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Elective Topic III (Thin Films)
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Lecture (1) Semiconductor Materials

1. Introduction:

Materials can be classified according to their ability to conduct current (electric conductivity) into:

1- **Conductors** have high electrical conductivity. These materials allow easy flow of electric current.
2- **Insulators** have no electrical conductivity i.e. current cannot pass through them.
3- **Semiconductors** is between the two they possess moderate conductivity. Their resistivity might change according to the temperature for example. At a low temperature, almost no electricity passes through them. But when the temperature rises, electricity passes through them easily.

According to the atomic model: an atom is composed of a nucleus (protons and neutrons) and electrons in defined energy levels revolving around the atom. Electrons occupy certain energy levels according to their energy (Figure 1). The levels closer to the nucleus are of small energy and due to its nearness to the nucleus, they are tightly bound to the nucleus. Further from the nucleus, the energy of the electrons is higher and the energy that binds them to the nucleus is less. For each energy level there is a certain number of electrons allowed to occupy that level. Electrons in the inner energy levels can gain energy from outside sources so their energy increase and after losing the energy that bind them to their level, these electrons jump to higher energy levels according to their new energy. Being unstable at this situation, the excited electrons can return to their initial level, by emitting (loosing) the gained energy.

Since the electrons in the levels nearest to the nucleus are tightly bound to the nucleus, high energy is needed to get them out of these levels. While the electrons in the outermost levels can easily (small energy is needed) displaced from their levels. This is because these electrons are loosely bound to the nucleus. So the electrons in the outermost levels can be considered as free electrons.

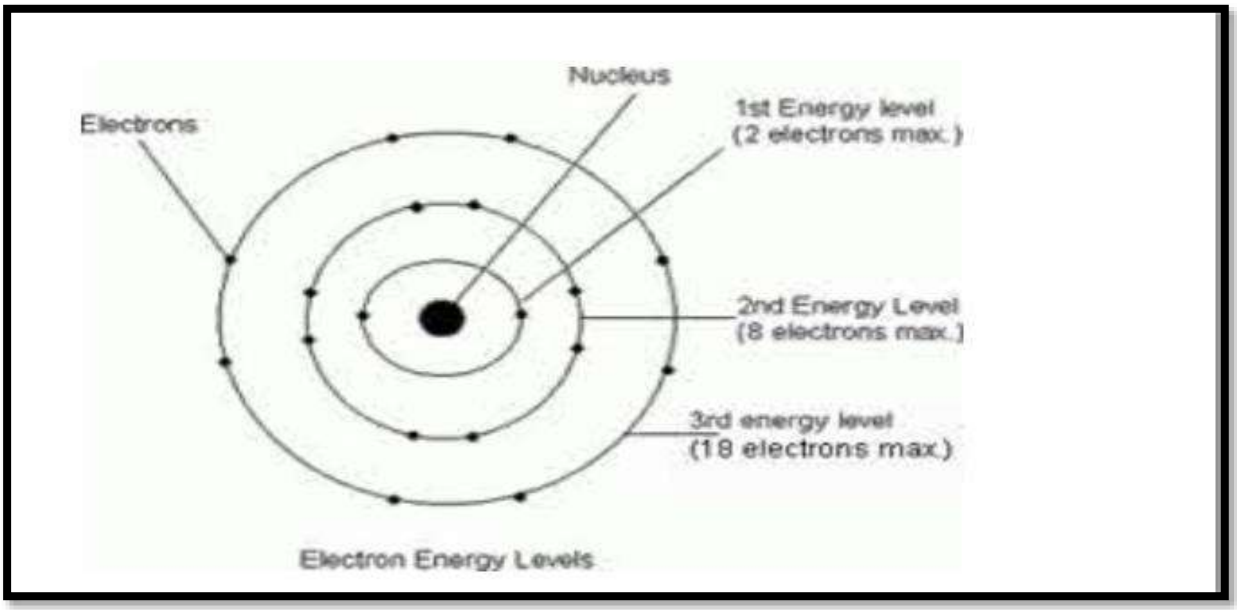

Figure (1) electron energy levels

For determines whether a solid is conductor, insulator or semiconductor is the number of electrons in the outermost orbit (valence orbit) and its nuclear attraction.

When the valence orbit is full and the nuclear attraction is strong, the material is an **insulator**. While, **conductors** have unsaturated valence orbit with weak attraction force, so a small energy can free the electron from the orbit. This free electrons is responsible for the electric current for example (Fe, Ag, Au). The **semiconductor** is in between the two cases as it be explained later. Therefore, the number of electrons in the valence orbit (outermost orbit) determines the electrical conductivity of a material for example (Si, Ge).

2. Energy Band Structure

A solid may be thought of as consisting of a large number of atoms initially separated from one another, which are subsequently brought together and bonded to form the ordered atomic arrangement found in the crystalline material. At relatively large separation distances, each atom is independent of all the others and will have the atomic energy levels and electron configuration as if isolated. However as the atoms come within close proximity of one another, electrons are acted upon or perturbed, by the electrons and nuclei of adjacent atoms. This influence is such that each distinct atomic state may split into a series of closely spaced electron states in the solid, to form what is termed an electron energy band.

According to the band theory (see figure 2), energy levels are grouped into two bands the conduction band (C.B) and the valence band .The valence band (V.B) is the lower level of electrons and the conduction band is the higher level of electrons. An energy gap exists between the bands where electrons can’t exist, its width affects the conductivity of materials.

Electrons can move from the valence band to the conduction band if they acquire enough energy to move them from the lower levels (in the valence band) to higher levels (in the conduction band). The band structure of a solid determines whether it behaves as a conductor, insulator, or semiconductor. Electrons in the conduction band are considered as free electrons and are responsible for the conductivity.

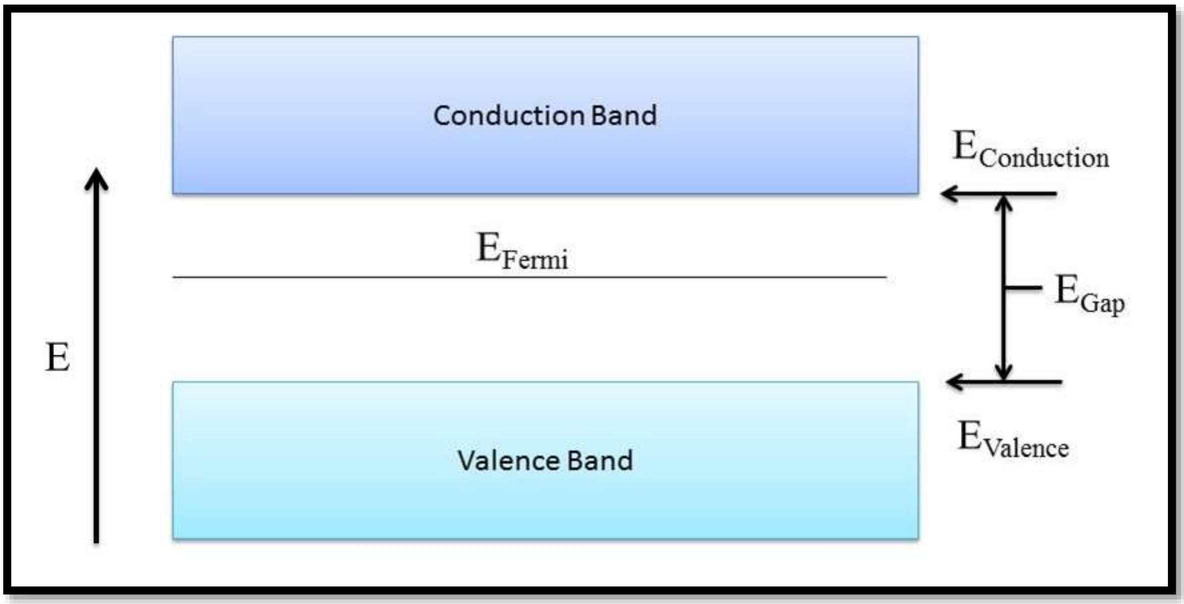

Figure (2) Band energy diagram

Fermi Level and Fermi energy

- The energy of the highest occupied level at absolute zero temperature is called Fermi-energy.
- The corresponding level is called Fermi level.
- The energy levels at absolute zero above Fermi level are completely empty, while those below are completely filled

Conductors, insulators and semiconductors can be explained according to the band theory

Insulators:

- the valence band is completely full with electrons
- the conduction band is empty.
- the band gap is large. Because of this, electrons cannot move from the valence band to the conduction band.

So, insulators are not conductive since they have no free electrons, and to get free electrons a great amount of energy has to be consumed to overcome the large band gap.

Conductors:

- The conduction band and the valence band overlap. This means that electrons can move freely between the valence band and the conduction band.
- there is no energy gap.
- the conduction band is partially filled.

When an external electric field is applied, the electrons acquire additional energy and move to higher energy levels. These mobile electrons constitute a current. The overlapping of conduction and valence band gives rise to high conductivity.

Semiconductors:

- Semiconductors are defined to have conductivity in between an insulator and a conductor.
- They get their characteristic conductivity from their small band gap (for Si $E_g = 0.7V$, for Ge $E_g = 0.3V$)
- At absolute zero the valence band is completely filled, and the conduction band is completely empty.
- As temperature increases the electrons in the valence band gain enough energy so they can jump to the conduction band, and so conductivity increases.

- At room temperatures some of the electrons are transferred from the valence band into the conduction band.

So, semiconductors behave as insulators at absolute zero, since all electrons are in the valence band. As temperature increases, the conductivity increases and they behave as conductors (see figure 3 and table 1).

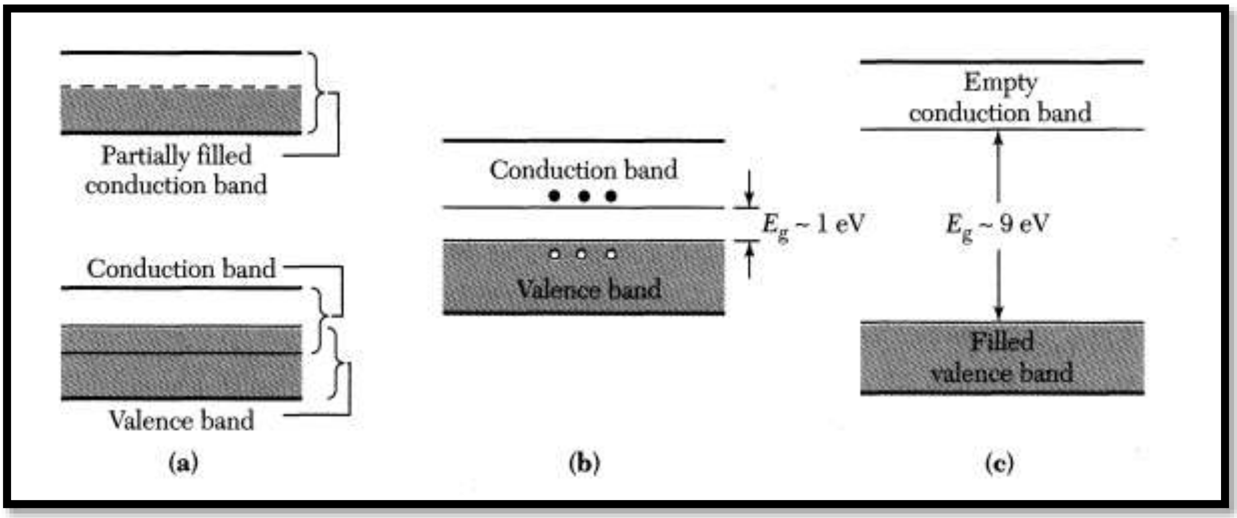

Figure (3)

Schematic energy band representations of (a) a conductor with two possibilities (either the partially filled conduction band shown at the upper portion or the overlapping bands shown at the lower portion), (b) a semiconductor, (c) Insulator

Table (1): Classification of solids materials according to their energy gap E_g

Type of solid	E_g (eV)	example
Metal	No energy gap	Au, Cu, Pb, Ag
Semiconductor	$0 < E_g < 4$	Si, Ge, GaAs, ZnSe
Insulator	$E_g \geq 4$	Quartz (SiO_2), CaF_2

When the valence electron moves from the valence band to the conduction band a vacancy is created in the valence band where an electron has left. Such vacancy is called hole. This is the generation of an electron and a hole. During the process of conduction of semiconductor, some electrons in the conduction band fall back to the valence band and recombine with a hole. This process is called recombination of an electron and a hole.

An electron has a negative charge while the hole, since it is the absence of an electron, so it behaves as if it is a positive charge.

An electron within the valence band may fill the hole, leaving another hole in its place. In this way a hole appears to move.

3. Semiconductors Types

Semiconductors are classified into:

1. Intrinsic semiconductor (pure, undoped).
2. Extrinsic semiconductor (doped).

3.1. Intrinsic semiconductor

It is pure semiconductor. The group IV elements of the periodic table form an intrinsic semiconductor. However, mainly **silicon (Si)** and **germanium (Ge)** are widely used. This is so because in their case only small energy is needed in order to break the covalent bond. It is a crystalline semiconductor in which some electrons are excited across the energy gap to the conduction band solely by thermal energy, creating an equal number of holes in the valence band. In this semiconductor, at any temperature the number of free electrons is equal to the number of holes. Crystal structure of Si the outermost orbit of a Si atom is capable to hold up to eight electrons. The atom which has eight electrons in the outermost orbit is said to be completely filled and most stable. The outermost orbit of silicon has only four electrons. It needs four more electrons to fill the outer orbit and so become most stable. So, for Si to become stable, it will share four electrons (by forming four covalent bonds) with four neighboring atoms. The outermost orbit of silicon is, then, completely filled and electrons are tightly bound to the nucleus (Figure 4).

In intrinsic semiconductors, at absolute zero temperature, free electrons are not present (since all electrons are engaged in covalent bonds). Therefore, intrinsic semiconductor behaves as perfect insulator.

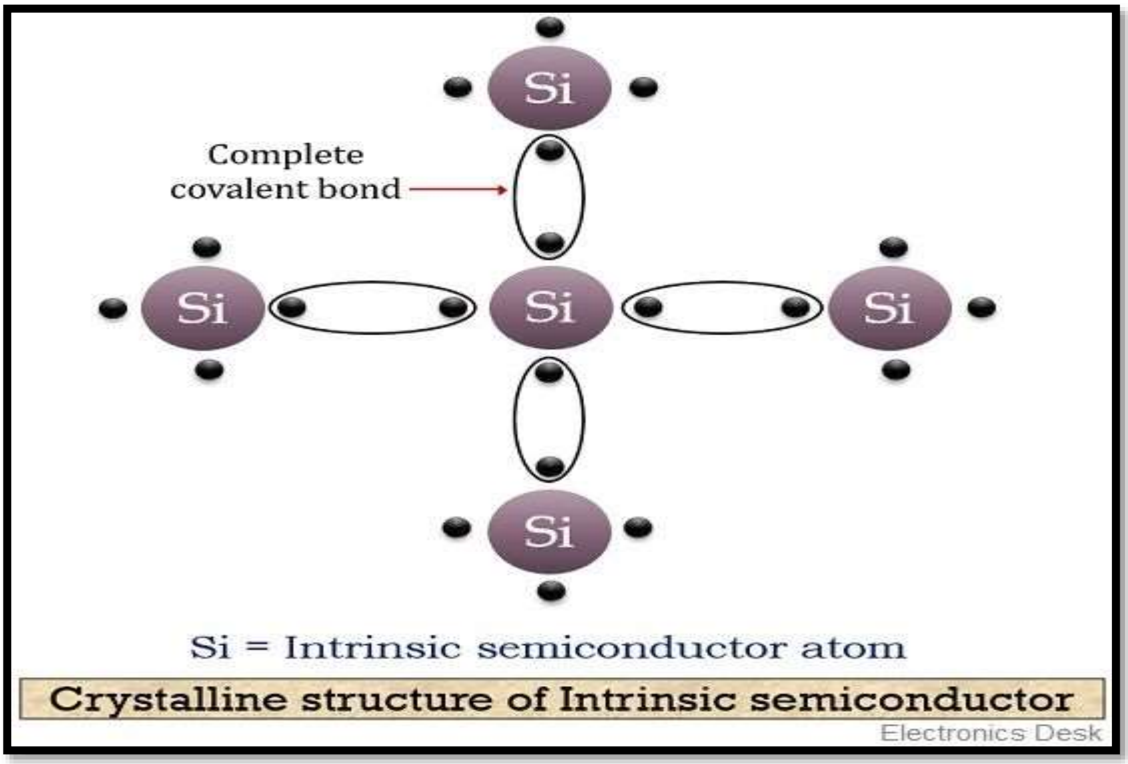

Figure (4)

As temperature increases the electrons in the covalent bond (in the valence band) can gain enough energy to break the bond and become a free electron (in the conduction band). Its place is left without an electron that is the hole. Hence the generation of an electron-hole pair.

These free electrons are free to move randomly within the lattice, till their energy is consumed and they will fall back into a hole. This is the recombination process. Therefore, in a semiconductor there are two types of charge carriers the electrons and the holes. As voltage is applied to a semiconductor, electrons will move towards the positive end of the battery (the electron current), while holes move towards the negative end of the battery (the hole current) (see Figure5). The ability of an electron to move through a metal or semiconductor, in the presence of applied electric field is called electron mobility. Mobility of holes is less than that of electrons.

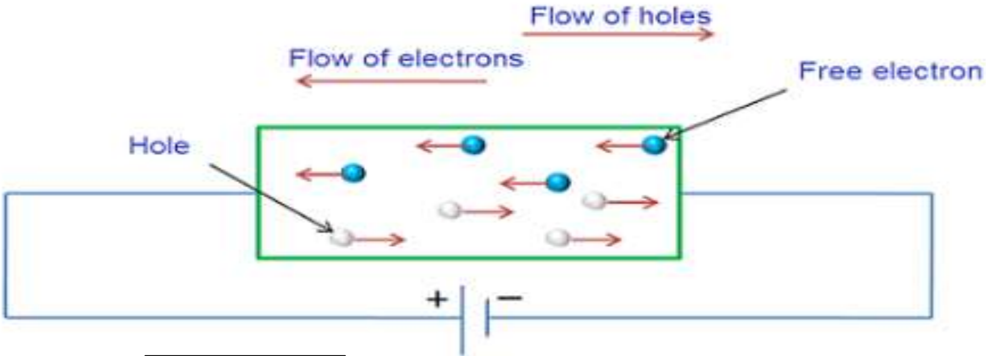

Figure (5)

Note that:

- the electron current is in opposite direction to the hole current.
- Holes do not actually move in the semiconductor.

Summary

1. Si and Ge are examples of semiconductor materials.

2. Semiconductors are characterized by their small energy band gap.

3. At absolute zero, the semiconductor behaves as an insulator.

4. as temperature increases, the electrical conductivity increases.

5. The increase of temperature produces electron- hole pairs (the number of electrons are equal to the number of holes).

6. In semiconductors, there are two type of charge carriers: electrons and holes.

7. on applying a potential difference across a semiconductor, two currents are generated the electron current and the hole current, which are in opposite directions.

3.2. Extrinsic semiconductor

The intrinsic semiconductor has small electrical conductivity at room temperature. To increase this, very small amounts of dopants (pentavalent or trivalent elements) (impurities) are added to the intrinsic semiconductor. This process is called doping)

(Pentavalent خماسية التكافؤ elements) or (group V elements): have 5 electrons in their outermost orbit).

(Trivalent ثلاثية التكافؤ elements) or (group III elements) : are those that have three electrons in their outermost orbit).

Extrinsic semiconductors are of two type:

1. n-type semiconductor: The intrinsic semiconductor is doped with a certain amount of pentavalent element like arsenic (As), antimony (Sb) and phosphorus (P). These dopants have 5 electrons in their outermost orbit, 4 of which will form

4 covalent bonds with 4 neighboring atoms of Si. The fifth electron is left free in the crystal lattice (Figure 6).

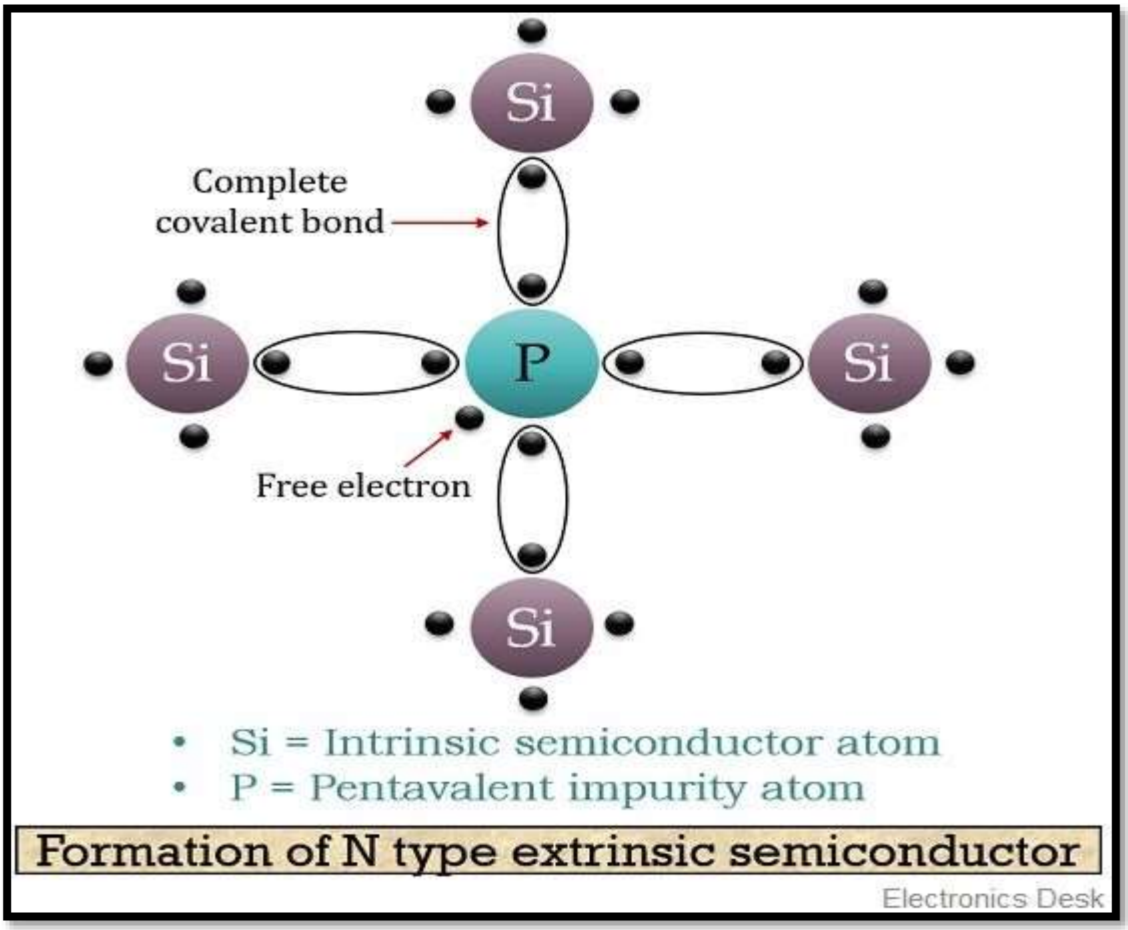

Figure (6)

Figure (7) is clear that the existence of the Fermi level is near the conduction band. We can see that the small energy difference exists between donor energy level and the conduction band. So, less energy is needed by the electrons to reach the conduction band.

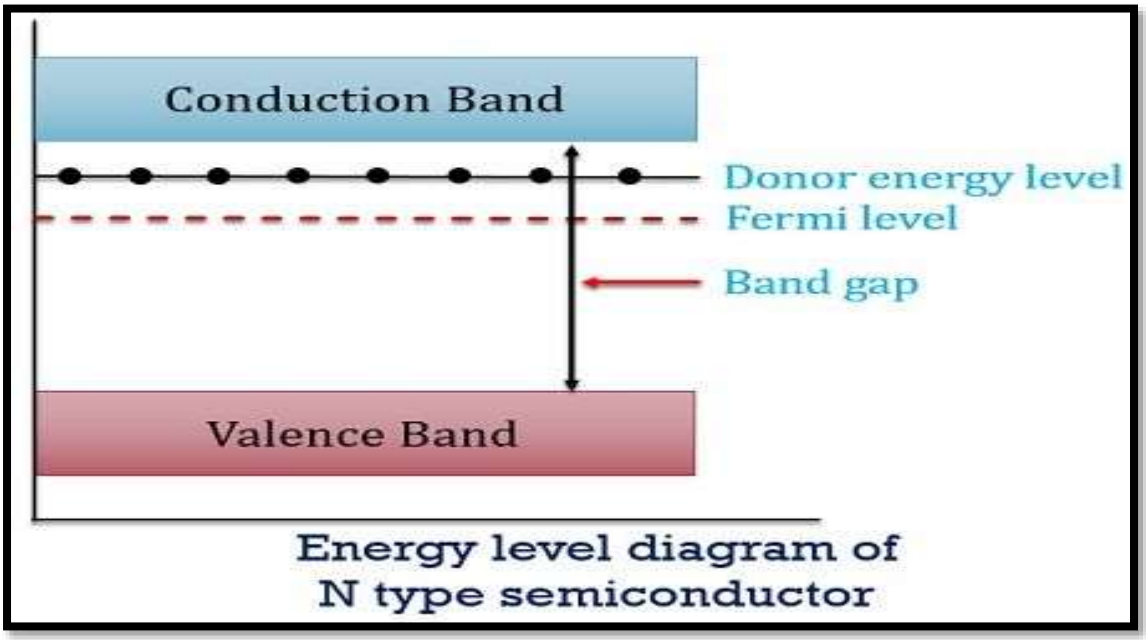

Figure (7)

For one dopant atom there will be one free electron. As the number of dopant atoms increases the number of free electrons will increase. The dopant atom is called the donor atom, since it donates a free electron to the semiconductor, which is the acceptor.

In addition, thermally generated electron-hole pairs are also present in the doped semiconductor. The number of holes (in the valence band) is less than the number of free electrons (in the conduction band).

The electrons are the negative charge carriers; they are called the majority charge carriers. Holes are the positive charge carrier, are called the minority charge carriers.

The majority charge carriers (electrons) are produced by doping, while the minority charge carriers (holes) are due to the increase of temperature.

2. P-type semiconductor: The intrinsic semiconductor is doped with a certain amount of trivalent element like indium (In), aluminum (Al), boron (B) and gallium (Ga). These dopants have 3 electrons in their outermost orbit which will form 3 covalent bonds with 3 neighboring atoms of Si. The fourth covalent bond will be short of an electron and that is a hole (Figure 7).

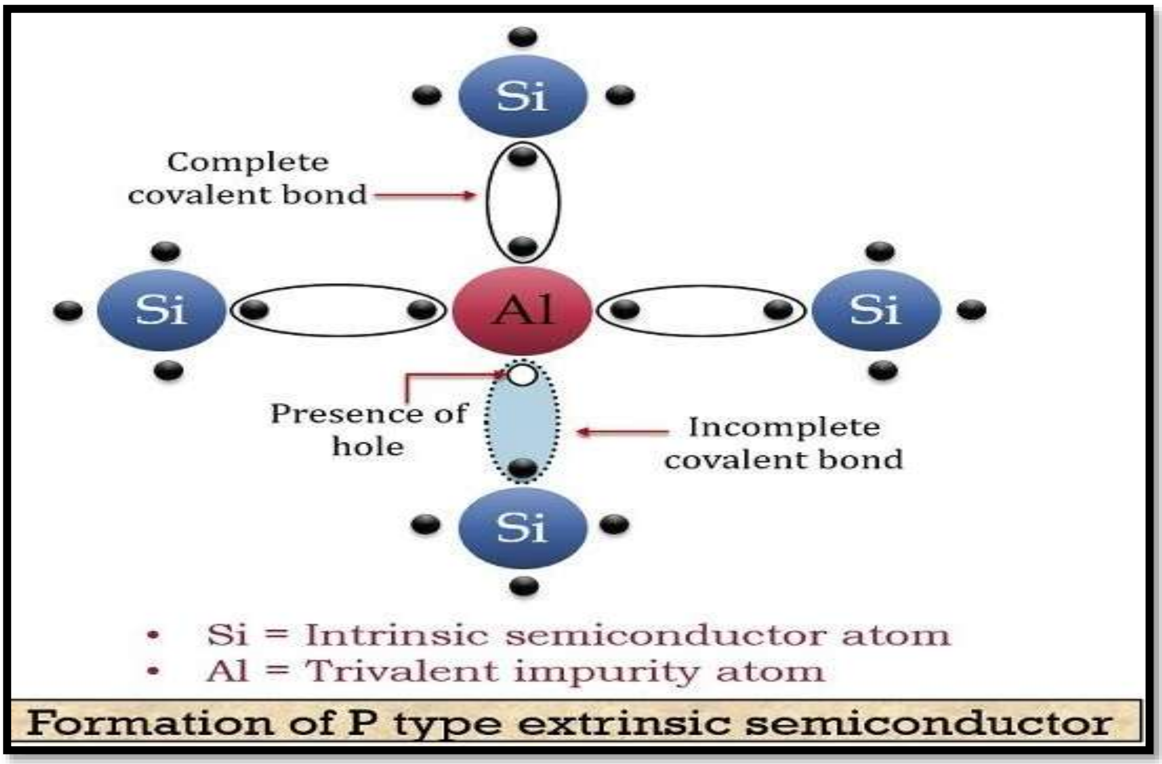

Figure (7)

For one dopant atom there will be one hole. As the number of dopant atoms increases the number of holes will increase. In addition, thermally generated electron-hole pairs are also present in the doped semiconductor. The number of holes is more than the number of free electrons. The holes are the majority charge carriers, electrons are the minority charge carriers.

The majority charge carriers (holes) are produced by doping, while the minority charge carriers (electrons) are due to the increase of temperature.

Here, we can see that the Fermi level (see figure 8) is present near the valence band. As it is clear from the figure 8 that there exists a very small energy difference between valence band and the acceptor energy level. Thus, electrons easily drift to acceptor energy level creating a vacancy of electrons. Hence, producing holes in the valence band.

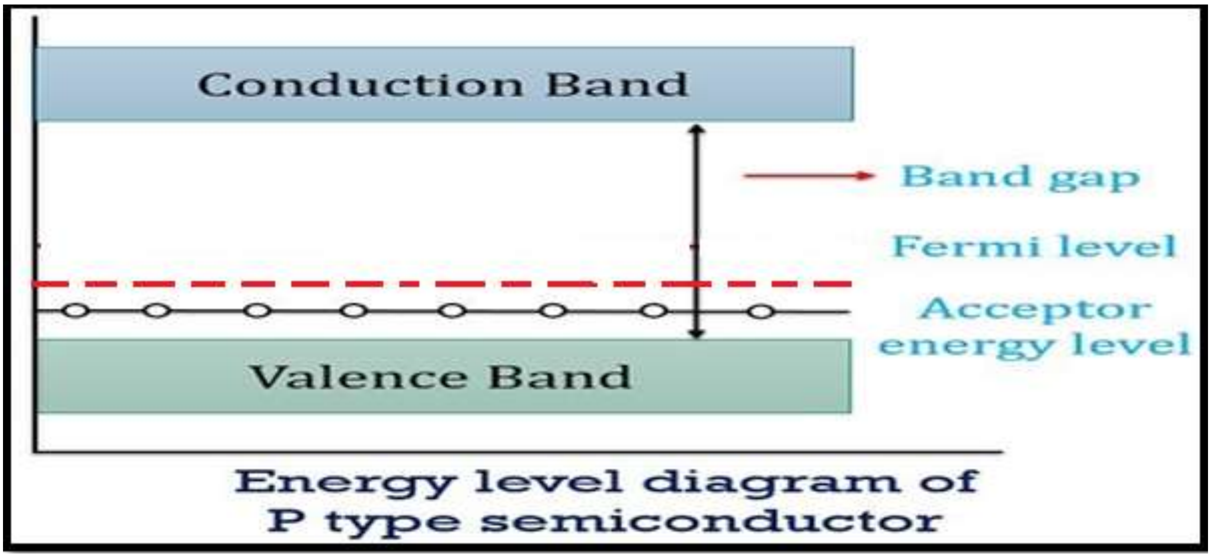

Figure (8)

From the above discussion, we can conclude that a:

p-type semiconductor is abbreviated so because these are positive semiconductors due to presence of extra holes.

n-type semiconductors are termed as negative semiconductors because of the presence of extra electrons.

4. Classification of Semiconductors

The structure of semiconductors can be classified into two groups according to the arrangement of their atoms.

1. Single crystal Semiconductors
2. Polycrystalline Semiconductors
3. Amorphous Semiconductors

Homework

What difference between n-type and p-type semiconductors???

Lecture (2) Introduction to Thin films

Outline of lecture (2)

1. Classification of materials
2. What is a thin Films?
3. Formation of thin films
4. Parameters effect on the formation of thin films
5. Deposition methods of films
6. Applications of thin films

1. Classification of Semiconductors

The physical way in which atoms come together to form a crystal structure determines the properties of the material. The structure of semiconductors can be classified into two groups according to the arrangement of their atoms.

1.1 Crystalline Semiconductors

A crystalline semiconductor is made up of a three-dimensional arrangement of atoms in a regular, definite and long range order. They have a homogeneous composition with characteristic geometrical shape.

There are two types of the ordered array of atoms in crystalline semiconductors: the first is **single crystal semiconductors** in this type there a periodicity to the lattice that extends right through the material. Therefore, these materials have a high degree of ordering and thus they have long range order [LRO] in three dimensions as shown in Fig. (1 a).

The second type is **polycrystalline semiconductors**, this structure consists of many tiny single crystal known as grains or crystallites which are separated by grain boundaries each of which contains a periodic array of atoms and is considered to pass long range order, while the grains in the polycrystalline state possess short range order [SRO] with random grain sites, shape and orientation packing as shown in Fig. (1b).

1.2 Amorphous Semiconductors

The atoms are arranged in an irregular and short range order [SRO]. They are not homogeneous in composition. The arrangement of atoms in these materials are not entirely random, but their periodicity is absent in three dimensions, they have ordering only within a few atomic or molecular dimensions as shown in Fig.(1c) which represented a type of amorphous structure.

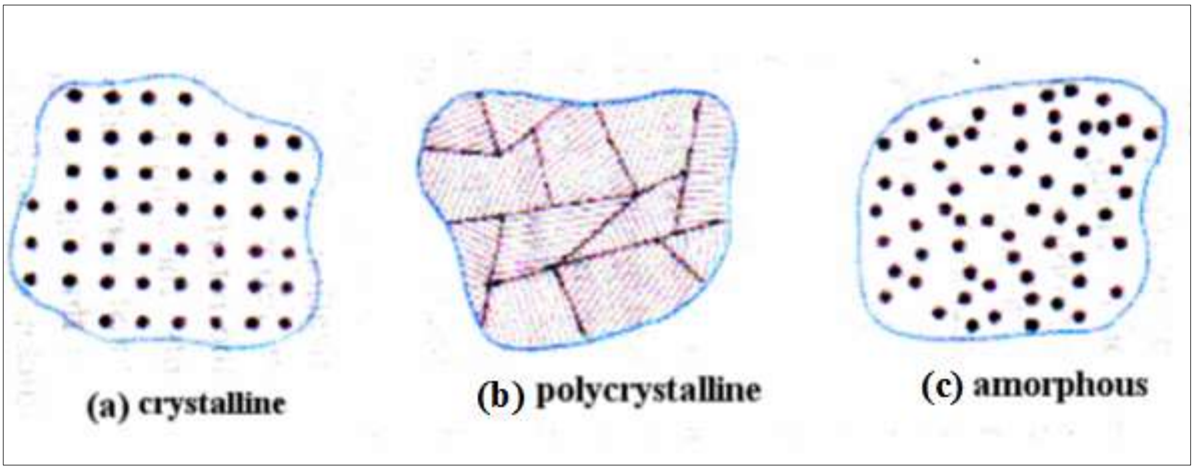

Fig. (1) Schematics of three general types of structure (a) Single Crystal (b) Polycrystalline (c) Amorphous

2. What is a Thin Films?

The expression (film) is used to explain a layer of thickness ranging between (10nm) and less than (1 µm.). The thin film is a two – dimensional form of solid material, whose on dimension, called the thickness, is much smaller than the other dimensions. The thin film is formed by atom to atom or molecule to molecule condensation process.

The properties of thin films are usually different from those of the bulk because of the two dimensions nature of thin films. In bulk “three dimensions” the particles are under the influence of forces at all directions, while in thin films the forces act upon the particles at the surface only.

The film layer is deposited on certain plates **(substrate)** chosen according to the nature of the study or the scientific need. Such plates could be glass slides, silicon wafers, aluminum, quartz and others.

The controlled synthesis of materials as thin films (a process referred to as **deposition**)

3. Formation of thin films

1. Thermal compatibility: that is, the substrate is thermally prepared to receive the shocked atoms.
2. Bonding: It is the stage of bonding of the atoms to the surface of the substrate after the substrate has been exposed to the vapor of the substance.
3. Surface spread: After the atoms are attached to the hot surface of the substrate, they will be distributed regularly in the form of **clusters** that resemble clusters and are capable of growth as they are small and fast moving, and thus a membrane will form. Until the process of the growth of these clusters, the atoms fall on the surface and roll and go towards the clusters to coalesce with them to grow and turn into a thin film.
4. The nucleation process: It is the process of forming a cluster on the condition that the surface of the substrate is uneven or contains protrusions that lead to obstruction of the atoms scattering on the surface and their survival for a sufficient time to assemble and form the cluster
5. Islands growth: it is the growth of clusters to transform into a membrane. There are three models for the growth of islands, which are:

1. **Island growth: 3D** islands formation; film atoms more strongly bound to each other than to substrate and/ or slow diffusion.

2. **Layer-by-layer growth:** generally the highest crystalline quality film atoms more strongly bound to substrate than to each other and/or fast diffusion.

3. **mixed growth**: initially layer-by-layer, then 2D islands

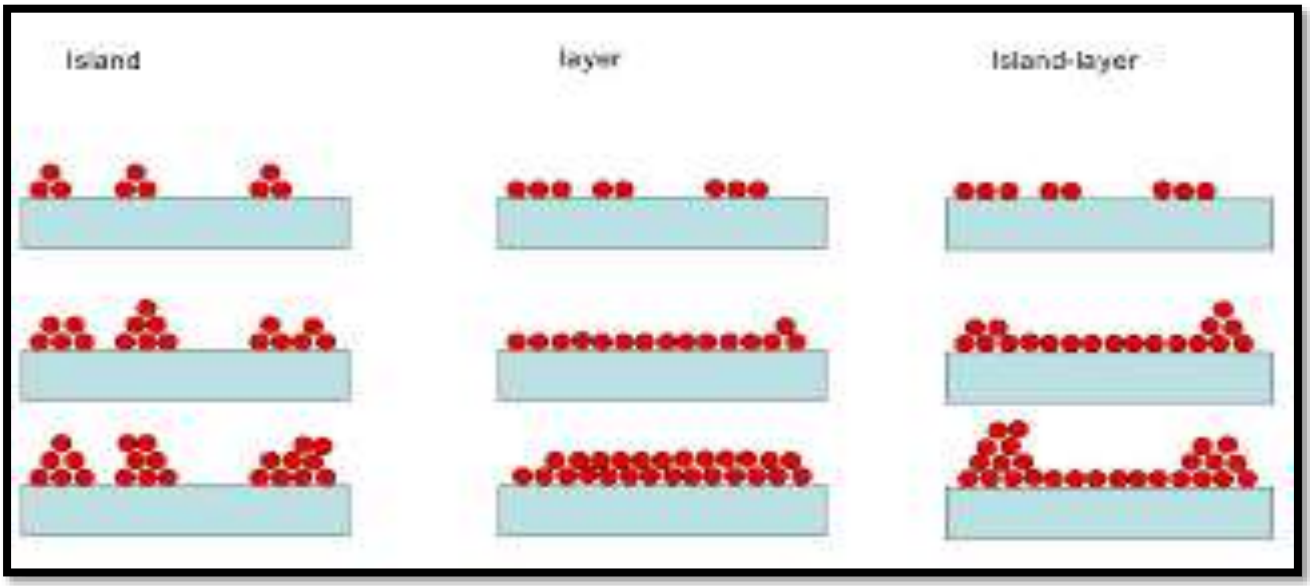

Fig. (2)Basic modes of thin films growth

6. The Coalescence of the islands with each other: in this stage, the atoms and the small islands leave towards the large islands, as well as the swallowing of small clusters that move randomly by the large islands.

4. Parametrs effect on the formation of thin films

1. crystal structure of substrate
2. temperature of substrate
3. position and area of substrate
4. rotation the substrte

5. Deposition methods of films

The methods of preparing thin films can be divided basically into two main groups, namely, physical and chemical methods. These methods are shown in figure (3).

Physical methods involve the techniques in which the deposition occurs after the material to be deposited has been transferred to a gaseous state. It can happen either by evaporation or an impact process.

Chemical methods in chemical deposition method, thin films are deposited on the substrate from aqueous solution either by passing a current or by chemical reaction under appropriate conditions.

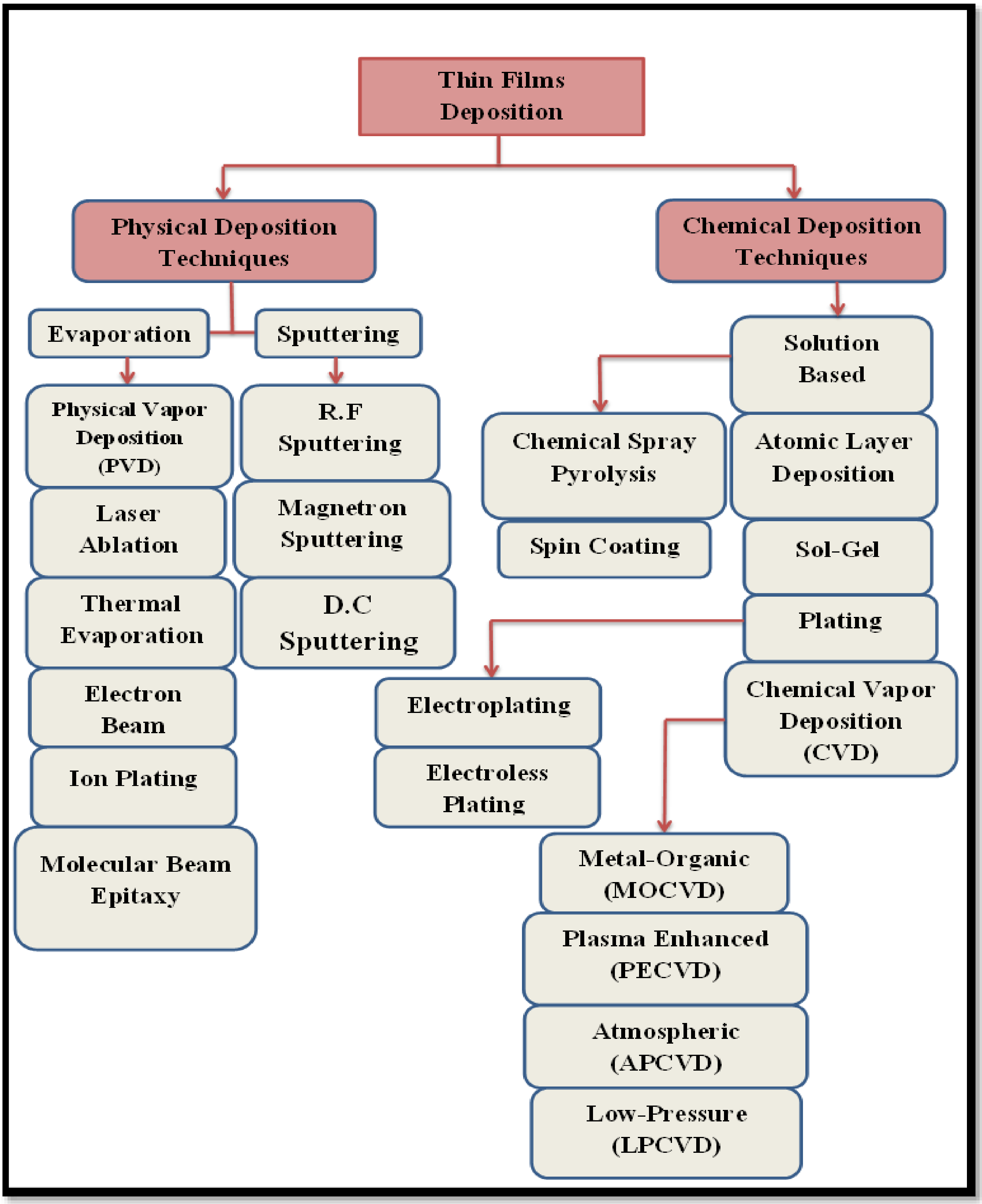

Figure (3): Classification of thin film deposition techniques

Spin coating technique

Spin coating is the most widely used deposition technique. Highly reproducible as well as very homogenous films can be deposited by this technique. Two forces are acting on the solution during spin coating; the adhesive forces at the solution substrate interface and the centrifugal forces resulting from the high-speed rotation. These two competing forces will result in a strong shearing action at the interface which causes the solution to form a thin film with controllable thickness, depending on angular velocity, solution concentration and viscosity **[29]**. To get homogeneous films, several different factors are important and have to be considered which are evaporation rate of the solvent, viscosity of the fluid, concentration of the solution, angular velocity (rotating speed) and spinning time.

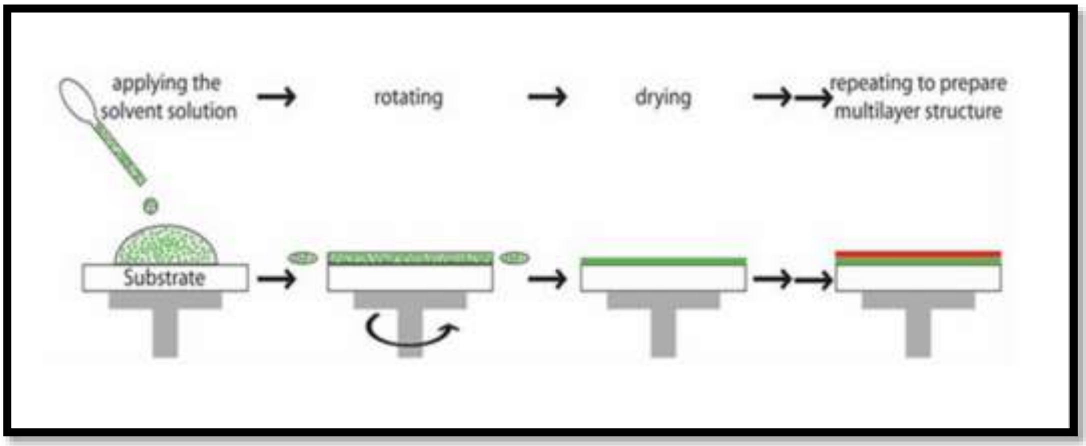

Figure (4) Schematic illustration of the spin coating technique.

6. Applications of thin films

There are so many applications of thin films such as the electronic and optical applications

1 - Electronic Applications:

Thin films were invested in manufacturing capacitors, diodes, and integrated circuits Resistors and conductors

2- Optical Applications:

Thin films were used in the manufacture of solar cells and the manufacture of optical fibers used in the transfer of information and communications, and the manufacture of optical filters and anti-reflective coatings to reduce the losses associated with the reflection of light from the surfaces of these cells. It was also used in the manufacture of optical detectors, as well as its use in laser optics as reflective metallic coatings that have the ability to withstand high radiation intensity. This leads to study of electronic and optical properties of thin films.

H.W

1- What are factors to be considered to get homogeneous films by spin coating technique?

2- Numerate three physical methods for preparing thin films.

3- Numerate three chemical methods for preparing thin films.

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Lecture (3) Optical Properties of thin films

Many properties can be studied for thin films semiconductor such as: optical properties, structural properties, and electrical properties.

1. Optical properties

Optical properties of a semiconductor can be defined as any properties that involves the interaction between electromagnetic radiation or light and the semiconductor, including absorption, diffraction, polarization, reflection, and scattering effects. These properties are important for the understanding of the mechanism of electron transition between energy bands during the measuring of absorption and transmission of a semiconductor.

2. Optical Absorption

The **fundamental absorption** is the most important absorption process which involves the transition of electrons from the valence to the conduction band, which manifests itself by a rapid rise in absorption and this can be used to determine the energy gap of the semiconductor.

The semiconductor absorbs photon from the incident beam, the absorption depends on the photon energy (hν); where (h) is Plank's constant, (ν) is the incident photon frequency, the absorption associated with the electronic transition between the V.B and the C.B in the material starting at the **absorption edge** which corresponds to minimum energy difference (E^o_g) between the lowest minimum of the C.B. and the highest maximum of the V.B . If the photon energy (hν) is equal or more than energy gap (E^o_g) then, the photon can interact with a valence electron, elevates the electron into the C.B and creates an electron–hole pair. The maximum wavelength (λ) of the incident photon which creates the electron–hole pair defined as:

$$\lambda(\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The intensity of the photon flux decreases exponentially with distance through the semiconductor according to the following equation:

$$I = I_0 \exp(-\alpha t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where I_0, I are the incident and the transmitted photon intensity respectively and (α) is the absorption coefficient, which is defined as the relative number of the photons absorbed per unit distance of semiconductor, and (t) is the thickness of the material.

3. Types of the optical transitions

There are two types of the optical transitions, as shown in Fig. (1)

1. Direct Transitions

The direct transition in general occurs between top of valence band and bottom of conduction band (vertical transition) at the same wave vector k = 0 for conservation of momentum. The **allowed direct transition** refers to that transition which occurs between top of the valence band and bottom of the conduction band when the change in the wave vector equal to zero (Δk = 0) as shown in Figure (1a).

This transition is described by the following relation:

$$\alpha h\upsilon = B(h\upsilon - E_g)^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where B is inversely proportional to amorphousity.

If the transition occurs also between states of the same wave vector, but the wave vector does not equal to zero, when the change in the wave vector equal to zero ($\Delta k = 0$) the transition is called **forbidden direct transition** as shown in Figure (1b), it obeys the following relation.

$$\alpha h\upsilon = B(h\upsilon - E_g)^{3/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

2. *Indirect Transitions*

In indirect transition there is a large momentum difference between the points to which the transition takes place in valence and conduction bands, this means that the conduction band minima are not at the same value of k as the valence band maxima, then, assistance of a phonon is necessary to conserve the momentum, therefore :

$$h\upsilon = E_g \pm E_p \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where E_p is the energy of an absorbed or emitted phonon.

For an **allowed indirect transition**, the transition occurs from the top of the valence band to the bottom of the conduction band as shown in Figure (1c) so that:

$$\alpha h\upsilon = B(h\upsilon - E_g)^2 \qquad (6)$$

While, **the forbidden indirect transitions** occur from any point near the top of V.B to any point other than the bottom of the C.B, as shown in Figure (1d), then we have:

$$\alpha h\upsilon = B(h\upsilon - E_g)^3 \qquad (7)$$

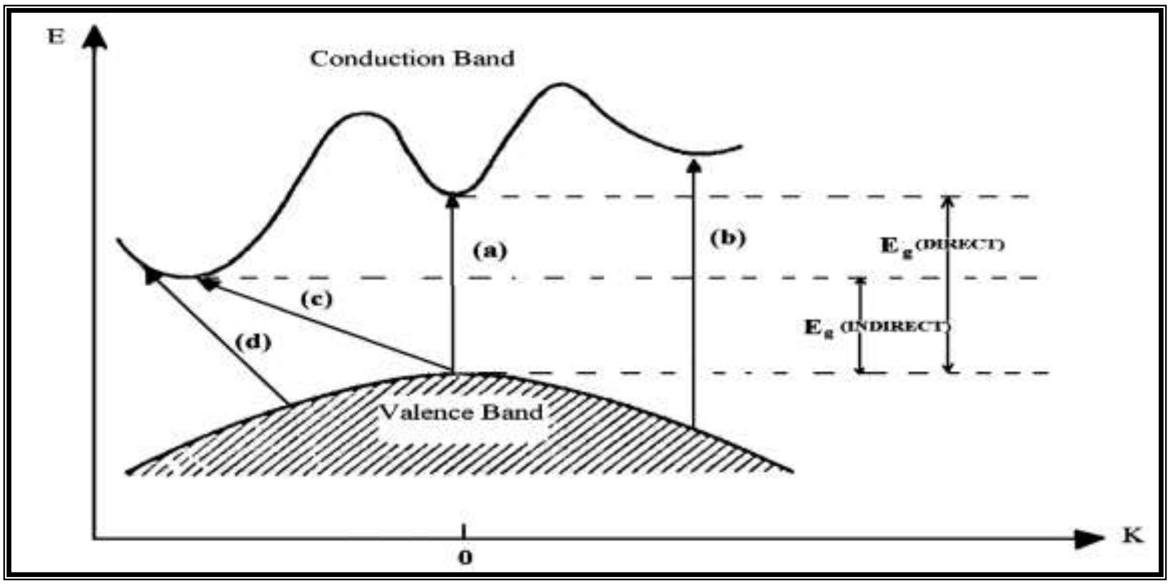
Experimentally it is possible to differentiate between direct and indirect processes by the level of the absorption coefficient (α); α takes values from 10^4 to 10^5 cm^{-1} for direct transitions and 10 to 10^3 cm^{-1} for indirect transitions at the absorption edge.

Summary

r is a parameter that has different values (1/2, 3/2, 2, 3) depending on the material and form of optical transitions.

Taus relation is given as:
$\alpha h\upsilon = B(h\upsilon - E_g)^r$

The value of r in the Taus relation is equal to:
1/2 for allowed direct transition
3/2 for forbidden direct transition
2 for allowed indirect transition,
3 for forbidden indirect.



Figure(1): The optical transitions (a) Allowed direct, (b) Forbidden direct; (c) Allowed indirect, (d) Forbidden indirect

The coefficient of transmission (T) is defined likewise as the ratio of the transmitted power to the incident power.

The absorption of light by an optical medium is quantified by its absorption coefficient (α),

The relation between absorptivity (A) and Transmission (T) is:

$$A = \log 10\ 1/T \ldots\ldots\ldots (8)$$

And

$$\alpha = 2.303\ A/t \ldots\ldots\ldots\ldots (9)$$

<u>H.W:</u> what difference between phonon and photon

Lecture (4) Structure Properties of thin films

For study the structure properties of materials there are many methods such as: X-Ray Diffraction (XRD), Atomic Force Microscopy (AFM), Fourier Transform Infrared (FTIR), Field Emission Scanning Electron Microscope (FESEM)

1. X-Ray Diffraction (XRD)

X-rays is a form of electromagnetic radiation. Most X-rays have a wavelength in the range of (0.01 to 10 nm). X-ray wavelengths are shorter than those of UV rays and typically longer than those of gamma rays. The wavelength must be equal to or roughly comparable to the lattice constant in order to investigate the structure of materials.

2. Structure of Thin Films

One of the most well known methods for studying the structure of bulk materials as thin films is the x-ray diffraction (XRD).

The analysis of the diffraction pattern may give information about the crystallization and interplanner spacing of substance examined.

The Bragg's condition for the diffraction can be written as:

$$2d_{hkl} sin\theta = n\lambda \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

as shown in Figure (1), where d is the spacing between the planes, θ is the angle that the X-ray beam makes with respect to the plane, λ is the wavelength of the X rays, and $n = 1,2,3, \ldots$ is an integer that usually has the value $n = 1$ which represents the diffraction order.

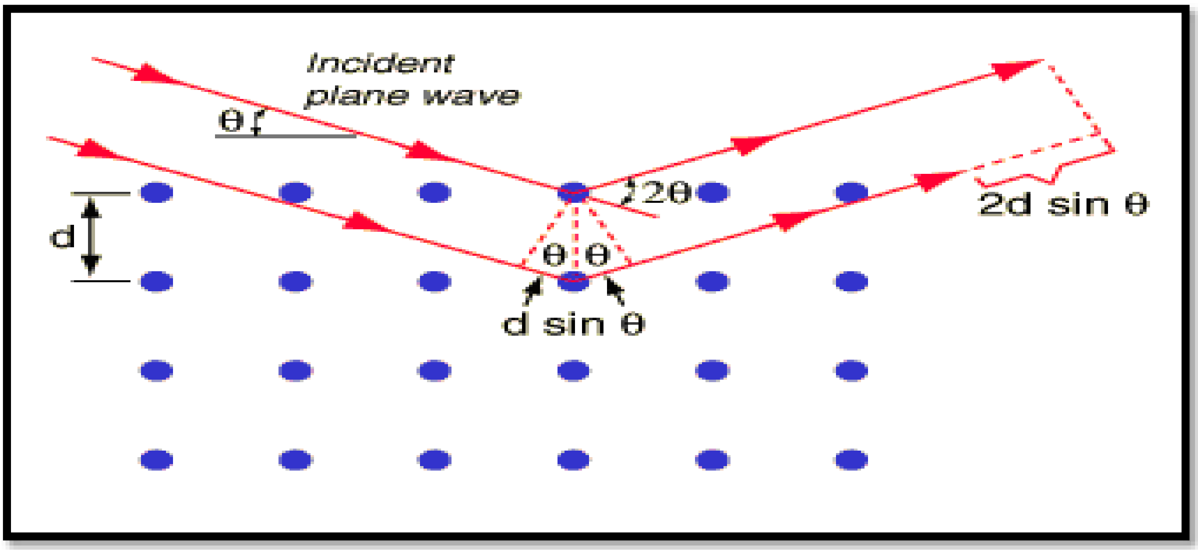


Fig (1) show the (XRD) that satisfies Bragg's condition.

According to the (XRD), in the case of polycrystalline films the (XRD) shows various peaks at different angles of diffraction and diffraction pattern as shown in figure (2)a The single crystal material exhibits sharp reflections (sharp peaks). as shown in figure (2)b . For the amorphous films material, the diffraction does not exhibit any sharp peaks. This can be simply represented in fig (2) c.

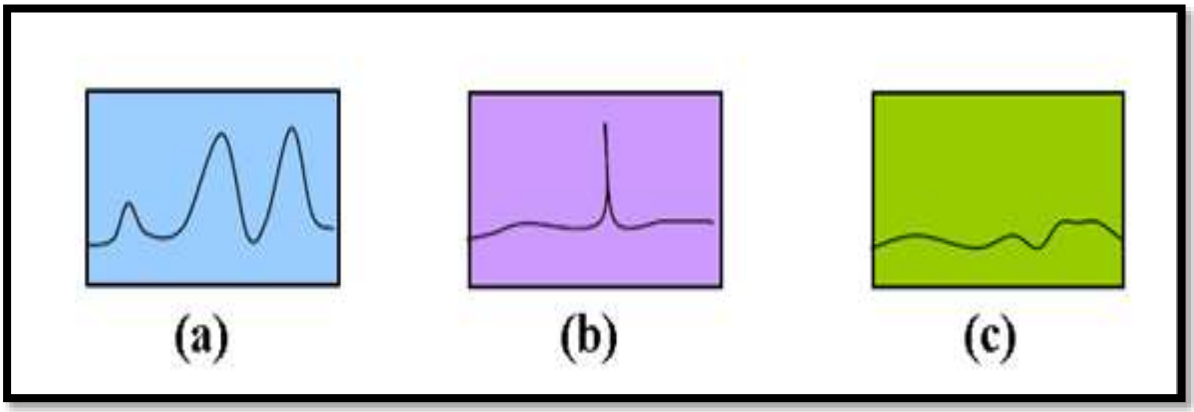


Figure (2): (XRD) of semiconductors.

(a)Polycrystalline (b) Single material (c) Amorphous material

3. Structural Parameters

1. Lattice Constant (a)

The distance *d* between parallel crystallographic planes with indices (*hkl)* for a simple cubic lattice of lattice constant a has the particularly simple form:

$$d = \frac{a}{(h^2 + k^2 + l^2)^{1/2}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

2. Average crystallite size (D_{av})

The average crystallite size (D_{av}) can be estimated using **Scherrer method** to estimate the average crystallite size from the measured width of their diffraction curves (XRD pattern), we used the Scherrer formula:

$$D=K\lambda/\beta\cos\theta \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

In this equation, shape factor (K)=0.9, λ represents the wavelength of the X-ray radiation, β is the full width at half maximum (FWHM) of the diffraction peak (in radians) and θ is Bragg diffraction angle of the diffraction peak .

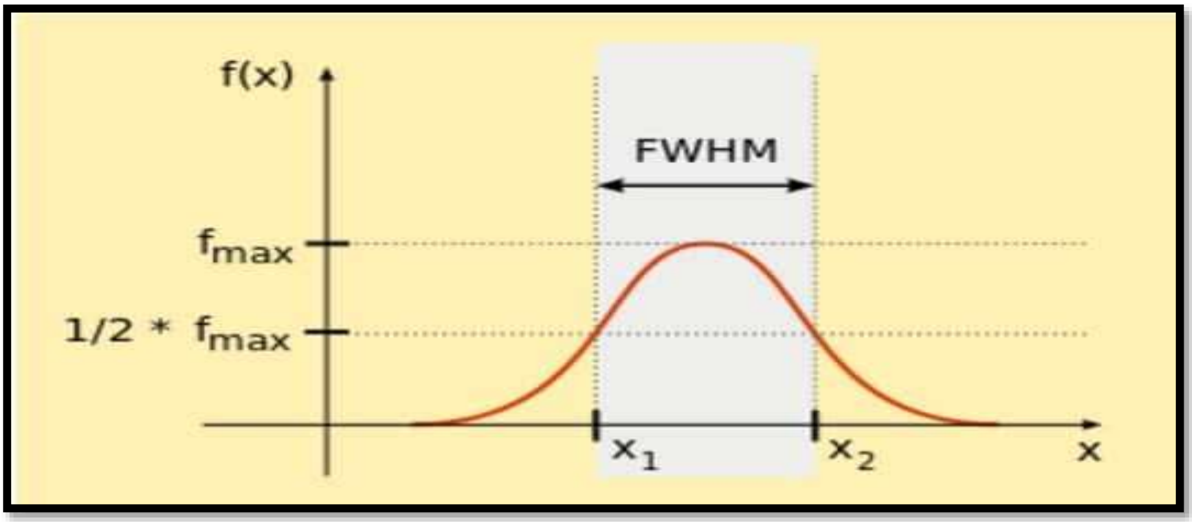


Figure (3) show Full width at Half Maximum

3. Number of crystallites

Can be calculated from the relation:

$$N_o = t/D_{av}^3 \ldots\ldots\ldots\ldots..(4)$$

Where t: is the thickness and N_o: is the number of crystallites.

4. Strain (s)

The Strain (s) is calculated using the following relation**:**

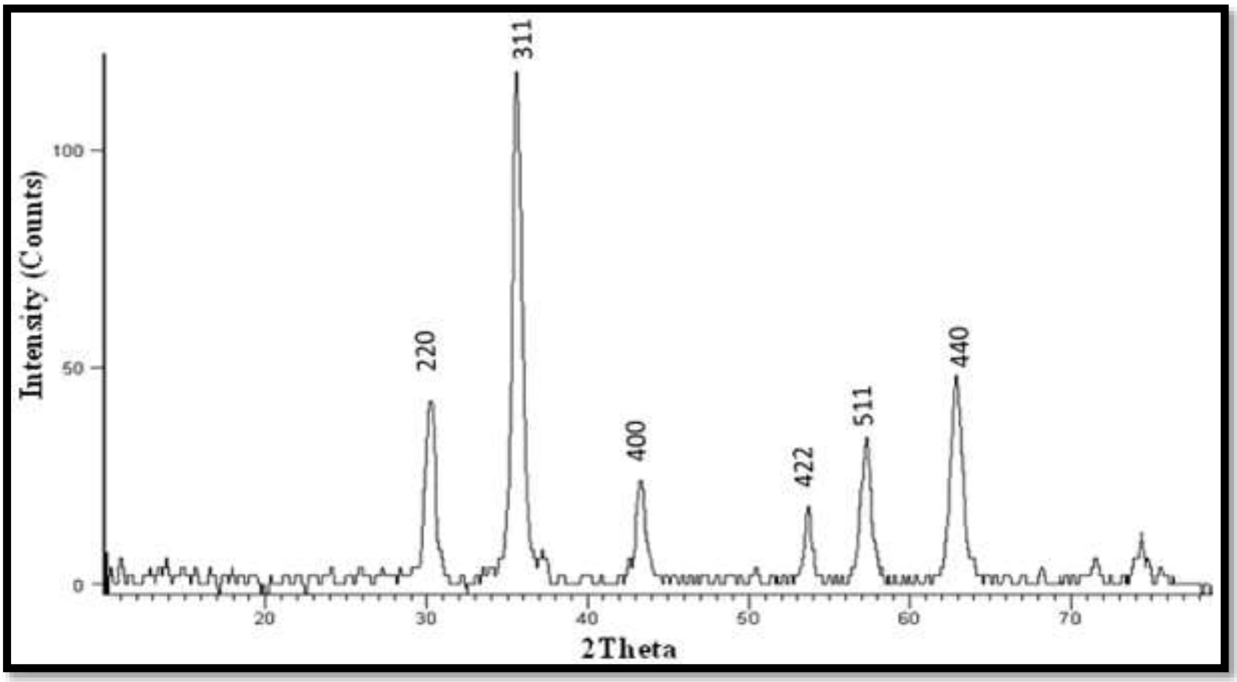
$$s = \frac{a - a_o}{a_o} x100\% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where a_o is the standard lattice constant and a is the experimental lattice constant.

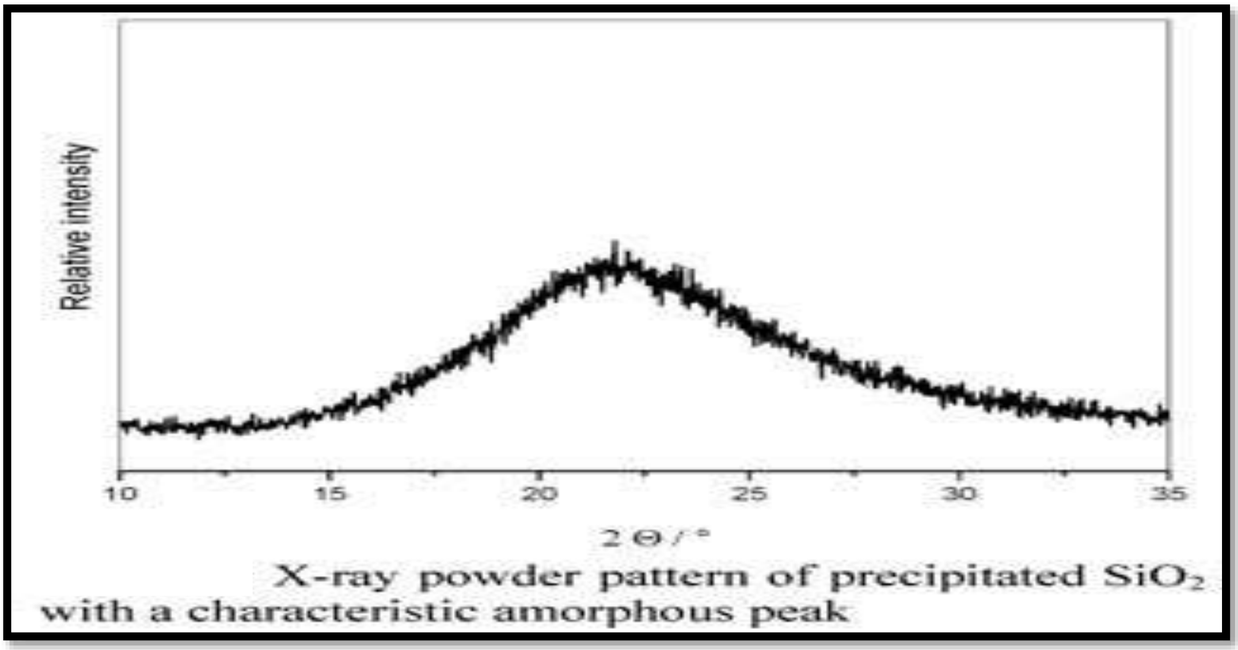
5. Dislocation density

The dislocation density (δ) which represents the amount of defects in the sample is calculated using the relation:

$$\delta=1/D^2_{av}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$



(a)



X-ray powder pattern of precipitated SiO_2 with a characteristic amorphous peak

(b)

Figure (5) show XRD pattern (a) Polycrystalline (b) Amorphous

Lecture (5) Electrical Properties of thin films

For study electrical properties of thin films we requirement measurements D.C. Conductivity, A.C. Conductivity, I-V characteristics, Hall Effect....etc.

D.C. Conductivity

The D.C. conductivity in crystalline semiconductor depends on the presence of free electrons and free positive holes. At T=0 K, the valence band is completely filled, while the conduction band is empty. Under this condition, the semiconductor behaves as an insulator. When the temperature is increased, the electrons are transferred from valence band to the conduction band, leaving vacant levels (holes) in the valence band. This transition is responsible for the conduction properties of the semiconductor.

In semiconductor, the conductivity (σ) is due to movement of charge carries when an electric field is applied.

Electrical conductivity (σ) is defined as the proportional factor between the current density (J) and the electric field (E), and it is given by Ohm’s law:

$$J = \sigma E \quad \dots\dots\dots\dots (1)$$

Where:

$$\sigma = n\, q\, \mu \quad \dots\dots\dots\dots (2)$$

or

$$\sigma = \frac{n q^2 \tau}{m^*} \quad \dots\dots\dots\dots (3)$$

Where: μ: is the mobility, τ: is the carrier's lifetime, n: is the carrier concentration, m*: is the effective mass of the carrier, q : is the electron charge.

In semiconductors the relation between the current density and electric field is given by:

$$J = q (n \mu_n + p \mu_p) E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where : P is the hole concentration, μ_n and μ_p are the mobility of electron and hole, respectively,

Where:

$$\mu = \frac{v_d}{E} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where: v_d is the drift velocity.

Then the relation between the conductivity and electron-hole concentration is

:

$$\sigma = q (n \mu_n + p \mu_p) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

In practice, the material will be either n-type or p-type, and then equation

(66) will be:

$$\sigma_n = qn\mu_n \quad \text{for} \quad \text{n-type} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

and

$$\sigma_p = q\, p\, \mu_p \quad \text{for} \quad \text{p-type} \quad \ldots\ldots\ldots\ldots\ldots (8)$$

For most cases of semiconductor the following equation gives the change of the electrical conductivity with temperature:

$$\sigma = \sigma_o \exp (-E_a/K_BT) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where: σ_o : is the minimum electrical conductivity at 0 °K, E_a : is the activation energy which corresponds to ($E_g/2$) for intrinsic conduction, T: is the temperature and K_B is the Boltzman's constant.

Resistivity ρ for semiconductor is:

$$\rho = \frac{1}{\sigma} \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Hall Effect

Hall measurements are used in the initial characterization of semiconductors to measure the carriers concentration, mobility and it is used to distinguish whether a semiconductor is n or p–type. When a constant current (I) follows along the x–axis from left to right in the presence of a z–directional magnetic field (B). Electrons are subjected to the Lorentz force initially and they drift toward the negative y–axis, resulting an excess surface electrical charge on the side of the sample and causing a transverse voltage, this transverse voltage is known as the Hall voltage (V_H) as shown in Figure (1). The Hall coefficient R_H is determined by measuring the Hall voltage that generates the Hall field across the sample of thickness (t), by

$$R_H = \frac{V_H}{I}\frac{t}{B} \ldots\ldots\ldots\ldots \quad (11)$$

From the Hall coefficient equation we can determine the carrier concentration of the semiconductor and the carrier type, since R_H is negative and positive, for n– and p– type, respectively

$$R_H = \frac{-1}{qn} \ldots\ldots\ldots\ldots\ldots \quad (12)$$

$$R_H = \frac{1}{qp} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (13\ )$$

where *n*: is the elections concentration, *p* is the holes concentration, *q*: is the electron charge. We can measure the Hall mobility (μ_H) from relation:

$$\mu_H = \frac{\sigma}{n.e} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (14)$$

$$\mu_H = \sigma|R_H| \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\ 15)$$

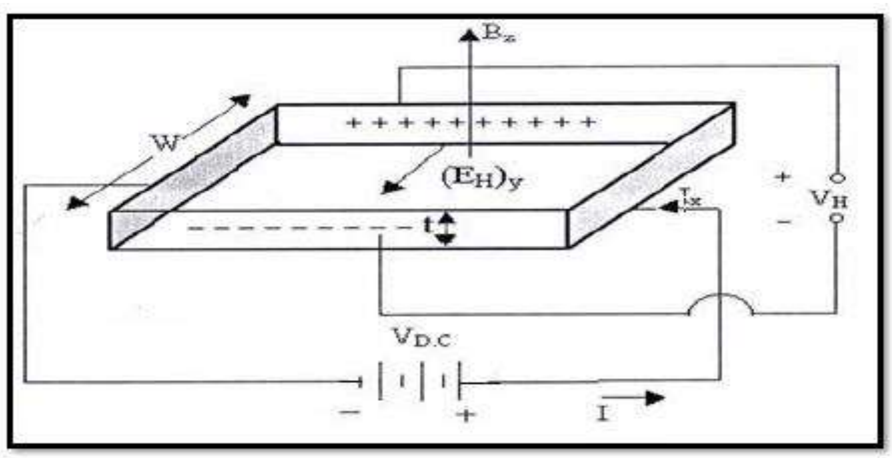


Figure 1 Hall Effect measurement circuit.

Lec. (6) P-N Junction

1. What is P-N Junction?

A p-n junction is an interface or a boundary between two semiconductor material types, p-type and the n-type, inside a semiconductor. The p-side or the positive side of the semiconductor has an excess of holes and the n-side or the negative side has an excess of electrons.

2. Formation of P-N Junction

When the N-type semiconductor and P-type semiconductor materials are first joined together a very large density gradient exists between both sides of the PN junction. The result is that some of the free electrons from the donor impurity atoms begin to migrate across this newly formed junction to fill up the holes in the P-type material producing negative ions.

However, because the electrons have moved across the PN junction from the N-type to the P-type silicon, they leave behind positively charged donor ions (N_D) on the negative side and now the holes from the acceptor impurity migrate across the junction in the opposite direction into the region where there are large numbers of free electrons.

As a result, the charge density of the P-type along the junction is filled with negatively charged acceptor ions (N_A), and the charge density of the and the charge density of the N-type along the junction becomes positive. This charge transfer of electrons and holes across the PN junction is known as **diffusion**.

This process continues back and forth until the number of electrons which have crossed the junction have a large enough electrical charge to repel or prevent any more charge carriers from crossing over the junction. Eventually a state of equilibrium (electrically neutral situation) will occur producing a “potential barrier” zone around the area of the junction as the donor atoms repel the holes and the acceptor atoms repel the electrons.

Since no free charge carriers can rest in a position where there is a potential barrier, the regions on either sides of the junction now become completely depleted of any more free carriers in comparison to the N and P type materials further away from the junction. This area around the PN Junction is now called the **Depletion Layer or the space charge layer.**

The total charge on each side of a PN Junction must be equal and opposite to maintain a neutral charge condition around the junction.

- In equilibrium, diffusion current (I_D) is balanced by drift current (I_S)

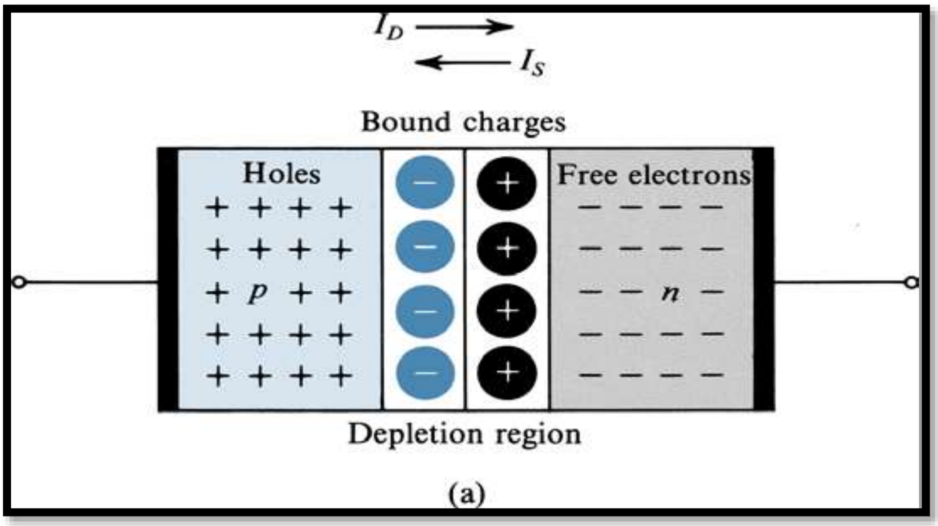


Figure (1) P-N junction

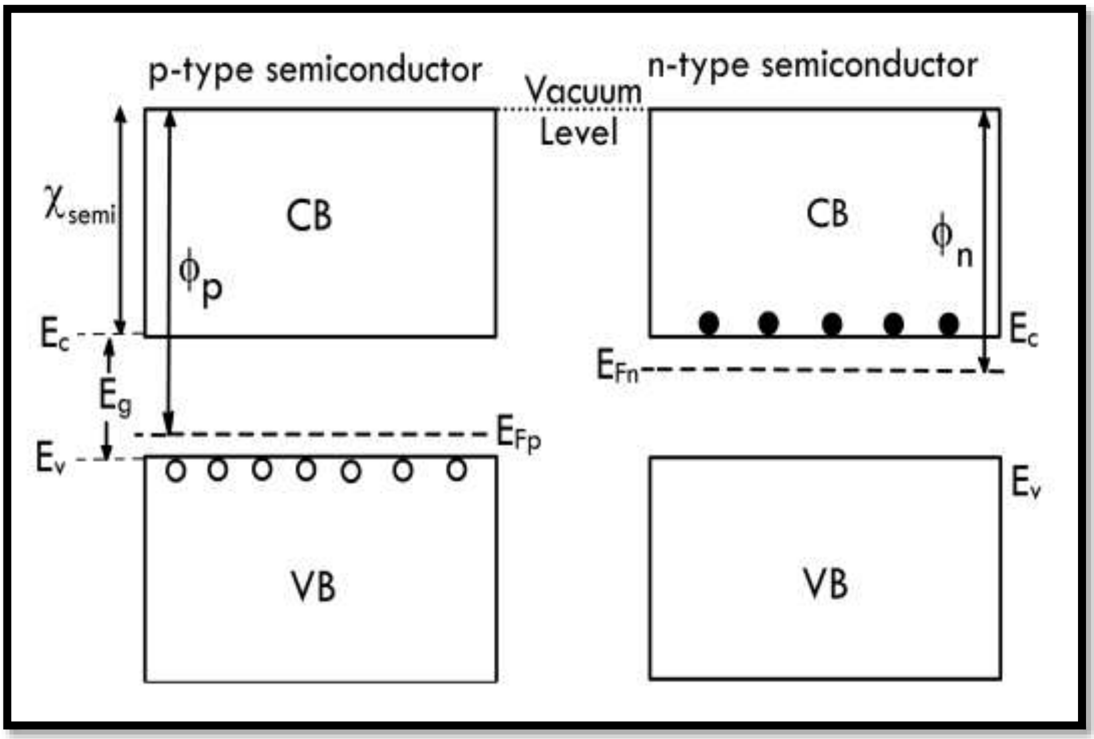


Figure (2)

Energy band diagram of p and n type Si before the junction is formed. The location of the Fermi level is different for the two semiconductors.

The processes that follow after the formation of a p-n junction are of two types – diffusion and drift. As we know, there is a difference in the concentration of holes and electrons at the two sides of a junction, the holes from the p-side diffuse to the n-side and the electrons from the n-side diffuse to the p-side. These give rise to a diffusion current across the junction.

an electric field is formed from the n-side to the p-side and there is a built-in potential, from the p to the n side. This potential is called the junction potential or contact potential.

Due to depletion region an electric field direction from a positive charge towards the negative charge is developed. Due to this electric field, an electron on the p-side of the junction moves to the n-side of the junction.

This motion is termed as the drift. Here, we see that the direction of drift current is opposite to that of the diffusion current.

- Holes and electrons move through a semiconductor by two mechanisms:

Diffusion – random motion due to thermal excitation and moves from area of higher concentration to area of lower concentration and is a function of the concentration gradient

Drift – carrier drift occurs due to an electric field applied, the field accelerates the carriers (electrons or holes) and acquire a velocity, called drift velocity, dependent on a constant called mobility μ

3. Contact potential

The band diagram when the pn junction is formed (at equilibrium) is shown in figure (3). When the two materials are brought together, the Fermi levels line up at equilibrium.

The space charge layer (SCL) extends on both the n and p side and the contact potential (V_{bi}) is equal to the difference between the work functions of the p and n side (φ_p-φ_n).

$$V_{bi}=\varphi_p-\varphi_n$$

$$V_{bi}=\frac{KT}{q}ln\left(\frac{N_D N_A}{ni^2}\right)$$

Where K plank constant, T absolut temperature, N_D and N_A are the impurity concentrations and n_i is the intrinsic semicondctor concentration.

Define work function (H.W)

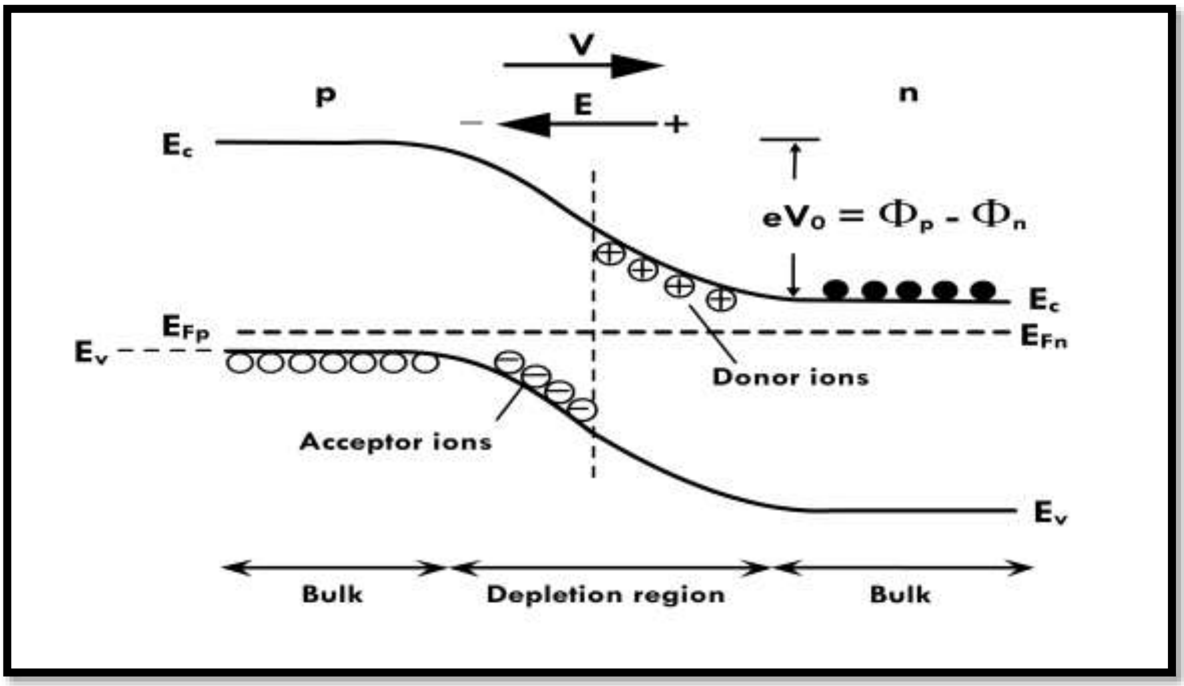


Figure (3) band diagram of PN-junction

Typically at room temperature the voltage across the depletion layer for silicon is about 0.6 – 0.7 volts and for germanium is about 0.3 – 0.35 volts. This potential barrier will always exist even if the device is not connected to any external power source, as seen in diodes.

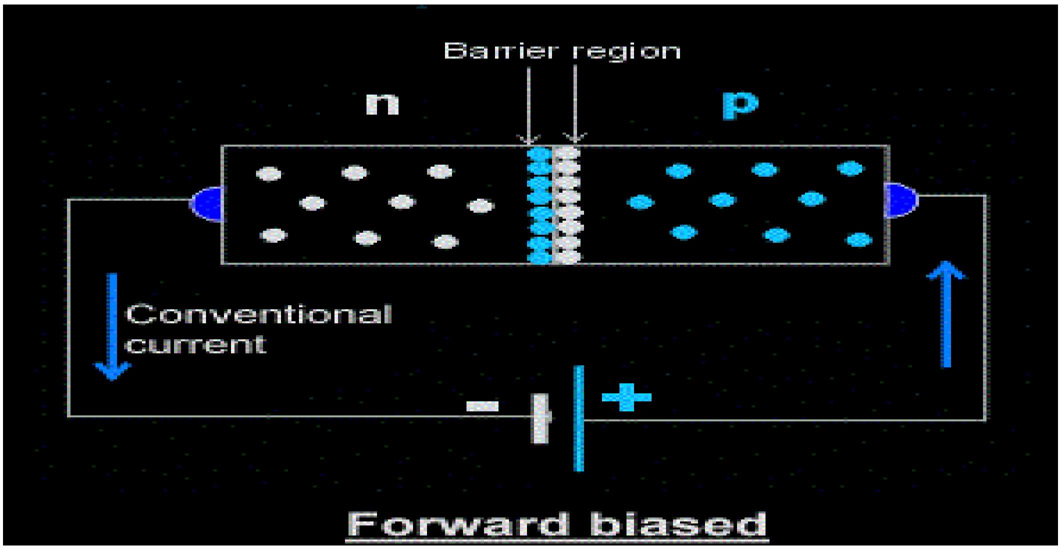
4. Biasing conditions for the p-n Junction Diode

The external voltage required to overcome this potential barrier that now exists is very much dependent upon the type of semiconductor material used and its actual temperature.

There are three biasing conditions for p-n junction diode and this is based on the voltage applied:

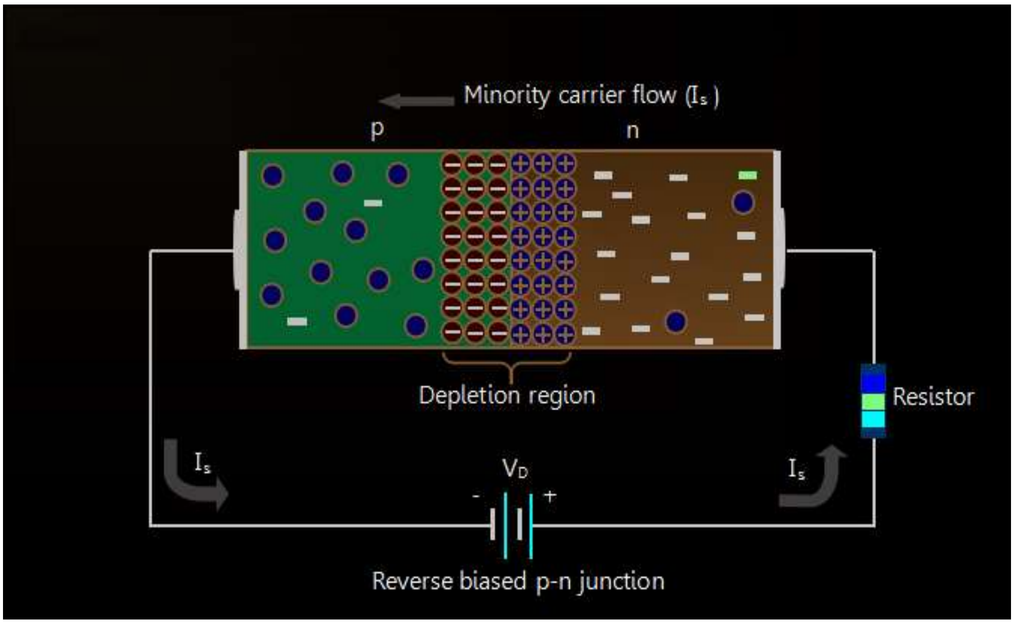
- Zero bias: There is no external voltage applied to the p-n junction diode.
- Forward bias: The positive terminal of the voltage potential is connected to the p-type while the negative terminal is connected to the n-type.
- Reverse bias: The negative terminal of the voltage potential is connected to the p-type and the positive is connected to the n-type.

P-N Junction Diode Under Forward Bias



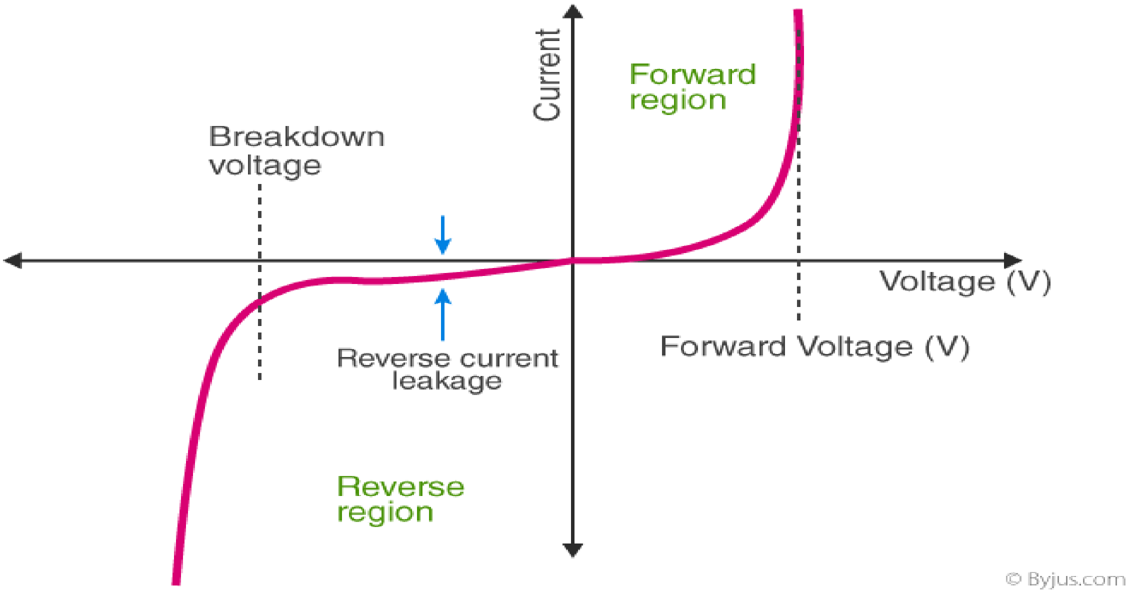
When we apply the external voltage across the semiconductor diode in such a way that the p-side is connected to the positive terminal of the battery and the n-side is connected to the negative terminal, then the semiconductor diode is said to be forward-biased. In this case, the built-in potential of the diode and thus the width of the depletion region decreases, and the height of the barrier gets reduced. The overall barrier voltage, in this case, comes out to be V_0-V, which is the difference between the built-in potential (V_0) and the applied potential (V). As we supply a small amount of voltage, the reduction in the barrier voltage from the above-given formula is very less and thus only a small number of current carriers cross the junction in this case. Whereas, if the potential is increased by a significant value, the reduction in the barrier height will be more, thus allowing the passage of more number of carriers.

pn Junction in Reverse Bias



When we apply the external voltage across the semiconductor diode in such a way that the positive terminal of the battery is connected to its n-side and the negative terminal of the battery is connected to the p-side of the diode, then it is said to be in the condition of reverse bias. When an external voltage is applied across the diode, as the direction of the external voltage is the same as that of the barrier potential, the total voltage barrier sums up to be (V_0+V). Also, the width of the depletion region increases. As a result of this, the motion of carriers from one side of the junction to another decreases significantly.

5. I-V Characteristics of PN Junction Diode



VI characteristics of PN junction diodes is a curve between the voltage and current through the circuit. Voltage is taken along the x-axis while the current is taken along the y-axis. The above graph is the VI characteristics curve of the PN junction diode.

When the PN junction diode is under zero bias condition, there is no external voltage applied and this means that the potential barrier at the junction does not allow the flow of current.

When the diode is in forward bias, the current increases slowly and the curve obtained is non-linear as the voltage applied to the diode is overcoming the potential barrier. Once the potential barrier is overcome by the diode, the diode behaves normally and the curve rises sharply as the external voltage increases and the curve obtained is linear.

When the PN junction diode is reverse bias, this results in an increase in the potential barrier. Reverse saturation current flows in the beginning as minority carriers are present in the junction.

When the applied voltage is increased, the minority charges will have increased kinetic energy which affects the majority charges. This is the stage when the diode breaks down. This may also destroy the diode.

6. Types of Diodes

The various types of diodes are as follows:

1- Zener diode
2- Avalanche diode
3- Photodiode
4- Light Emitting Diode
5- Laser diode
6- Tunnel diode
7- Schottky diode
8- Varactor diode
9- P-N junction diode

Lec. (7) Metal-Semiconductor Contacts

This lecture analyzes the electrical characteristics of a metal semiconductor Contact (MS), two different types of contacts can be produced:

1. A non-linear, rectifying contact called a Schottky contact.
2. A linear, non-rectifying contact called an ohmic contact.

1. Schottky diode

A Schottky contact or Schottky diode is formed when a rectifying contact is formed between a metal and a semiconductor as shown figure (1). The rectifying properties of the contact are similar to those of a PN junction diode.

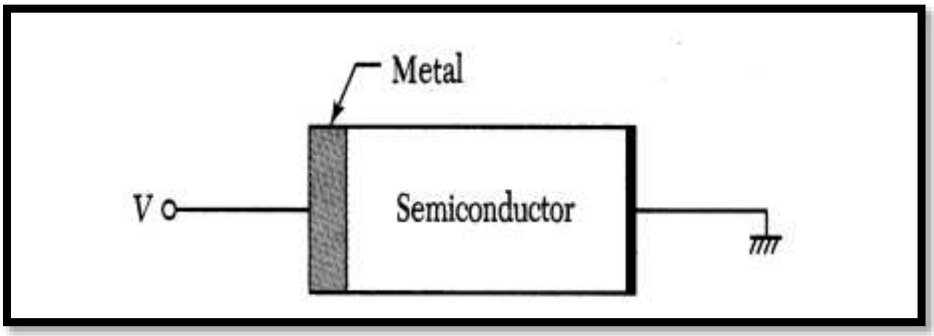


Figure (1) One-dimensional structure of a metal-semiconductor contact.

2. Energy band diagram

Consider an N-type semiconductor crystal and a metal. The energy band diagrams of these two materials are shown in Figure (2). We know because of the photoelectric effect, that electrons can be extracted from a metal in a vacuum, when light with a proper wavelength is shone onto the metal. In order to observe this effect the wavelength of the incident light must have a higher energy than a given critical value. In other words, the photons must carry enough energy to extract electrons from the metal and eject them into the vacuum.

This energy $E = hv$ must be at least equal to the "work function" of the metal, noted $q\emptyset_m$ the work function is, therefore, defined as the energy that must be supplied to an electron with an energy E_{Fm} (the metal Fermi level) in order for the electron to be ejected from the metal.

Similarly, the work function of the semiconductor is the energy required to extract an electron located at its Fermi level E_{Fsc}

We know that in a semiconductor some electrons have an energy higher than E_{Fsc} these can be found in the conduction band, and their energy is approximately equal to E_c .The energy needed to extract an electron from the conduction band into a vacuum is called the "electron affinity", and noted $q\chi$. In this Section we will consider an N-type semiconductor and a metal such that $E_{Fm} < E_{FSc}$.

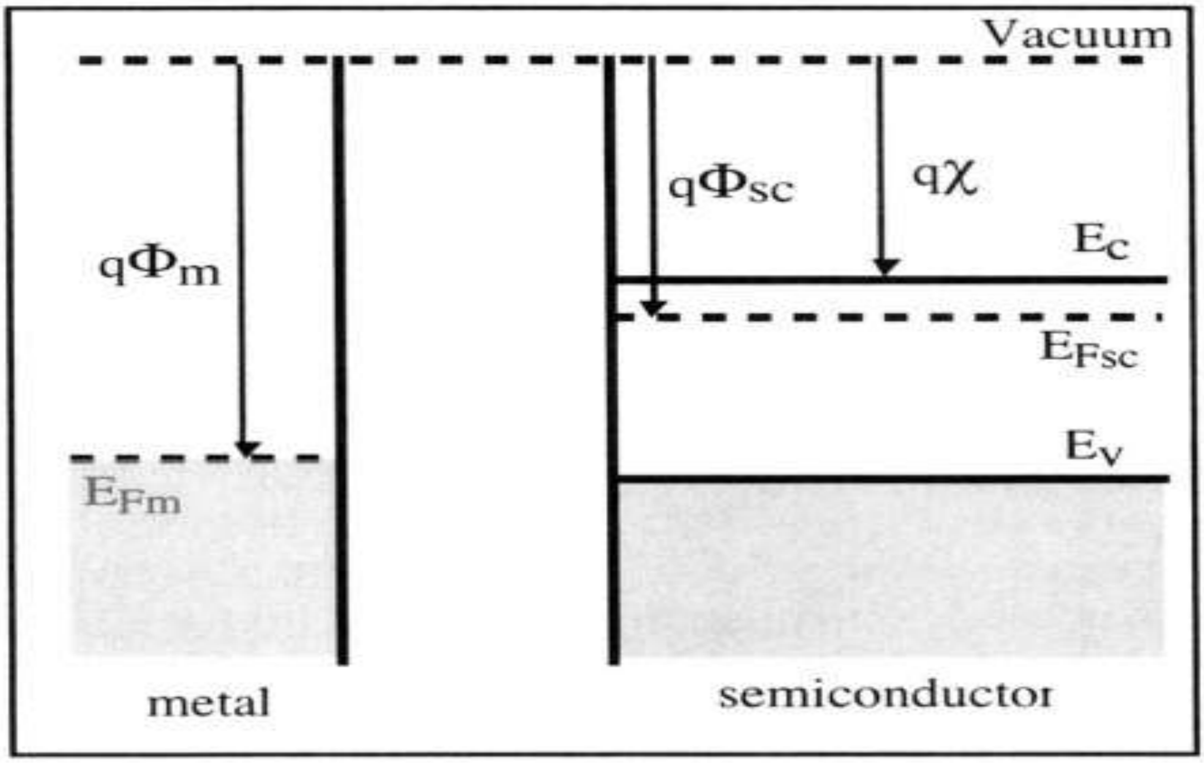


Figure (2) energy bands in a metal and a semiconductor

When the metal is contacted with the semiconductor as shown in figure (3) the Fermi levels align and thermodynamic equilibrium is established through the transfer of electrons from the semiconductor conduction band into the metal, since $\boldsymbol{E_c < E_{Fm}}$ .These electrons "leave behind" positively charged donor impurity atoms in the semiconductor. A space-charge region corresponding to the zone depleted of electrons, is, therefore, formed in the semiconductor near the interface with the metal. The width of this depletion region is noted W_o .

Because of the alignment of the Fermi levels and the presence of a depletion region the band bending in the semiconductor is equal to:

$$\boldsymbol{qV_i = q(\emptyset_m - \emptyset_s)}$$

This bending corresponds to a potential barrier V_i, which prevents further electrons from migrating into the metal. Electrons in the metal, on the other hand, see a potential barrier $\emptyset_b$, having an amplitude equal to:

$$\boldsymbol{q\emptyset_b = q(\emptyset_m - \chi) = qV_i + (E_c - E_F)}$$

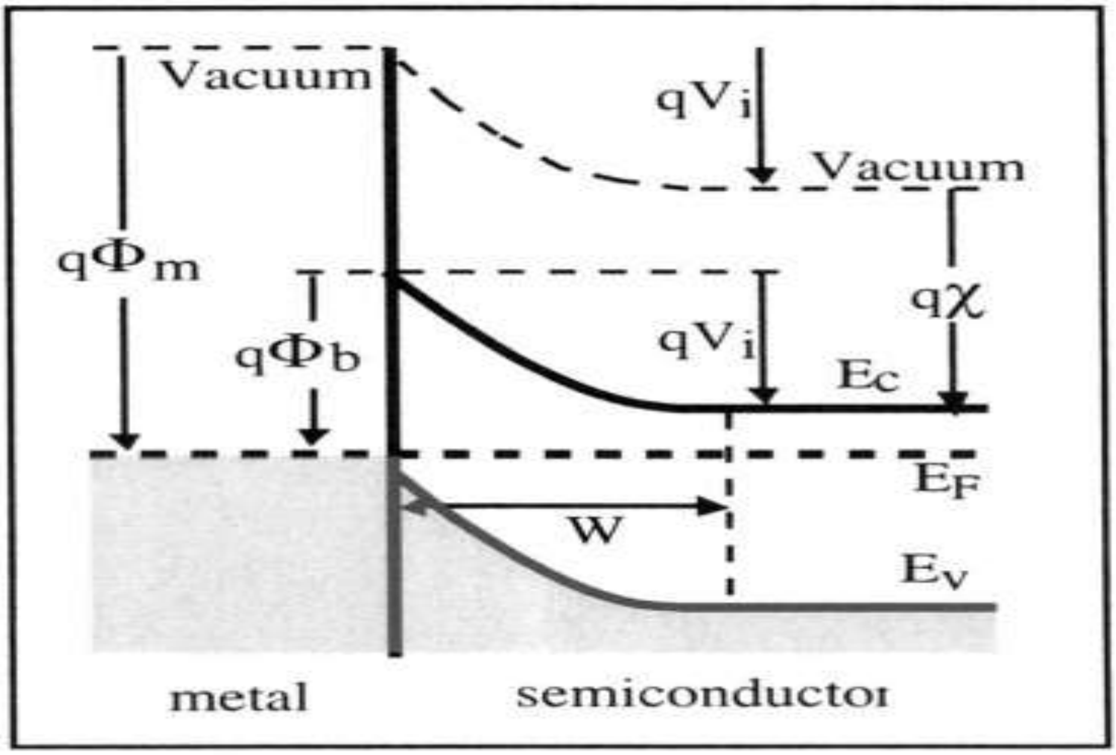


Figure (3) energy band diagram of the Schottky contact

At room temperature these potential barriers are significantly larger than kT/q and only a few electrons possess sufficient energy to overcome them. The current resulting from electrons from the semiconductor overcoming the barrier and migrating into the metal.

At thermodynamic equilibrium and in the absence of any external bias the current is exactly balanced by a current of electrons flowing from the metal into the semiconductor.

3. Ohmic contact

An ohmic contact is a non-rectifying contact. The current-voltage characteristics of the contact should obey Ohm's law $V=IR$ and the resistance of the contact should be as low as possible. Consider the contact between the metal and the semiconductor shown in Figure (4). In this particular example $\mathbf{E_{FM}<E_F}$ such that the energy bands of the N-type semiconductor are bent downwards near the contact. The magnitude of the band bending and its extension into the semiconductor are very small. As a result there is virtually no potential barrier between the metal and the semiconductor and electrons can flow freely through the contact. Such a contact is ohmic.

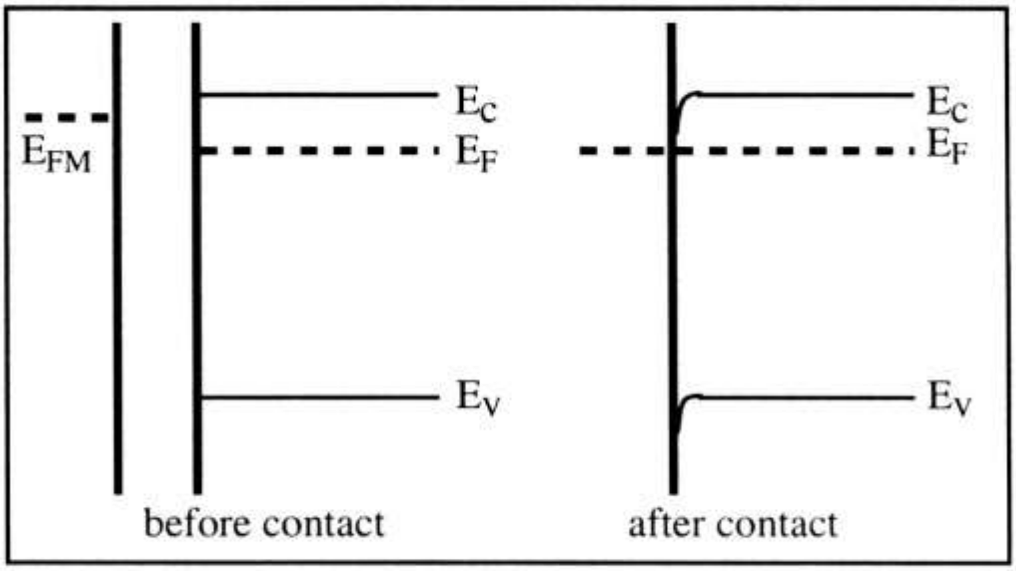


Figure (4) energy bands of Ohmic contact

4. I-V characteristics of schottky diode

The I-V (Current -Voltage) characteristics of schottky diode is shown in the below figure (5). The vertical line in the below figure represents the current flow in the schottky diode and the horizontal line represents the voltage applied across the schottky diode.

The V-I characteristics of schottky diode is almost similar to the P-N junction diode. However, the forward voltage drop of schottky diode is very low as compared to the P-N junction diode

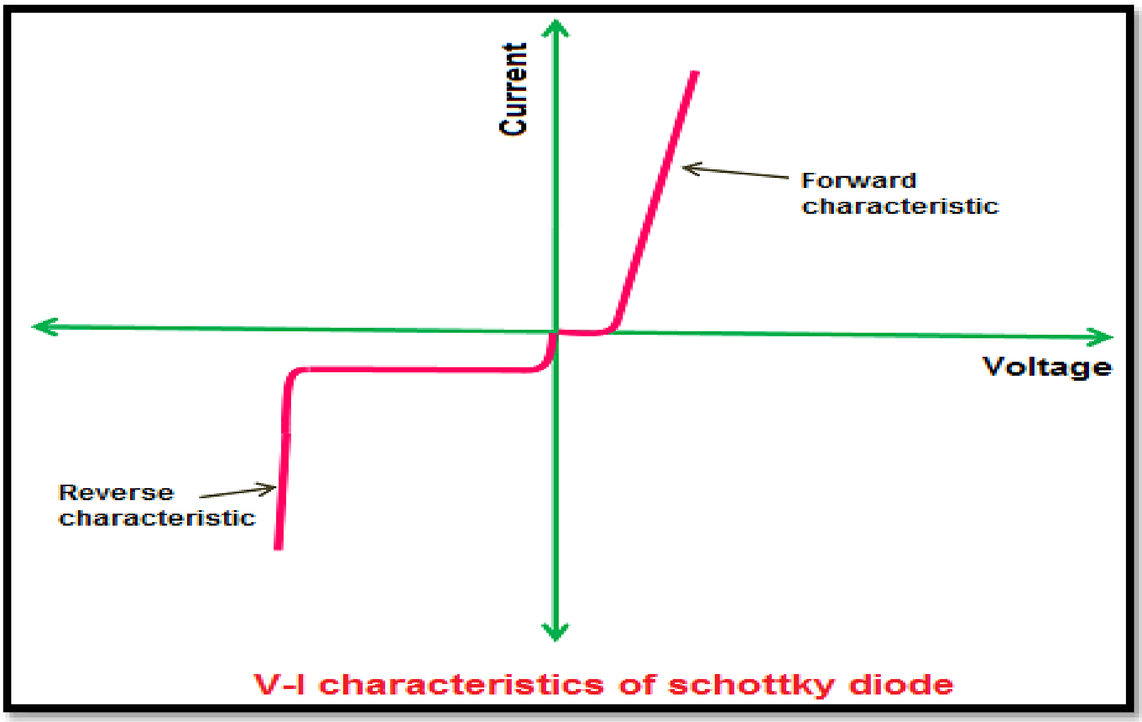


Figure (5) V-I characteristics of schottky diode

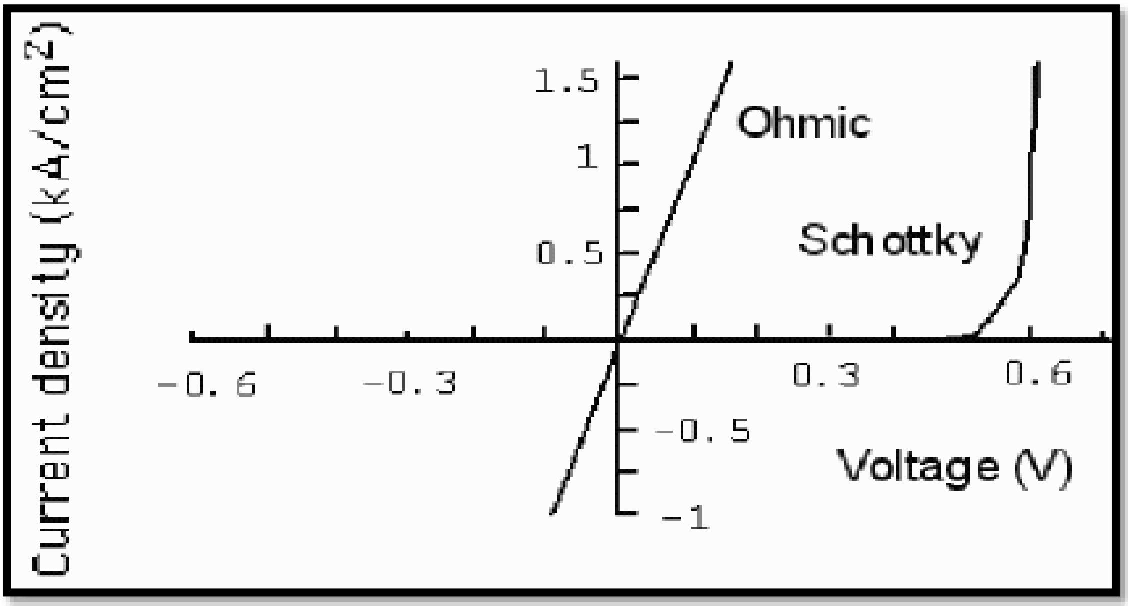


Figure (6) Current-voltage characteristics of ohmic and Schottky barrier metal-semiconductor contacts to GaAs.

5. Difference between schottky diode and P-N junction diode

The main difference between schottky diode and p-n junction diode is as follows:

-The **forward voltage drop** of schottky diode is 0.2 to 0.3 volts whereas the forward voltage drop of silicon P-N junction diode is 0.6 to 0.7 volts.

-If the **forward bias voltage** is greater than 0.2 or 0.3 volts, electric current starts flowing through the schottky diode.

-In schottky diode, the **reverse saturation current** occurs at a very low voltage as compared to the silicon diode

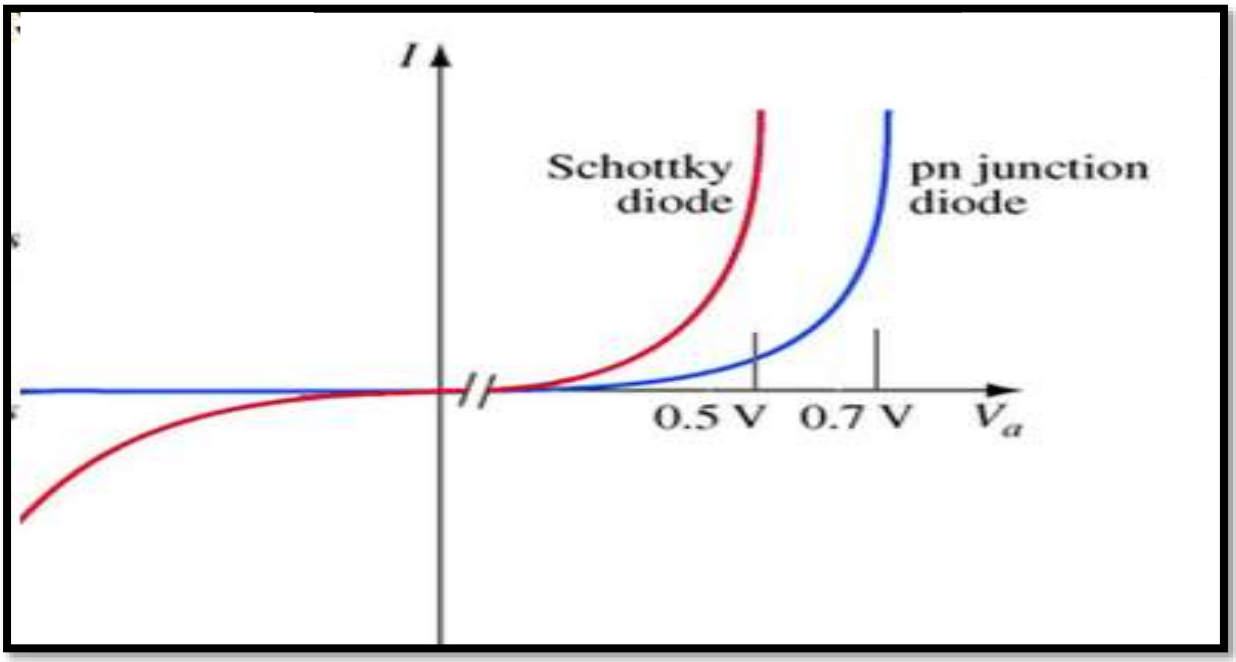


Figure (7) Current-voltage characteristics of PN jnction and Schottky barrier metal-semiconductor contacts.

Lec. (8)

Continuation of lectures 6 and 7.

Compare Schottky barrier diode and PN junction diode

Schottky Diode	**PN Junction Diode**
Forward current mechanism majority carrier transport.	Forward current mechanism due to diffusion currents, i.e. minority carrier transport.
Reverse current results from majority carriers that overcome the barrier. This is less temperature dependent than for standard PN junction.	Reverse current results from the minority carriers diffusing through the depletion layer. It has a strong temperature dependence.
Turn on voltage small - around 0.2 V.	Turn on voltage large - around 0.7 V.
Metal-semiconductor contact	semiconductor -semiconductor contact

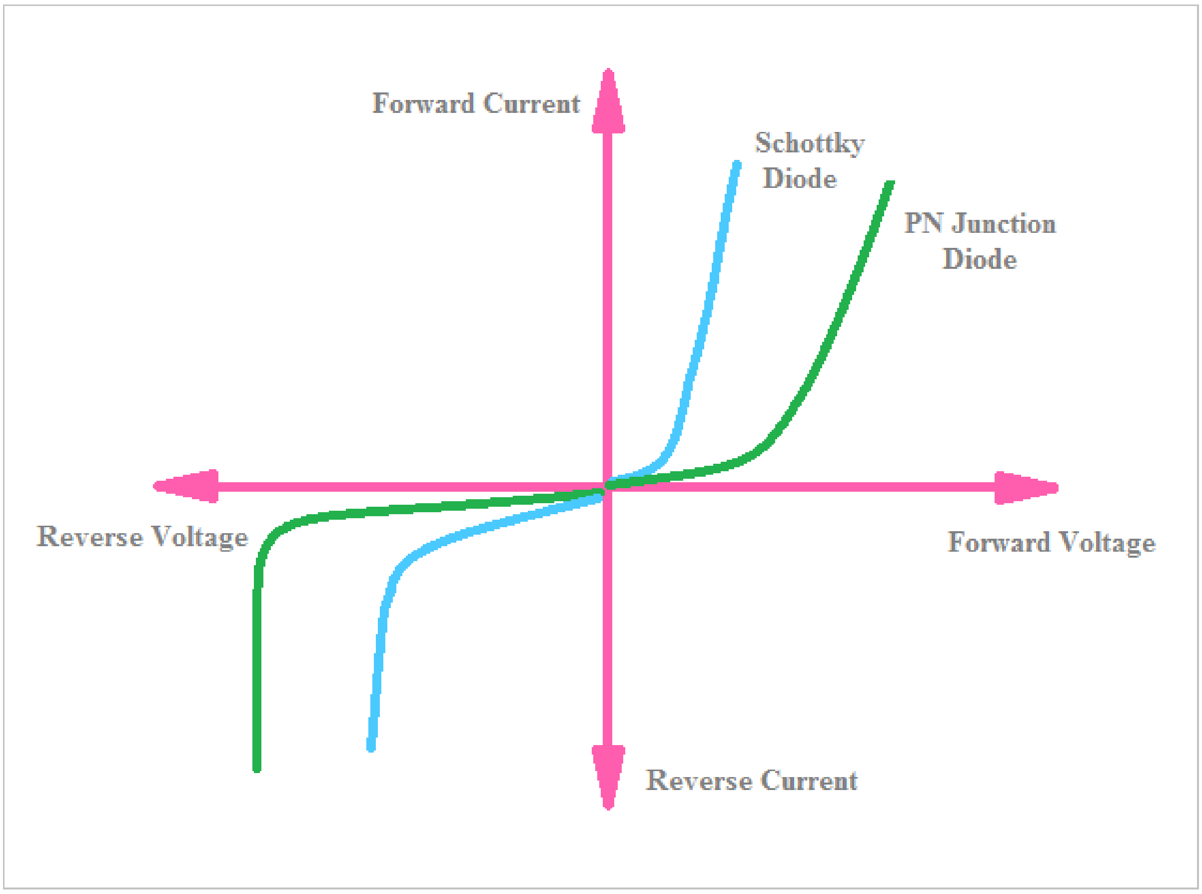


Figure (1) Current-voltage characteristics of PN jnction and Schottky barrier metal-semiconductor contacts.

Define Depletion Region?

The region around the junction is completely ionized on formation of p-n junction. As a result, there are no free electrons on the n-side nor the holes on the p-side. Since the region around the junction is depleted of mobile charges, it is called the depletion region.

Define Breakdown voltage of A P-n Junction Diode?

Is defined as the reverse voltage at which p-n junction breaks down with sudden rise with reverse current.

Define Cut-in Voltage of A P-n Junction Diode?

The forward voltage, at which the current through the p-n junction starts increasing rapidly, is called the cut-in voltage.

Define p-n junction diode?

P-n junction diode is the two terminal device, which allows the electric current in one direction and blocks in another direction.

List various applications of diodes?

The various applications of diodes include computers, mobile phones, radios, television, and so on.

Define zero bias p-n junction diode?

The p-n junction diode in which no voltage is applied is called zero bias p-n junction diode.

What is the meaning of Ohmic contact?

The Ohmic contact is a low resistance junction (non-rectifying) provides current conduction from metal to semiconductor and vice versa. Theoretically speaking the current should increase/ decrease linearly with the applied voltage.

Questions for students

What differences between Ohmic and schottky contact?

What happens to the depletion region when P -N junction is connected to an external voltage?

Define barrier voltage?

Barrier voltage is the voltage or electric field build near the p-n junction, which prevents the electric current through the semiconductor.

Define biasing of diode?

The process of applying voltage across the p-n junction diode is called biasing of diode.

Lec (9): A.C Conductivity

1: A.C Conductivity

Information about the nature of the conduction mechanism in material can be obtained from a.c conductivity. The electrical conductivity is measured as a function of the frequency (ω) where ω=2πf which is the angular frequency and f is the frequency of an alternating electric field

$$\sigma(\omega) = A\omega^s \qquad \ldots\ldots\ldots\ldots \quad (1)$$

where A is the multiplicity factor, s is the exponent factor and ω is the angular frequency.

The value of s is less than one if A & s are temperature independent, but if they are temperature dependent, s will equal unity at low temperature.

So the total conductivity $\sigma_{tot}(\omega)$ at particular frequency is given by.

$$\sigma_{tot}(\omega) = \sigma_{dc} + A\omega^s \qquad \ldots\ldots\ldots\ldots \quad (2)$$

where $\sigma_{d.c}$ is the dc conductivity at zero frequency.

Figure (1) reveals the ac-conductivity versus angular frequency (ω). Region (a) occurs at a very low frequency which is attributed to electrode polarization. Region (b) is due to the dc conductivity. Dispersion (c) is due to high frequency and take the power law form (ω^s).This dispersion occurs at frequency larger than ($1/\tau$), (where τ is the relaxation time).The difference between ac and dc conductivity is not because they have different experimental results only but also because they use different models to analyze their data.

According to equation (2) $\sigma_{(\omega)}$ dominates at high frequencies or low temperatures while σ_{dc} dominate at low frequencies or high temperatures.
It is found that the temperature dependence of $\sigma\,(\omega)$ is less than that for $\sigma_{d.c}$. This means that dc-activation energy is always greater than for ac-conductivity. There are several models that had been proposed for ac-conductivity which explain the experimental data for amorphous semiconductors and chalcogenide. These models are briefly reviewed.

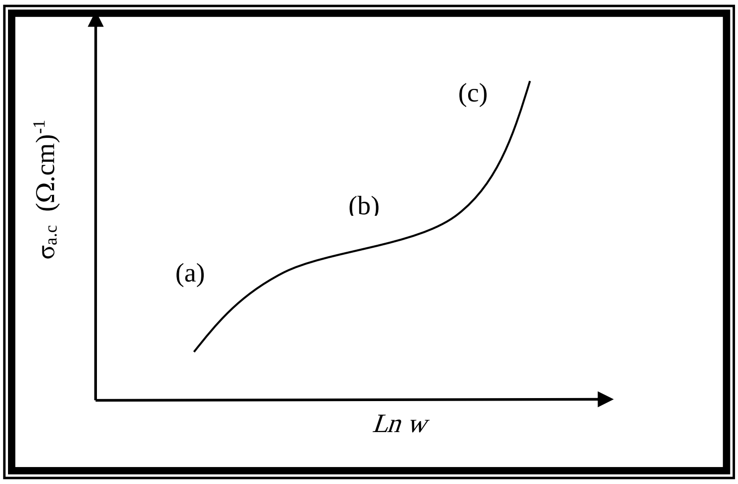


Figure (1): The variation of total conductivity v angular frequency **[105].**

2: Models of A.C Conductivity:

2.1 Quantum Mechanical Tunneling model (QMT):

Austen and Mott 1969, Pollak 1979 assumed that in the (QMT) model carrier motion occurs between states close to the Fermi level. This model is widely used for deep state within the energy gap.The ac conductivity for (QMT) is given by:

$$\sigma(w)=\frac{Cq^2K_BT}{\alpha N^2(E_f)\omega R_\omega^4} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where C is a constant and equals ($\pi^2/4$), N (E$_f$) is the density of states within which conduction takes place.

R$_\omega$ is the tunneling distance and is given by:

$$R_\omega = \frac{1}{2\alpha Ln(1/\omega\tau_\circ)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots... (4)$$

where α is the decay of localized states wave function. $\sigma(\omega)$ is predicated by equation (3) and can be written as a power law (equation). The exponent (S) will then be:

$$s = \frac{dLn\sigma(\omega)}{dLn(\omega)} \quad .. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Then:

$$s = 1 - \frac{4}{Ln(\omega\tau_\circ)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Note that in this model the exponent (s) is temperature independent but it is frequency dependent [102].

2.2 Small Polaron Tunneling (SP):

A small polaron may be formed in a covalent solid. The addition of charge carrier to a sit causes a large degree of local lattice distortion that the total energy (electron + distortion) of the system is lowered by an amount (ω_p), the polaron energy.

The ac-conductivity may be represented by equation (3) and the exponent (s) may be given as follows:

$$s = 1 + \frac{1}{[\ln(\omega\tau_\circ + \omega_H / K_B T)]} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where (ω_H) is the vibration frequency describing the lattice distortion equation (7) it predicts that (s) increases as (T) increases.

2.3 Large Polaron Tunneling (LP):

Elliott (1987) reports that when the polaron energy is derived from polarization changes in the deformed lattice, the resultant excitation is called a large polaron because of a long coulomb interaction.

The ac-conductivity for this overlapping large polaron model is given by:

$$\sigma(\omega)=\frac{\pi^{4}}{12}N^{2}(E)(K_{B}T)^{2}q^{2}\frac{\omega R_{w}^{4}}{\left(2\alpha K_{B}T+\omega_{H_{o}}r_{\circ}\middle/R_{\xi}^{2}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (8)$$

Where (R_ξ) is the hopping length at a frequency (ω) and r_o is polaron radius.

This overlapping-polaron model predicts that (S) should be both temperature and frequency dependent.

2.4Correlated Barrier Hopping Model (CBH) :

Primarily, this mechanism had been first explained by Pike (1972). Elliott (1977) [112] followed Pike and developed a new model for ac-conduction for chalcogenide material based on Pick’s concepts as Correlated Barrier Hopping (CBH). In this model the electrons hop over the potential barriers between two sites see Figure (2)

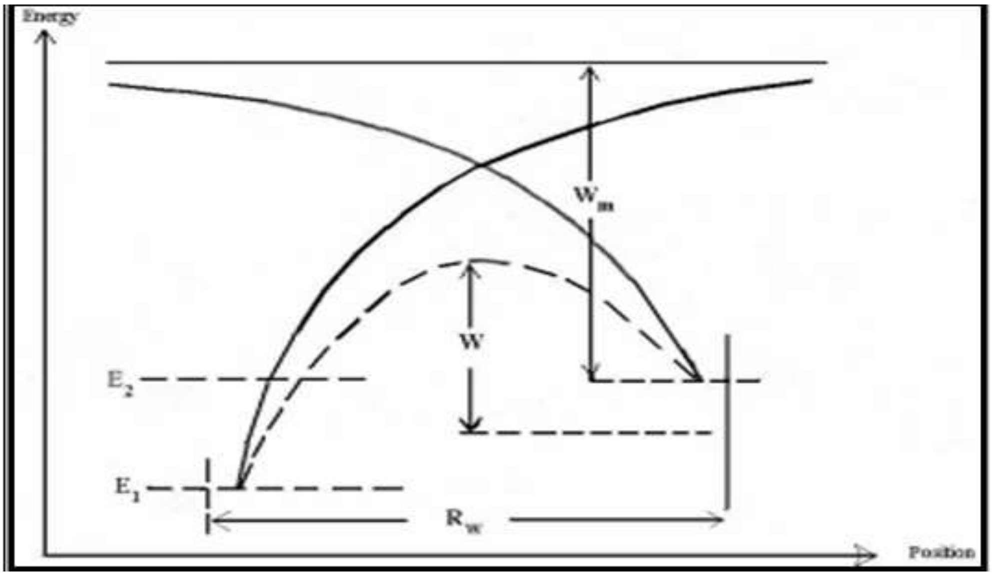


Figure (2): Two level systems with coulomb like potential of the barrier height separated between two charge carriers in case of (CBH) [112].

If we consider a single electron hopping positive defect center, then the potential barrier will be reduced by the coulomb interaction. The ac-conductivity can be evaluated for this mechanism and for the narrow-band limit ($\Delta << K_B T$) in which all centers are degenerated and where two electrons are assumed to hop simultaneously between randomly situated defect centers. The result is:

$$\sigma(\omega) = \frac{\pi^3}{12} N^2 \varepsilon\varepsilon_\circ R_\omega^6 \qquad (9)$$

where (ε) is the dielectric constant, ($\varepsilon_\circ$) is permittivity of space concentration. The hopping distance during frequency is given by:

$$R\omega = \frac{2q^2}{\left[\pi\varepsilon\varepsilon_\circ\left[\omega_m + K_B T \ln(\omega\tau_\circ)\right]\right]} \qquad (10)$$

where (ω_m) is the maximum barrier height. The frequency exponent for this model can be:

$$s = 1 - \frac{6K_B T}{\omega_m + K_B T \ln(\omega\tau_\circ)} \qquad (11)$$

(s) is predicted to decrease from unity with increasing temperature. The different characters of exponent (s) are dependent on frequency and temperature, as shown in Figure (3).

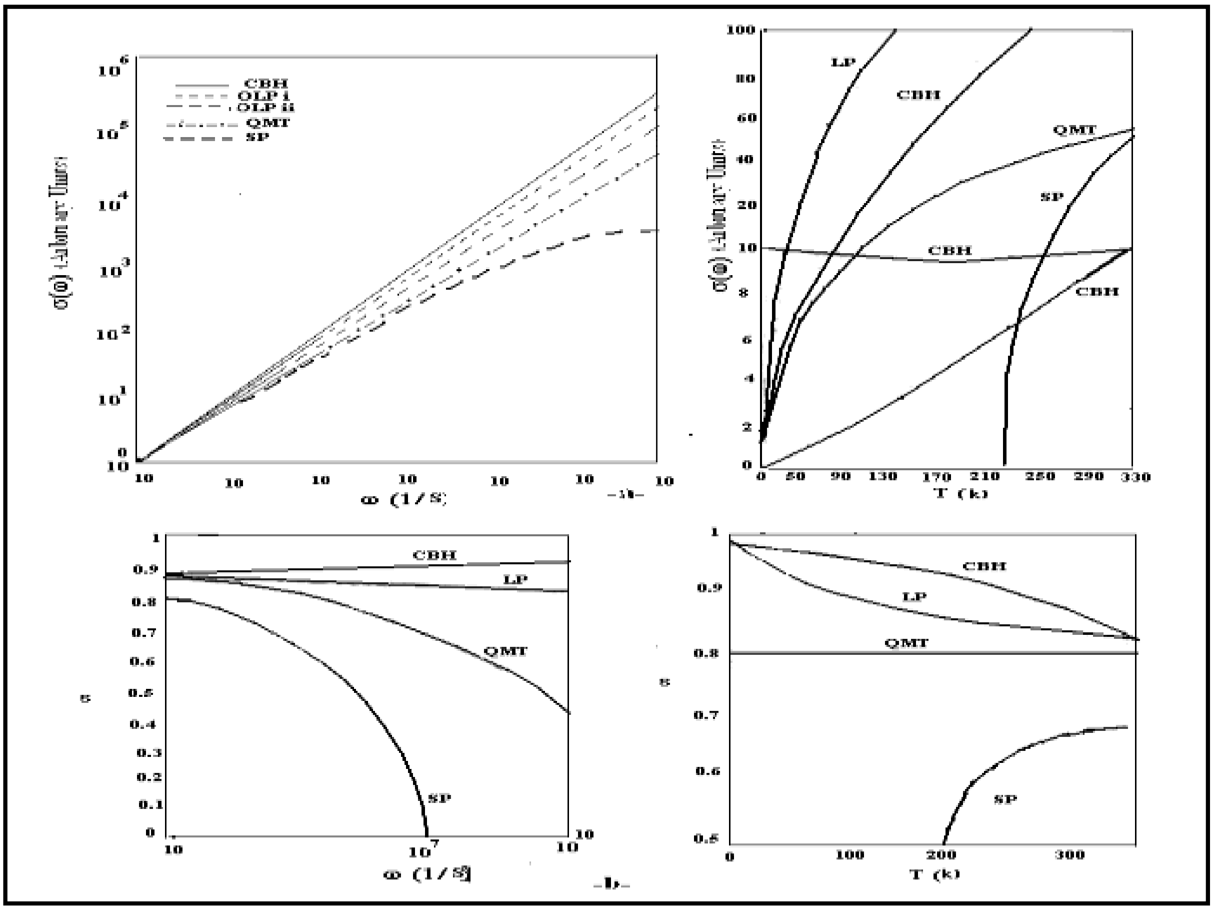


Figure (3): a- Frequency dependence of frequency exponent (S).b- Temperature dependence of frequency exponent (S) in case of CBH, QMT, SP and LP[102].

The well-known method of displaying Debye type relaxation is by drawing

Lec (10)

Electrical properties of Heterojunction

1. Electrical properties of Heterojunctions

The electrical properties which explain the characterizes of a hetrojunction are the capacitance-voltage and current-voltage charaterstics. In fact, these properties which not only yield information regarding the band structure of a hererojunction (i.e. the type of heterojunction and built – in junction potential) but also enable one to determine its device usefulness. These properties of a heterojunction depend strongly on the method of formation and the doping levels of the two semiconductors forming it.

2. Capacitance –voltage characteristics

Capacitance versus voltage, referred to as C-V measurements can be used to study the most basic properties of semiconductors devices, for example to analyze the depletion potential region and the charge distribution in heterojunction.

3. Anisotype Heterojunction

For an abrupt anisotype heterojunction, Anderson shows that the junction capacitance per unit area can be written as:

$$\frac{1}{C^2}=\left[\frac{2(\varepsilon_p N_p+\varepsilon_n N_n)}{qN_p N_n \varepsilon_p \varepsilon_n}\right]\cdot(V_D-V) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where N_n and N_p are the donor and acceptor concentrations, ε_p and ε_n are the dielectric constants of n and p type semiconductors respectively, V_D is the built-in junction potential, and V_a is the applied voltage. It can be seen from this expression that a plot of $1/C^2$ against applied reverse voltage V_a is linear and its Extrapolated to intercept the voltage axis gives the built-in junction potential V_D as shown in Figure (1), and the linear variation of the experimental curve C^2 versus V gives an indication of the presence of abrupt hetrojunction. The width of the depletion region can be calculated by:

$$W = \varepsilon_s/C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where C_0 is the capacitance at zero biasing voltage, and $\varepsilon_s=\frac{\varepsilon n\ \varepsilon p}{\varepsilon n+\ \varepsilon p}$ where ε_p and ε_n are the dielectric constant for ZnS and Si respectively.

The charge-carrier density N_d is calculated by the equation:

$$N_d = \frac{2}{q\varepsilon s}\left[\frac{1}{\frac{d\left(\frac{A}{C}\right)^2}{dV}}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where the ε_s is the semiconductor permittivity and the A is the active area.

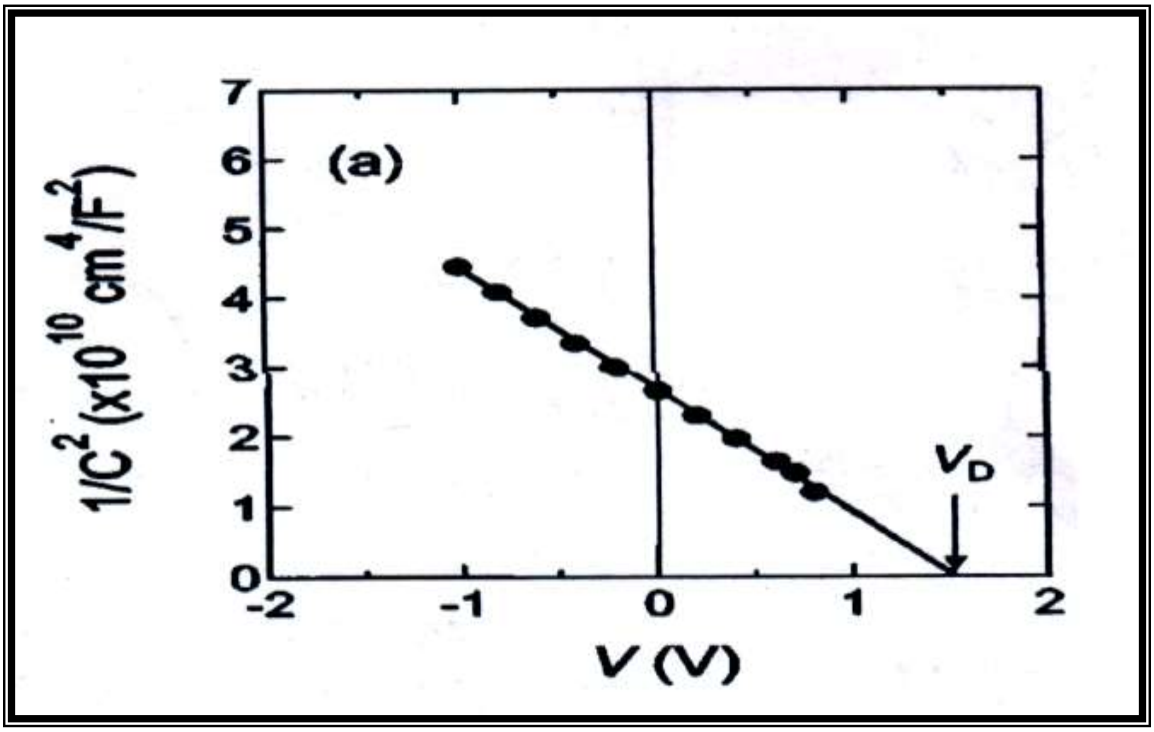


Figure (1): The capacitance- voltage characteristic for hetrojunction

4. Current-Voltage Characteristics

The current–voltage characteristics, are studied to explain the electrical conduction, and used to determine the built–in junction potential and energy discontinuities in the conduction and valence band edges at the interface of a heterojunction. Depending on the polarity of the applied voltage, these characteristics can be classified as forward or reverse bias.