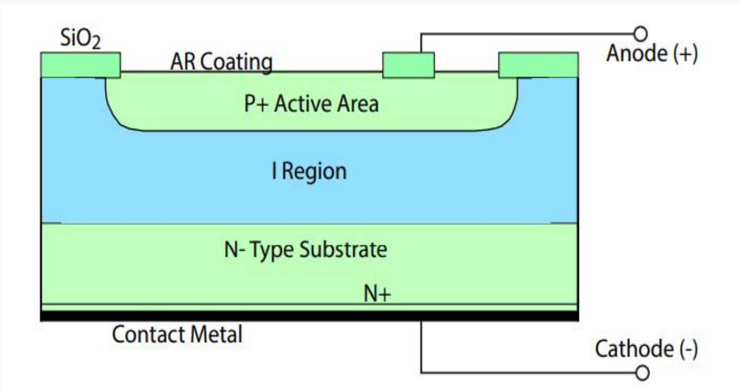


Figure 5.5: PIN Photodiode Cross-section

photocarriers

Incident photon, generates free (mobile) electron-hole pairs in the intrinsic region. These charge carriers are known as photocarriers, since they are generated by a photon.

photocurrent

The electric field across the device causes the photocarriers to be swept out of the intrinsic region, thereby giving rise to a current flow in an external circuit. This current flow is known as the photocurrent.

As shown in **Figure 5.6**, the high electric field present in the depletion region causes photogenerated carriers to separate and be collected across the reverse – biased junction. This gives rise to a current flow in an external circuit, known as photocurrent.

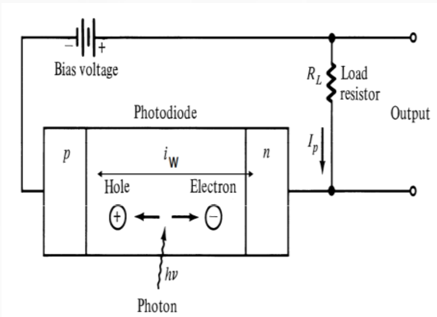


Figure 5.6: PIN Photodiode working principle

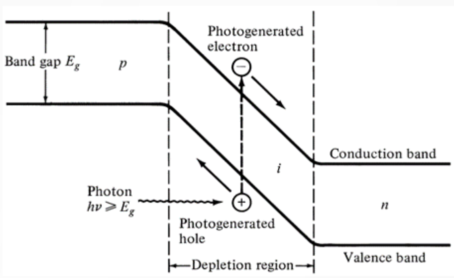


Figure 7: Energy-Band diagram for a *pin* photodiode

Photodiode Detector

AVALANCHE PHOTODIODE

Introduction

- The diode as shown in **Figure 5.8** which uses the avalanche method to provide extra performance as compared to other diodes is known as avalanche photodiode.
- These diodes are used to change the signals from optical to electrical. These diodes can be operated in high reverse bias. The avalanche photodiode symbol is like the Zener

Figure 5.8: Avalanche Photodiode

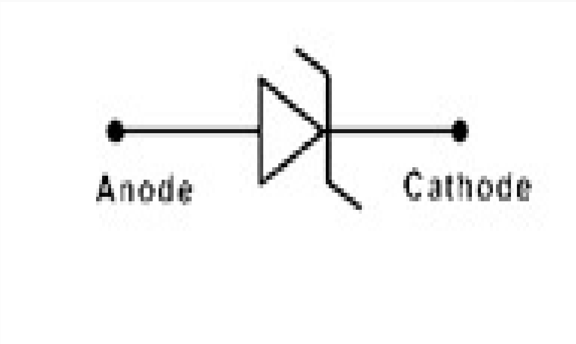


Figure 5.9: Avalanche Photodiode symbol

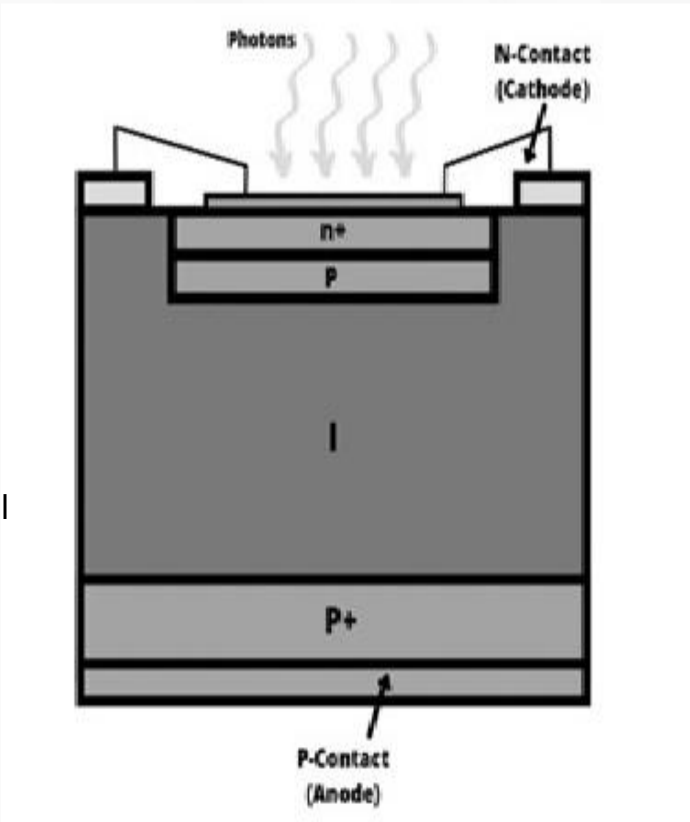


Figure 5.10: Avalanche Photodiode construction

Construction

- The construction of both the PIN photodiode and Avalanche photodiode is similar as shown in **Figure 5.10**. This diode includes two heavily doped & two lightly doped regions.
- Here, heavily doped regions are P+ & N+ whereas lightly doped regions are I & P.

Photodiode Detector

AVALANCHE PHOTODIODE

OPERATION

- The internal gain of the APD is obtained by having a high electric field that energizes photo-generated electrons and holes as shown in **Figure 5.11**.
- These electrons and holes ionize bound electrons in the valence band upon colliding with them.
- This mechanism is known as impact ionization.
- The newly generated electrons and holes are also accelerated by the high electric field.
- They gain enough energy to cause further impact ionization.
- This phenomenon is the avalanche effect.

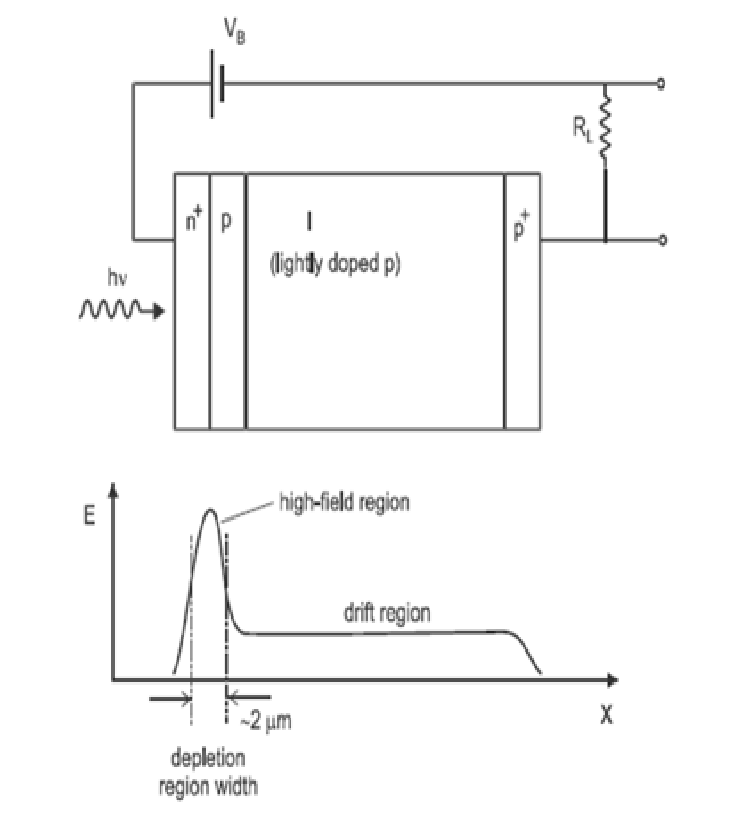


Figure 5.11: In an avalanche photodiode (APD), electrons photoexcited in a nearly intrinsic region are swept out by a small electric field there, and injected into a high-field region between highly doped n and p layers. Avalanche multiplication occurs primarily in the high-field region.

APPLICATION

- Laser Scanner
- Barcode reader
- Speed gun
- Laser microscopy

SCHOTTKY DIODE

Structure

Utilizes a metal – semiconductor junction to separate and collect the photogenerated charge carriers. The most common type is the metal-n-n+ configuration. Like PIN photodiode but having metal layer instead of p-layer.

Operations

Photons pass through a partially transparent metallic layer which often will be gold and are absorbed in the n-type semiconductor as shown in **Figure 5.12**.

Photodiode Detector

SCHOTTKY DIODE

Charge carrier is generated within the depletion region are efficiently swept out by the built-in electrical field. This gives a rise to the photocurrent. The diffusion tail in the time response can be minimized by adjusting the donor concentration in the n-type region for the depletion region extend all the way through the n- layer.

Advantages

One advantage is a practical issue in the manufacturing the device. Only one metal-semiconductor connection must be made (metal –n-) to connect this device with wire because the ohmic contact is already available at the junction. Has improved time response. No remnant tail diffusion rising due to lack of p-type layer and important for short wavelengths. Metal junction can be made with a wide variety of semiconductor, including those with wide bandgap such as SiC and GaN.

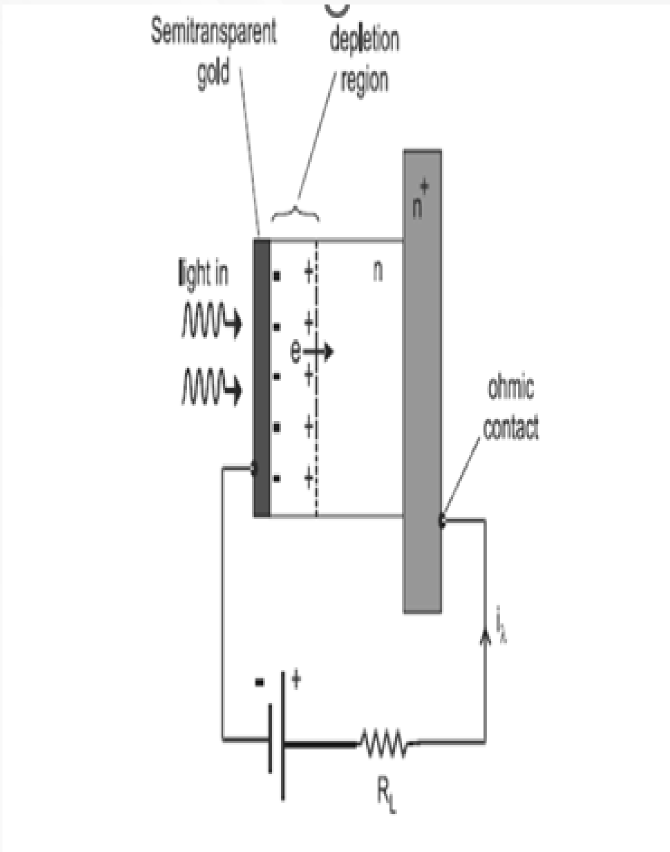


Figure 5.12: In Schottky photodiode, light is absorbed in the depletion region of an n-type semiconductor after passing through a semi-transparent metallic film.

Disadvantages

They tend to be less efficient than PIN photodiode at longer wavelength due to reflection and absorption of light in the metal layer. Antireflection coating which is used to reduce reflection complicates the manufacturing process of the device.

Application

Used to detect blue or UV wavelength or in high-speed application, where loss in efficiency can be tolerated.

Photodiode Detector

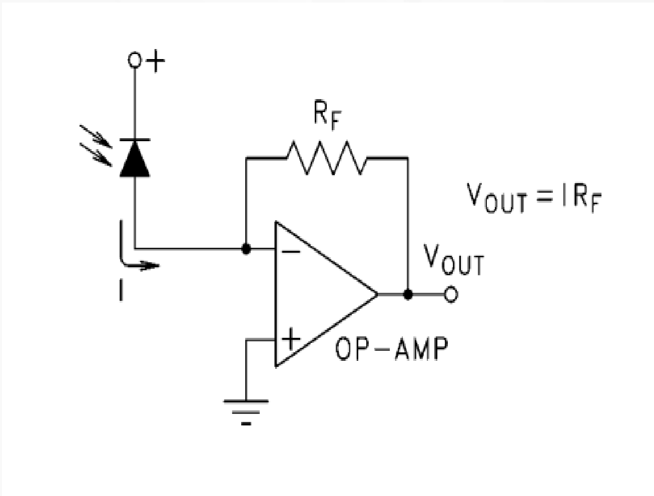
SCHOTTKY DIODE

Detector Circuit

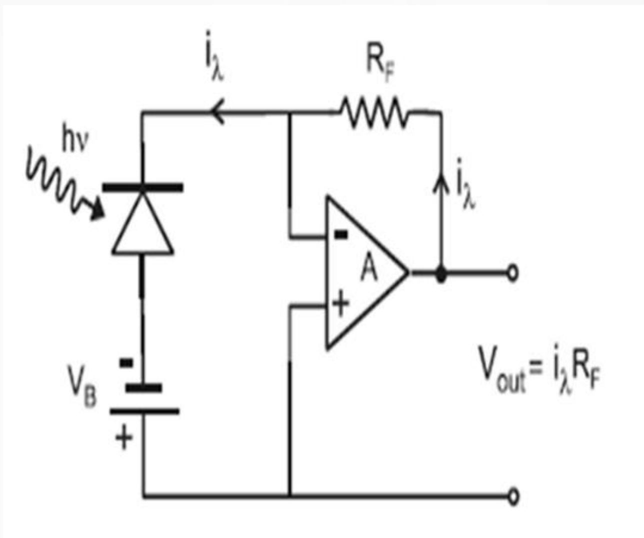
Add Field Effect Transistor (FET) as additional amplification stage. The voltage generated across the load resistor is applied between gate (G) and source (S) of the FET which results an amplified output voltage between $2\pi R\_L\ C\_Diode)$ as shown in **Figure 5.13.** This circuit suffers from the same sensitivity/time response trade-off. It has higher bandwidth and preferred in many situations because of very high speed and large dynamic range. This gives best possible linearity and dynamic range for the photodiode, and the output is only limited by the maximum output voltage of the op-amp. The drawback is in obtaining the best possible SNR for weak signal.

Typical Application Circuits

Uses an operational amplifier (op-amp) to convert the photocurrent directly into an output voltage as shown in **Figure 5.14**. The op-amp has the property that the two input terminals are held at nearly the same potential (virtual ground), while at the same time very little current is allowed to flow into or out of either terminal. For the purpose of biasing the photodiode, the op-amp input acts like a short circuit (R_L= 0), which keeps the diode below saturation for any level of light input. Any photocurrent must flow not through the input terminals of the op-amp, but through feedback resistor R_F. This circuit no longer limits the time response.



(a)



(b)

Figure 5.14: Basic Transimpedance Op-Amp Circuit

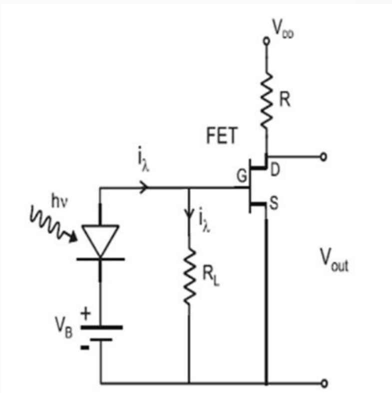


Figure 5.13: High-impedance FET amplifier circuit

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