
Semester-I

19BECS141 Semi- Conductor Physics 7H-5C

(Theory & Lab.)

Instruction Hours/week: L:3 T:1 P:3 **Marks:** Internal**:40** External**:60** Total**:100**

End Semester Exam:3 Hours

(i) Theory

Course Objectives

- To understand the fundamentals of quantum physics and their applications.
- To inculcate the characteristics of electronic materials through basics.
- To divulge knowledge on the basics of semiconducting materials for diode applications.
- To introduce the features of light interaction with semiconductor for optoelectronic applications.
- To impart the basic knowledge of new semiconducting materials for engineering applications.

Course Outcomes

Upon completion of this course, the students will be able to

1. Develop the idea of quantum mechanics through applications.
2. Apply the concepts of quantum theory for various methodologies.
3. Explain the basic ideas of classical electron theory and energy band structures.
4. Illustrate the basics of semiconductor physics and its applications in various electronic devices.
5. Identify the basic properties and functioning of optical materials for optoelectronics.
6. Summarize the features of low dimensional materials for engineering applications.

Unit 1 - Quantum Mechanics

Introduction to quantum theory, merits of quantum theory, black body radiation, laws of blackbody radiation, dual nature of matter and radiation, de Broglie wavelength, uncertainty principle, Schrodinger’s wave equation, time dependent and time independent equations, physical significance of wave function, particle in one dimensional box , degenerate and non-degenerate states, scanning electron microscope.

Unit 2 - Electronic materials

Free electron theory, energy band diagrams, Bloch theorem -Kronig-Penny model (to introduce origin of band gap), Energy bands in solids, Direct and indirect bandgaps, Types of electronic materials: metals, semiconductors and insulators, density of states, occupation probability, Fermi level, effective mass, phonons.

Unit 3 - Semiconductors

Intrinsic and extrinsic semiconductors, Dependence of Fermi level on carrier-concentration and temperature (equilibrium carrier statistics), carrier generation and recombination, Carrier transport: diffusion and drift, p-n junction, metal-semiconductor junction (Ohmic and Schottky).

Unit 4 - Light-semiconductor interaction

Optical transitions in bulk semiconductors: absorption, emission and scattering - Transition rates (Fermi's golden rule), optical loss and gain; photovoltaic effect, exciton, Drude model, LED, solar cell, photo diode.

Unit 5 - Engineered semiconductor materials

Density of states in 2D, 1D and 0D (qualitatively), practical examples of low-dimensional systems such as quantum wells, wires, and dots: design, fabrication, methods of fabrication (CVD, PVD), Coulomb blockade, single electron transistor, Giant Magneto Resistance, Spintronics.

SUGGESTED READINGS

1. Bhattacharya D.K. &PoonamT.,Engineering Physics, Oxford University Press, (2015)
2. Ganesan.S and Baskar.T,(2015)Engineering Physics I, GEMS Publisher, Coimbatore-641001
3. J. Singh, (2095)Semiconductor Optoelectronics: Physics and Technology, McGraw-Hill Inc.
4. B. E. A. Saleh and M. C. Teich,(2007) Fundamentals of Photonics, John Wiley & Sons, Inc.,
5. S. M. Sze, (2008)Semiconductor Devices: Physics and Technology, Wiley
6. A. Yariv and P. Yeh,(2007) Photonics: Optical Electronics in Modern Communications, Oxford University Press, New York

KARPAGAM ACADEMY OF HIGHER EDUCATION
(Deemed to be University Established under Section 3 of UGC Act 1956)
COIMBATORE – 641021

FACULTY OF ENGINEERING
DEPARTMENT OF SCIENCE AND HUMANITIES

LECTURE PLAN

Subject : SEMICONDUCTOR PHYSICS
Code : 19BECS141

Unit No.	List of Topics	No. of Hours
UNIT I	**QuantumMechanics**	
	Introduction to quantum theory and its merits	1
	Black body radiation and its laws	1
	Dual nature of matter and radiation	1
	De Broglie wavelength , Uncertainty principle	1
	Schrödinger's wave equation – time dependent equation	1
	Time independent equations, Physical significance of wave function	1
	Tutorial	1
	Particle in one dimensional box	1
	Degenerate and non degenerate states, Scanning electron microscope	1
	Tutorial	1
	TOTAL	10
UNIT – II	**Electronic materials**	
	Free electron theory, energy band diagrams	1
	Bloch theorem	1
	Kronig-Penny model (to introduce origin of bandgap)	1
	Energy bands in solids, Direct and indirect bandgaps	1
	Tutorial	1
	Types of electronic materials :metals, semiconductors & insulators	1
	Density of states	1
	Occupation probability , Fermi level	1
	Effective mass, Phonons	1
	Tutorial	1
	TOTAL	10
UNIT – III	**Semiconductors**	
	Introduction	1
	Intrinsic and extrinsic semiconductors	1
	Dependence of Fermi level on carrier- concentration and temperature (Equilibrium carrier statistics)	2
	Tutorial	1
	Carrier generation and Recombination	1
	Carrier transport: diffusion and drift	1
	P-N junction	1

	Metal-semiconductor junction (Ohmic and Schottky)	1
	Tutorial	1
	TOTAL	10
UNIT – IV	**Light-semiconductor interaction**	
	Optical transitions in bulk semiconductor:Absorption, emission and scattering	1
	Transition rates(Fermi's golden rule)	1
	Optical loss and gain	1
	Photovoltaic effect	1
	Tutorial	1
	Exciton , Drude model	1
	LED	1
	Solar cell	1
	Photo diode	1
	Tutorial	1
	TOTAL	10
UNIT – V	**Engineered semiconductor materials**	
	Density of states in 2d,1dand 0d (qualitatively)	1
	Practical examples of low-dimensional systems such as quantum wells, wires ,and dots	1
	Design	1
	Fabrication	1
	Tutorial	1
	Methods of fabrication (CVD, PVD)	1
	Coulomb blockade	1
	Single Electron Transistor	1
	Giant Magneto Resistance, Spintronics	1
	Tutorial	1
	TOTAL	10
	TOTAL NO OF HOURS	50

TEXT BOOK& REFERENCES:

S.NO	AUTHOR(S) NAME	TITLE OFTHEBOOK	PUBLISHER	YEAROF PUBLICATION
1	D.K. Bhattacharya and Poonam T	Engineering Physics	Oxford University Press, New York	2015
2	Ganesan.Sand Baskar.T	Engineering Physics I	GEMS Publisher, Coimbatore-641 001	2015
3	J. Singh	Semiconductor Optoelectronics: Physics and Technology	McGraw-HillInc.	1995
4	B. E. A. Saleh and M. C. Teich	Fundamentals of Photonics	JohnWiley&Sons, Inc.,	2007
5	S. M. Sze	Semiconductor Devices: Physics and Technology	Wiley	2008
6	A. Yariv and P. Yeh	Photonics: Optical Electronics in Modern Communications	Oxford University Press, New York	2007

WEBSITES:

1. www.nptel.ac.in
2. www.ocw.mit.edu

STAFF IN-CHARGE

HOD
6/8/19.

UNIT I

QUANTUM MECHANICS

INTRODUCTION TO QUANTUM THEORY

Laws of thermodynamics and classical laws of electricity and magnetism provide the basis for explanation of all phenomena in classical physics. It was general belief of the scientists that these laws would suffice to account for any subsequent discovered phenomena. Classical mechanics successfully explained the motion of the objects, which are directly observable. When the objects are not observable, then the concept of classical mechanics cannot be applied.

The phenomena in the realm of the atoms, nuclei and elementary particles are commonly referred to as quantum phenomena and subject matter containing all these phenomena constitutes what is known as Quantum Physics.

Inadequacy of classical mechanics:

According to the classical mechanics, if we consider the case of an electron moving round the nucleus, its energy should decrease (because the accelerated charged particle loses energy in the form of electromagnetic waves) and therefore its velocity should decrease continuously. The ultimate result is that the electron comes closer and closer to the nucleus until it collapses. This shows the instability of the atom; it is in contradiction to the observed fact of the stability of an atom. Thus the classical mechanics fails to explain the stability of an atom.

The classical mechanics also failed to explain the spectrum of the hydrogen atom. According to the classical theory, the excited atoms of hydrogen emit electromagnetic radiations of all wavelengths continuously, while it is observed that they emit the radiation of certain wavelengths only.

Difficulties with classical theories of Black Body Radiation and Origin of Quantum Theory of Radiation:

We know that when bodies radiate energy, their temperature falls until the loss of energy is compensated by an external source. In case of heat radiation, we can obtain the thermal equilibrium by maintaining the body at a fixed temperature with the help of some heat-giving source. In this case the body gives as much radiation as it receives. If the body absorbs all the incident radiation, then it is called Black Body radiation. In actual practice, it is not possible to realize a perfectly black body, but an enclosure provided with a small opening serves the purpose because the radiation entering the enclosure will be reflected many times inside the enclosure and ultimately absorbed.

BLACK BODY RADIATION

Perfect black body:

A perfect black body is one which absorbs and emits in all the radiations (corresponding to all wavelengths) that fall on it. The radiation given out by a perfect black body is called Black body radiation.

Kirchoff's law:

Ratio of emissive power to the coefficient of absorption of any given wavelength is the same for all bodies at a given temperature and is equal to the emissive power of the black body at that temperature.

$$E_\lambda = \frac{e_\lambda}{a_\lambda}$$

Experiment:

In practice a perfect black body is not available. Therefore let us consider a hollow sphere coated with lamp black on its inner surface.

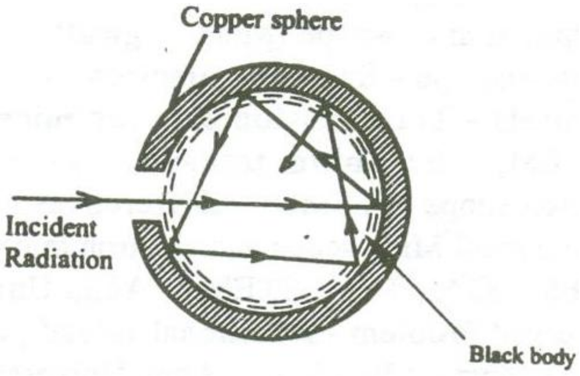


Fig 3.1

A fine hole is made for radiations to enter into the sphere as shown in the fig 3.1.

Now when the radiations are made to pass through the hole it undergoes multiple reflections and are completely absorbed. Thus the black body acts as a perfect absorber. Now when the black body is placed in a temperature bath of fixed temperature, the heat radiations will come out only through the hole in the sphere and not through the walls of the sphere.

Therefore, we can conclude that the radiations are emitted from the inner surface of the sphere and not from the outer surface of the sphere. Thus a perfect black body is a perfect absorber and also a perfect radiator of all wavelengths.

Energy spectrum:

When a perfect black body is allowed to emit radiations at different temperatures, then the distribution of the energy for different wavelengths at various temperatures is obtained as shown in the fig 3.2.

From figure the following results are formulated.

i. The energy distribution is not uniform for a given temperature.

ii. The intensity of radiation (E) increases with respect to the increase in wavelength at particular wavelength in becomes maximum (λ_m) and after this it starts decreasing with respect to the increase in wavelength.

iii. When the temperature is increased, the maximum wavelength (λ_m) decreases.

iv. For all the wavelengths an increase in its temperature causes increase in energy.

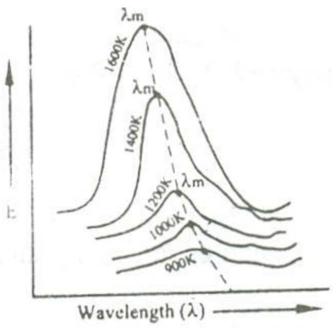


Fig 3.2

v. The total energy emitted at any particular temperature can be calculated from the area under that particular curve.

PHOTON AND ITS PROPERTIES:

According to the Quantum theory of radiation, we know that the exchange of energy values between the light radiation and particles have discrete energy values.

Photon

The discrete energy values in the form of small packets (or) bundles (or) quantas of definite frequency or wavelength are called photon. These photons are propagates like a particle like a particle but with the speed of light ($3x10^8$m/s).

Properties of photon:

- Photons are similar to that of electrons.
- We know for electrons the definite quantities are ‘e’ and ‘m’. Similarly for photons the definite quantities are ‘h’ and ‘c’.
- Photons will not have any charge. They are neutral and hence they are not affected by magnetic (or) electric fields.
- They do not ionize gases.
- The energy of the photon is given by $E = h\nu$, which varies with respect to the type of radiation frequencies.
- The momentum of photon is given by $p = mc$, where ‘m’ is the mass of the photon and ‘c’ is the velocity of light.
- The relation between energy and the momentum of the photon is given by $E = pc$.

  [i.e., $E = mc^2 = mc(c) = pc$].

DUAL NATURE OF RADIATION (LIGHT) AND MATTER (PARTICLES) – MATTER WAVES

De- Broglie concept of dual nature:

The universe is made of radiation (light) and matter (particles). The light exhibits the dual nature (ie.) it can behave both a wave (interference, diffraction, phenomenon) and as a particle (Compton Effect, photo electric effect etc.)

Since the nature loves symmetry, in 1923 Louis debroglie suggested that an electron or any other material particle must exhibit wave like properties in addition to particle nature.

The waves associated with a material particle are called as matter waves.

De-Broglie wavelength:

From the theory of light, considering a photon as a particle the total energy of the photon is given by

$$E = mc^2 \qquad \text{---(1)}$$

Where, 'm' is the mass of the particle and 'c' is the velocity of light.

Considering the photon as a wave, the total energy is given by

$$E = h\nu \qquad \text{--- (2)}$$

Where, 'h' is the Planck's constant and 'ν' is the frequency of the radiation.

From equations (1) and (2)

$$E = mc^2 = h\nu \qquad \text{--- (3)}$$

We know Momentum = Mass × velocity

$$p = mc$$

∴ Equation (3) becomes $h\nu = pc$

$$p = \frac{h\nu}{c}$$

Since $\lambda = \frac{c}{\nu}$ we can write $p = \frac{h}{\lambda}$

(or) The wavelength of a photon $\lambda = \frac{h}{p}$ --- (4)

de-Broglie suggested that the equation 3 can be applied both for photons and material particles. If m is the mass of the particle and v is the velocity the particle, then

Momentum $p = mv$

∴ de-Broglie wavelength $\lambda = \frac{h}{mv}$ --- (5)

De-Broglie wavelength in terms of energy:

We know kinetic energy $E = \frac{1}{2}mv^2$

Multiplying by 'm' on both sides we get

$$Em = \frac{1}{2}m^2v^2$$

$$2Em = m^2v^2$$

(or) $mv = \sqrt{2mE}$

∴ de-Broglie wavelength $\lambda = \frac{h}{\sqrt{2mE}}$ --- (6)

De-Broglie wavelength in terms of Voltage

If a charged particle of charge 'e' is accelerated through a potential difference 'v', Then the Kinetic Energy of the particle = $\frac{1}{2}mv^2$ --- (7)

Also we know energy = eV --- (8)

Equating (7) and (8), we get,

$$\frac{1}{2}mv^2 = eV$$

Multiplying by 'm' on both sides we get

$$\frac{1}{2}m^2v^2 = meV$$

$$m^2v^2 = 2meV$$

(or) $mv = \sqrt{2meV}$ --- (9)

Substituting equation (9) in equation (5), we get

∴ de-Broglie wavelength $\lambda = \frac{h}{\sqrt{2meV}}$ --- (10)

De-Broglie wavelength in terms of Temperature:

When a particle like neutron is in thermal equilibrium at temperature T, then they possess Maxwell distribution of velocities.

∴ Their kinetic energy $E_k = \frac{1}{2}mv_{rms}^2$ --- (11)

Where, 'v_{rms}' is the Root mean square velocity of the particle.

Also, we know energy = $\frac{3}{2}K_BT$ --- (12)

Where, 'K_B' is the Boltzmann constant.

Equating (11) and (12) we get

$$\frac{1}{2}mv^2 = \frac{3}{2}K_BT$$

Multiplying by 'm' on both sides we get

$$\frac{1}{2}m^2v^2 = \frac{3}{2}mK_BT$$

$$m^2v^2 = 3mK_BT$$

(or) $mv = \sqrt{3mK_BT}$

∴ De-Broglie wavelength $\lambda = \frac{h}{\sqrt{3mK_BT}}$

PROPERTIES OF MATTER WAVES:

- Matter waves are not electromagnetic waves.
- Matter waves are new kind of waves in which due to the motion of the charged particles, electromagnetic waves are produced.
- The wave and particle aspects cannot appear together.
- Locating the exact position of the particle in the wave is uncertain.
- Lighter particles will have high wavelength.

- Particles moving with less velocity will have high wavelength.
- The velocity of matter wave is not a constant; it depends on the velocity of the particle.
- The velocity of matter wave is greater than the velocity of light.

UNCERTAINITY PRINCIPLE

According to classical ideas, it is possible for a particle to occupy a fixed position and have a definite momentum. Hence we can predict exactly its position and momentum, at any time.

But according to quantum mechanics, there is an inherent uncertainity in the determination of the position and momentum of the particle. According to Heisenberg's principle the position and momentum of a particle cannot be determined simultaneously to any degree of accuracy.

Statement

It is impossible to determine precisely and simultaneously the values of both the position and momentum of a particle.

Example

Considering the position and momentum as a pair of physical variables. These quantiTIes are related as

$$\Delta x \Delta p \approx \frac{h}{2\pi}$$

where Δx is the error in determining position

Δp is error in determining momentum of the particle.

Similarly we have

$$\Delta E \Delta t \approx \frac{h}{2\pi}$$

$$\Delta J \Delta \theta \approx \frac{h}{2\pi}$$

where ΔE and Δt is the error in determining energy and time respectively and ΔJ and $\Delta \theta$ are the error in determining the angular momentum and angle respectively.

SCHROEDINGER WAVE EQUATION:

Schroedinger wave equation describes the wave nature of a particle in the mathematical form. It is the basic equation of motion of matter waves.

If the particle has wave properties, then there should be some sort of wave equation to describe the behavior of that particle.

Schrodinger connected the expression of de-Broglie's wavelength with the classical wave equation for a moving particle and he obtained a new wave equation

FORMS OF SCHROEDINGER WAVE EQUATION

There are two forms of Schroedinger wave equation. They are

a. Time independent wave equation

b. Time dependent wave equation

SCHROEDINGER TIME INDEPENDENT WAVE EQUATION:

Consider a wave associated with a moving particle.

Let x, y, z be the coordinates of the particle and ψ wave function for de – Broglie's waves at any given instant of time't'.

The classical differential equation for wave motion is given by

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}=\frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2} \qquad \text{--- (1)}$$

Here, 'v' is wave velocity.

The eqn (1) is written as

$$\nabla^2\psi=\frac{1}{v^2}\frac{\partial^2\psi}{\partial t^2} \qquad \text{--- (2)}$$

Where, $\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$ is a Laplacian's operator.

The solution of eqn (2) gives ψ as a periodic variations in terms of 't',

$$\psi(x, y, z, t) = \psi_0(x, y, z)\, e^{-i\omega t} \qquad \text{--- (3)}$$

Here, $\psi_0(x, y, z)$ is a function of x, y, zonly, which is the amplitude at the point considered. 'ω' is angular velocity of the wave.

Differentiating eqn (3) with respect to 't', we get

$$\frac{\partial\psi}{\partial t}=-i\omega\psi_0 e^{-i\omega t}$$

Again differentiating with respect to 't', we have

$$\frac{\partial^2\psi}{\partial t^2}=(-i\omega)(-i\omega)\psi_0 e^{-i\omega t}$$

$$\frac{\partial^2\psi}{\partial t^2}=i^2\omega^2\psi_0 e^{-i\omega t}$$

$$\frac{\partial^2\psi}{\partial t^2}=-\omega^2\psi \text{ --- (4)}$$

Where, $i^2 = -1$ and $\psi= \psi_0 e^{-i\omega t}$

Substituting eqn (4) in eqn (2), we have

$$\nabla^2\psi=-\frac{\omega^2}{v^2}\psi$$

$$\nabla^2\psi+\frac{\omega^2}{v^2}\psi\ =0 \qquad \text{--- (5)}$$

We know that angular frequency $\omega = 2\pi\nu$

$$\omega = 2\pi\frac{v}{\lambda}$$

Where, $\nu = \frac{v}{\lambda}$, ν is the frequency and v is the wave velocity

$$\frac{\omega}{v} = \frac{2\pi}{\lambda} \qquad \text{--- (6)}$$

Squaring the eqn (6) on both sides, we get

$$\frac{\omega^2}{v^2} = \frac{2^2\pi^2}{\lambda^2}$$

$$\frac{\omega^2}{v^2} = \frac{4\pi^2}{\lambda^2} \qquad \text{--- (7)}$$

Substituting eqn (7) in eqn (5), we get

$$\nabla^2\psi + \frac{4\pi^2}{\lambda^2}\psi = 0 \qquad \text{--- (8)}$$

On substituting, $\lambda = \frac{h}{mv}$ in eqn (8), we get

$$\nabla^2\psi + \frac{4\pi^2}{\left(\frac{h}{mv}\right)^2}\psi = 0$$

$$\nabla^2\psi + \frac{4\pi^2}{\frac{h^2}{m^2v^2}}\psi = 0$$

$$\nabla^2\psi + \frac{4\pi^2 m^2 v^2}{h^2}\psi = 0 \qquad \text{--- (9)}$$

If 'E' is the total energy of the particle, 'V' is potential energy and $\frac{1}{2}mv^2$ is kinetic energy, then Total energy = Potential energy + Kinetic energy

$$E = V + \frac{1}{2}mv^2$$

$$E - V = \frac{1}{2}mv^2$$

$$2\,(E - V) = mv^2$$

Multiplying by 'm' on both sides, we have

$$2m\,(E - V) = m^2v^2 \qquad \text{--- (10)}$$

Substituting eqn (10) in eqn (9), we get

$$\nabla^2\psi + \frac{4\pi^2 2m\,(E - V)}{h^2}\psi = 0$$

$$\nabla^2\psi + \frac{8\pi^2 m}{h^2}(E - V)\psi = 0 \qquad \text{--- (11)}$$

The eqn (11) is known as Schroedinger time independent wave equation.

Let us know introduce $\hbar = \frac{h}{2\pi}$ in eqn (11),

$$\hbar^2 = \frac{h^2}{2^2\pi^2}$$

$$\hbar^2 = \frac{h^2}{4\pi^2} \qquad \text{--- (12)}$$

where, 'ħ' is a reduced Planck's constant.

The eqn (11) is modified by substituting ħ,

$$\nabla^2\psi + \frac{m\,(E - V)}{\frac{h^2}{8\pi^2}}\psi = 0$$

$$\nabla^2\psi + \frac{m\,(E - V)}{\frac{h^2}{2\mathrm{x}4\pi^2}}\psi = 0$$

$$\nabla^2\psi + \frac{2m\,(E - V)}{\frac{h^2}{4\pi^2}}\psi = 0 \qquad \text{--- (13)}$$

On substituting eqn (12) in eqn (13), Schroedinger time independent wave equation is written as,

$$\nabla^2\psi + \frac{2m}{\hbar^2}(E - V)\,\psi = 0 \qquad \text{--- (14)}$$

Special case:

If we consider one dimensional motion i.e., particle moving along only X-direction, then Schroedinger time independent wave equation (14) reduces to

$$\frac{\partial^2\psi}{\partial x^2} + \frac{2m}{\hbar^2}(E - V)\,\psi = 0 \qquad \text{--- (15)}$$

SCHROEDINGER TIME DEPENDENT WAVE EQUATION:

Schoredinger time independent wave equation is derived from Schroedinger time independent wave equation.

The solution of classical differential equation of the wave motion is given by

$$\psi(x, y, z, t) = \psi_0(x, y, z)\, e^{-i\omega t} \qquad \text{--- (1)}$$

Differentiating eqn (1) with respect to ‘t’, we get

$$\frac{\partial\psi}{\partial t} = -i\omega\psi_0 e^{-i\omega t} \qquad \text{--- (2)}$$

$$\frac{\partial\psi}{\partial t} = -i(2\pi\nu)\psi_0 e^{-i\omega t}$$

Where, $\omega = 2\pi\,\nu$

$$\frac{\partial\psi}{\partial t} = -i(2\pi\nu)\psi \qquad \text{--- (3)}$$

Where, $\psi = \psi_0 e^{-i\omega t}$

$$\frac{\partial\psi}{\partial t} = -2\pi i\,\frac{E}{h}\psi$$

Where, $E = h\nu$ (or) $\nu = \frac{E}{h}$

$$\frac{\partial\psi}{\partial t} = -i\,\frac{E}{\frac{h}{2\pi}}\psi$$

We know that $\hbar = \frac{h}{2\pi}$

$$\therefore\ \frac{\partial\psi}{\partial t} = -i\,\frac{E}{\hbar}\psi \qquad \text{--- (4)}$$

Multiplying ‘i’ on both sides in eqn (4), we get

$$i\,\frac{\partial\psi}{\partial t} = -i^2\,\frac{E}{\hbar}\psi$$

We know that $i^2 = -1$

$$\therefore\ i\,\frac{\partial\psi}{\partial t} = -(-1)\,\frac{E}{\hbar}\psi$$

$$i\,\frac{\partial\psi}{\partial t} = \frac{E}{\hbar}\psi$$

$$i\hbar\,\frac{\partial\psi}{\partial t} = E\psi \qquad \text{--- (5)}$$

Schroedinger time independent wave equation is given by

$$\nabla^2\psi + \frac{2m}{\hbar^2}(E - V)\,\psi = 0$$

$$\nabla^2\psi + \frac{2m}{\hbar^2}(E\psi - V\psi) = 0 \qquad \text{--- (6)}$$

Substituting eqn (5) in eqn (6), we get

$$\nabla^2\psi + \frac{2m}{\hbar^2}\left(i\hbar\frac{\partial\psi}{\partial t} - V\psi\right) = 0$$

$$\nabla^2\psi = -\frac{2m}{\hbar^2}\left(i\hbar\frac{\partial\psi}{\partial t} - V\psi\right)$$

$$-\frac{\hbar^2}{2m}\nabla^2\psi = i\hbar\frac{\partial\psi}{\partial t} - V\psi$$

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = i\hbar\frac{\partial\psi}{\partial t}$$

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\psi = i\hbar\frac{\partial\psi}{\partial t} \qquad \text{--- (7)}$$

$$\text{(or) } H\psi = E\psi \qquad \text{--- (8)}$$

Where, H = $\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)$ is Hamiltotnian operator and E = $i\hbar\frac{\partial}{\partial t}$ is energy operator

The eqn (8) is known as Schroedinger time dependent wave equation

PHYSICAL SIGNIFICANCE OF WAVE FUNCTION:

Wave function:

It is the variable quantity that is associated with a moving particle at any position (x, y, z) and at any time‘t’ and it relates the probability of finding the particle at that point and at that time.

- It relates the particle and the wave statistically (i.e.,) $\psi = \psi_0 e^{-i\omega t}$
- Wave function gives the information about the particle behavior.
- Ψ is a complex quantity and individually it does not have any meaning.
- $|\psi|^2 = \psi^*\psi$ is real and positive, it has physical meaning. This concept is similar to light. In light, amplitude may be positive (or) negative but the intensity, which is square amplitude, is real and is measurable.
- $|\psi|^2$ represents the probability density (or) probability of finding the particle per unit volume.
- For a given volume dτ, the probability of finding the particle is given by

  Probability (P) = $\iiint |\psi|^2 d\tau$

  Where, dτ = dx.dy.dz
- The probability will have any value between zero and one. (i.e.,)
  1. If P = 0 then there is no chance for finding the particle (i.e.,) there is no particle, within the given limits.
  2. If P = 1 then there is 100% chance for finding the particle (i.e.,) the particle is definitely present, within the given limits.

iii. If P = 0.7 then there is 70% chance for finding the particle and 30% there is no chance for finding the particle, within the given limits.

Example:

If a particle is definitely present within a one dimensional box (x-direction) of length ‘l’, then the probability of finding the particle can be written as

$$P = \int_0^l |\psi|^2 \, dx = 1$$

PARTICLE IN A ONE DIMENSIONAL BOX:

Let us consider particle (electron) of mass ’m’ moving along the x - axis, enclosed in a one dimensional potential box as shown in the figure 3.10.

Since the walls are of infinite potential the particle does not penetrate out from the box.

Also, the particle is confined between the length ‘l’ of the box and has elastic collisions with the walls. Therefore, the potential energy of the electron inside the box is constant and can be taken as zero for simplicity.

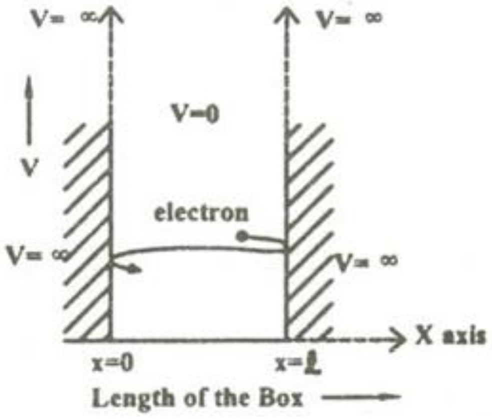


Fig 3.10

∴ We can say that the Outside the box and on the wall of the box, the potential energy V of the electron is ‘α’.

Inside the box the potential energy (V) of the electron is zero.

In other words we can write the boundary condition as

$$V(x) = 0 \text{ when } 0 < x < l$$

$$V(x) = \alpha \text{ when } 0 \geq x \geq l$$

Since the particle cannot exist outside the box the wave function $\psi = 0$ when$0 \geq x \geq l$.

To find the wave function of the particle within the box of length ‘l’, let us consider the Schroedinger one dimensional time independent wave equation(i.e.,)

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2}(E - V)\psi = 0$$

Since the potential energy inside the box is zero [i.e.V = 0], the particle has kinetic energy alone and thus it is named as a free particle (or) free electron

∴ For a free particle (electron), the Schroedinger wave equation is given by

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2} E\psi = 0$$

Or $$\frac{\partial^2 \psi}{\partial x^2} + k^2 E\psi = 0 \qquad \text{--- (1)}$$

Where, $$k^2 = \frac{2mE}{\hbar^2} \qquad \text{--- (2)}$$

Equation (1) is a second order differential equation; therefore, it should have solution with two arbitrary constants.

∴ The solution for equation (1) is given by

$$\Psi(x) = A \sin kx + B \cos kx \qquad \text{--- (3)}$$

Where, A and B are called Arbitrary constants, which can be found by applying the boundary conditions.

$$\text{(i.e.,) } V(x) = \alpha \text{ when } x = 0 \text{ and } x = l$$

Boundary condition (i) at x=0 Potential energy V = α. ∴ There is no chance for finding the particle at the walls of the box, ∴ $\psi(x) = 0$

∴ Equation (3) becomes

$$0 = A \sin 0 + B \cos 0$$

$$0 = 0 + B(1)$$

$$\therefore \mathbf{B = 0}$$

Boundary condition (ii) at x = l Potential energy V = α. ∴ There is no chance for finding the particle at the walls of the box, ∴ $\psi(x) = 0$

∴ Equation (3) becomes

$$0 = A \sin kl + B \cos kl$$

Since B = 0 (from the first boundary condition), we have

$$0 = A \sin kl$$

Since $A \neq 0$; $\sin kl = 0$

We know $\sin n\pi = 0$

Comparing these two equations,

We can write $kl = n\pi$

Where, n is an integer.

$$\text{(or) } k = \frac{n\pi}{l} \qquad \text{--- (4)}$$

Substituting the value of B and k in equation 3 we can write the wave function associated with the free electron confined in a one dimensional box as

$$\Psi_n(x) = A \sin \frac{n\pi}{l} \qquad \text{--- (5)}$$

Energy of the particle (Electron)

We know from equation (2),

$$k^2 = \frac{2mE}{\hbar^2}$$

Where, $\hbar^2 = \frac{h^2}{4\pi^2}$

$$k^2 = \frac{2mE}{\left(\frac{h^2}{4\pi^2}\right)}$$

$$\text{(or)} \qquad k^2 = \frac{8\pi^2 mE}{h^2} \qquad \text{--- (6)}$$

Squaring eqn (4), we get

$$k^2 = \frac{n^2\pi^2}{l^2} \qquad \text{--- (7)}$$

Equating (6) and (7), we can write

$$\frac{8\pi^2 mE}{h^2} = \frac{n^2\pi^2}{l^2}$$

$$E = \frac{n^2\cancel{\pi^2}h^2}{8\cancel{\pi^2}ml^2}$$

∴ Energy of the particle (electron) $E_n = \frac{n^2h^2}{8ml^2}$ --- (8)

∴ From equations (8) and (5) we can say that, for each value of ‘n’, there is an energy level and the corresponding wave function.

Thus we can say that, each value of E_n is known as Eigen value and the corresponding value of ψ_n is called Eigen function.

Energy levels of an electron

For various values of ‘n’ we get various energy values of the electron. The lowest energy value or ground state energy value can be got by substituting n = 1 in equation (8)

∴ When n= 1 we get $E_1 = \frac{1^2h^2}{8ml^2} = \frac{h^2}{8ml^2}$

Similarly we can get the other energy values

When n= 2, we get $E_2 = \frac{2^2h^2}{8ml^2} = \frac{4h^2}{8ml^2} = 4E_1$

When n = 3, we get $E_3 = \frac{3^2h^2}{8ml^2} = \frac{9h^2}{8ml^2} = 9E_1$

When n = 4, we get $E_4 = \frac{4h^2}{8ml^2} = \frac{16h^2}{8ml^2} = 16E_1$

∴ In general we can write the energy Eigen function as

$$\mathbf{E_n = n^2E_1} \qquad \text{--- (9)}$$

It is found that from the energy levels E_1, E_2, E_3 etc the energy levels of an electron are discrete.

This is the great success which is achieved in Quantum Mechanics than classical mechanics, in which the energy levels are found to be continuous.

The various energy Eigen values and their corresponding Eigen functions of an electron enclosed in a one dimensional box is as shown in the fig 3.11.

Thus we have discrete energy values.

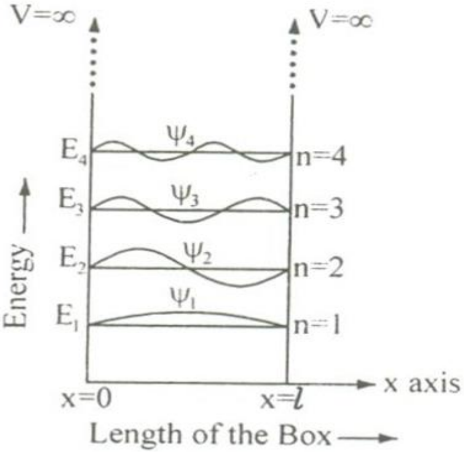


Fig 3.11

Normalization of the wave function:

Normalization:

It is the process by which the probability (P) of finding the particle (electron) inside the

$$\mathbf{A} = \sqrt{\frac{2}{l}}$$

Substituting the Value of A in equation (5),

The normalized wave function can be written as

$$\Psi_n = \sqrt{\frac{2}{l}} \sin \frac{n\pi}{l}$$

The normalized wave function and their energy values are as shown in the fig 3.12

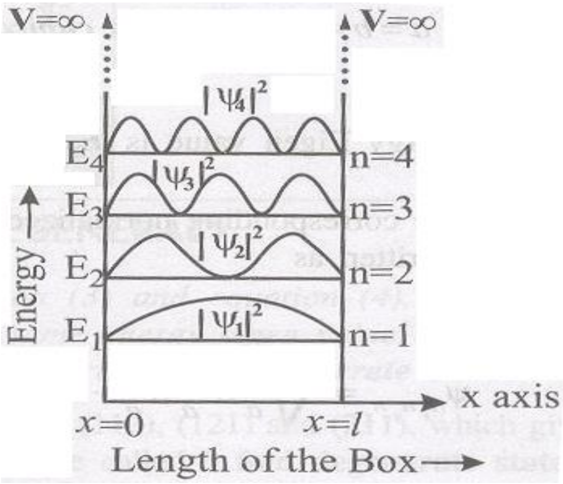


Fig 3.12

box can be done.

We know that the total probability (P) is equal to 1 means then there is a particle inside the box. Therefore, for a one dimensional potential box of length 'l' the probability

$$P = \int_0^l |\psi|^2 \, dx = 1 \qquad \text{--- (10)}$$

(Since the particle is present inside the well between the length 0 to 'l' the limits are chosen between 0 to l)

Substituting equation (5) in equation (10), we get

$$P = \int_0^l A^2 \sin^2 \frac{n\pi}{l} \, dx = 1$$

$$\text{(or) } A^2 \int_0^l \left[\frac{1-\cos 2\left(\frac{n\pi x}{l}\right)}{2}\right] dx = 1$$

$$A^2 \left[\frac{x}{2} - \frac{1}{2}\frac{\sin\left(\frac{2n\pi x}{l}\right)}{\left(\frac{2n\pi}{l}\right)}\right]_0^l = 1$$

$$A^2 \left[\frac{l}{2} - \frac{1}{2}\frac{\sin\left(\frac{2n\cancel{l}\pi}{\cancel{l}}\right)}{\left(\frac{2n\pi}{l}\right)}\right] = 1$$

$$A^2 \left[\frac{l}{2} - \frac{1}{2}\frac{\sin(2n\pi)}{\left(\frac{2n\pi}{l}\right)}\right] = 1$$

We know sin n π = 0 ∴ sin2nπ is also = 0

∴ Equation 11 can be written as

$$A^2 \left[\frac{l}{2}\right] = 1$$

$$A^2 = \frac{2}{l}$$

DEGENERACY AND NON-DEGENERACY:

Degeneracy:

It is seen from equation (3) and equation (3), for several combination of quantum numbers we have same energy Eigen value but different Eigen functions. Such states and energy levels are called Degenerate state.

The three combinations of quantum numbers (112), (121) and (211) which gives same Eigen value but different Eigen functions are 3 fold degenerate state.

Non –degeneracy:

For various combinations of quantum number if we have same energy value and same (one) Eigen function then such states and energy levels are called Non – degenerate state.

BASICS OF A MICROSCOPE:

A microscope is a device which is used to view the magnified image of a smaller object, which cannot be clearly seen through a naked eye.

In general we can classify the microscope as simple and compound microscope. A simple microscope is made up of a single biconvex magnifying lens held in a simple frame. A compound microscope is made up of two lenses (or) system of lenses for better magnification.

Depending on the field of application, many other microscopes such as phase contrast microscope, UV microscope, metallurgical microscope, electron microscope, etc are designed. These types of microscopes give a stereoscopic vision and reduce the strain of our eyes.

Magnifying power:

The magnifying power (M) of a microscope is defined as the ratio between the angle subtended by the final image at the eye (β) to the angle subtended by the object at the eye (α), placed at the near point.

$$M = \frac{\beta}{\alpha}$$

Resolving power:

It is the ability of an optical instrument to form a distinct and separable image of the two point objects which are close to each other.

If'd' is the least distance between two close point objects, then we can write

$$d = \frac{\lambda_0}{2\,NA}$$

∴ Resolving power = $\frac{I}{d} = \frac{2NA}{\lambda_0}$

Where, NA be the numerical aperture of the objective of the microscope and λ_0 be the wavelength of light through vacuum.

Therefore the resolving power of a microscope can be increased by decreasing the value of λ_0. Thus, by using UV light and quartz lenses, the resolving power can be increased.

ELECTRON MICROSCOPE

It is a type of microscope in which instead of light beam, a beam of electrons are used to form a large image of very small object. These microscopes are widely used in the field of engineering and medicine.

Principle:

A stream of electrons is passed through the object and the electron which carries the information about the object are focused by electric and magnetic fields.

Since the resolving power is inversely proportional to the wavelength, the electron microscope has high resolving power because of its shorter wavelength.

Construction:

An electron microscope is similar to that of an optical microscope. Here the focusing of electrons can be done either by magnetic lens or by electrostatic lens. Normally in electron microscope magnetic lenses are used for focusing.

In general, the magnetic lenses are made of two coils C1 and C2 enclosed inside the iron cases which have one hole as shown in fig 3.13. When the holes face each other, the magnetic field in space between the two coils focuses the electrons emerging out from the electron gun. Similarly the divergence of the electrons can also be made by adjusting the position of the holes in the iron cases.

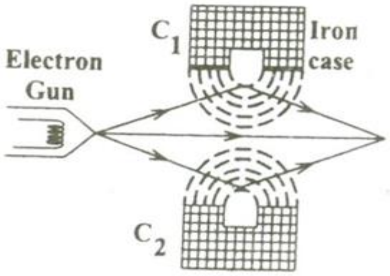


Fig 3.13

The essential parts of an electron microscope are as shown in the fig 3.14 and for comparison an optical microscope is also shown in fig 3.15.

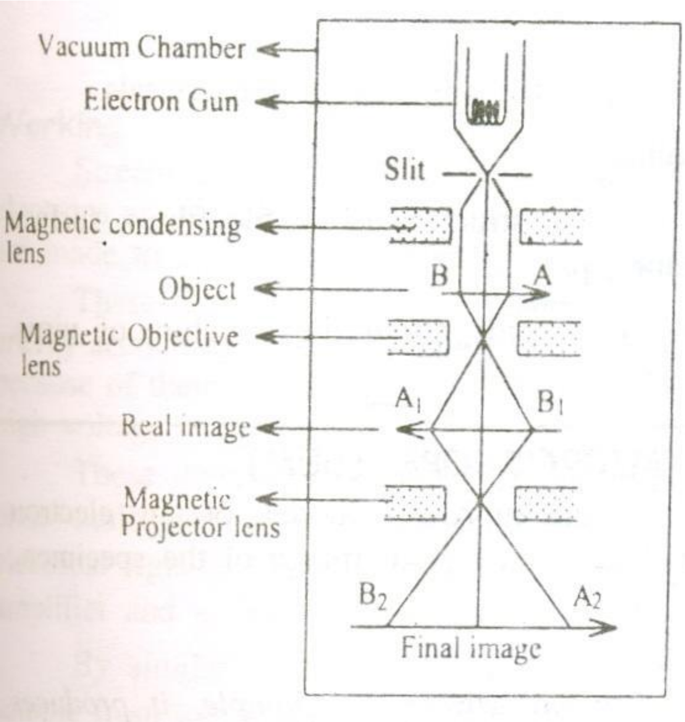


Fig 3.14

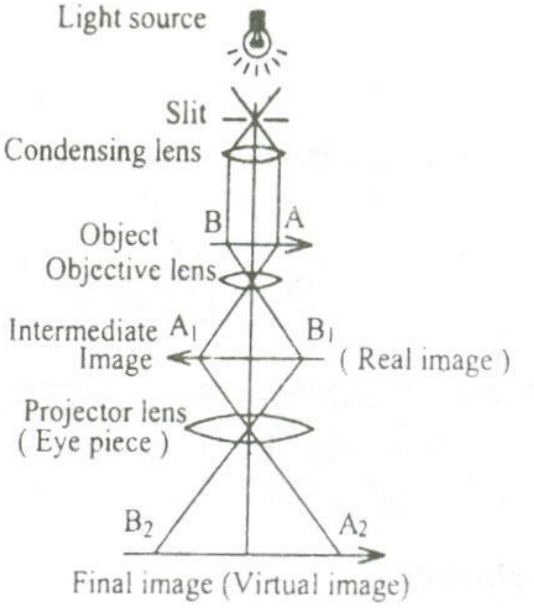


Fig 3.15

The electron microscope consists of an electron gun to produce the stream of electrons. Similar to the condensing lens, objective and eye piece in an optical microscope here three magnetic lenses are used.

- Magnetic condensing lens
- Magnetic objective lens
- Magnetic projector lens

The whole arrangement is kept inside a vacuum chamber to allow the passage of electron beam.

Working:

Stream of electrons are produced and accelerated by the electron gun. The electron beam is made to pass through the center of the doughnut shaped magnetic condensing lens. These electrons are made as parallel beam and are focused on to the object AB (fig 3.14). The electrons are transmitted more in the less dense region of the object and is transmitted less (i.e.,) absorbed by the denser region of the object. Thus the transmitted electron beam on the falling over the magnetic objective lens, resolves the structure of the object to form a magnified real image of the object. Further the image can be magnified by the magnetic projector lens and the final image is obtained on the fluorescent screen.

In order to make a permanent record of the image of the object, the final image can also be obtained on a photographic plate.

Advantages:

- It can produce magnification as high as 1, 00,000 times as that of the size of the object.

- The focal length of the microscopic system can be varied.

Applications:

It has a very wide area of applications (Eg.) in biology, metallurgy, physics, chemistry, medicine, engineering etc.

- It is used to determine the complicated structure of the crystals.
- It is used in the study of the colloids.
- In industries it is used to study the structure of textile fibers, surface of metals, composition of paper, paints etc.
- In the medical field it is used to study about the structure of virus, bacterial etc which are of smaller size.

SCANNING ELECTRON MICROSCOPE

Scanning electron microscope is an improved model of an electron microscope. SEM is used to study the three dimensional image of the specimen.

Principle:

When the accelerated primary electron strikes the sample, it produces secondary electrons. These secondary electrons are collected by a positive charged electron detector which in turn gives a 3- dimensional image of the sample.

Construction:

It consists of an electron gun to produce high energy electron beam. A magnetic condensing lens is used to condense the electron beam and a scanning coil is arranged in-between magnetic condensing lens and the sample.

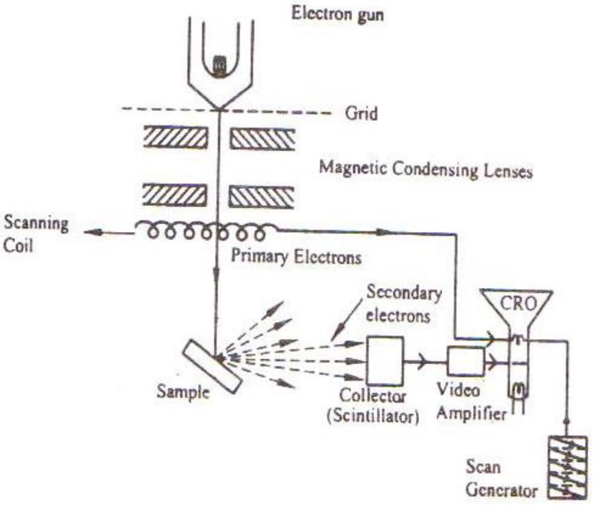


Fig 3.16

The electron detector (Scintillator) is used to collect the secondary electrons and can be converted into electrical signal. These signals can be fed into CRO through video amplifier as shown in fig 3.16.

Working:

Stream of electrons are produced by the electron gun and these primary electrons are accelerated by the grid and anode. These accelerated primary electrons are made to be incident on the sample through condensing lenses and scanning coil.

These high speed primary electrons on falling over the sample produce low energy secondary electrons. The collections of secondary electrons are very difficult and hence a high voltage is applied to the collector.

These collected electrons produce scintillations on to the photo multiplier tube are converted into electrical signals. These signals are amplified by the video amplifier and are fed to the CRO.

By similar procedure the electron beam scans from left to right and again right to left etc., similar to we read a book (fig 3.17) and the whole picture of the sample is obtained in the CRO screen.

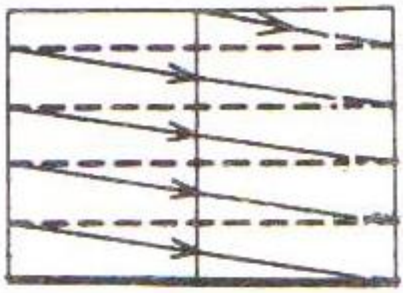


Fig 3.17

Advantages:

- It can be used to examine specimens of large thickness.
- It has large depth of focus.
- It can be used to get a three dimensional image of the object.
- Since the image can be directly viewed in the screen, structural details can be resolved in the precise manner.
- The magnification may be upto 3, 00,000 times greater than that of the size of the object.

Disadvantages:

The resolution of the image is limited to about 10-20 nm, hence it is very poor.

Applications:

- It is used to examine the structure of very large specimens in a three dimensional view.
- Similar to the application of electron microscope this SEM also has applications over various fields such as Biology, Industries, Engineering, Physics, Chemistry, etc.

PROBLEMS

1. **Calculate de-Broglie wavelength associated with a proton moving with a velocity equal to $\frac{1}{20}^{th}$ of the velocity of light.**

   Mass of proton = 1.675 x 10^{-27}kg

   Given data:

   Mass of proton m = 1.675 x 10^{-27}kg

   Velocity of proton v = $\frac{1}{20}$ x velocity of light

   $$v = \frac{1}{20} \times 3\times10^{8}$$

   $$v = 15 \times 10^{6} \text{ m/s}$$

   Solution:

   de-Broglie wavelength $\lambda = \frac{h}{mv}$

   $$\lambda = \frac{6.63\times10^{-34}}{1.675\times10^{-27}\times15\times10^{6}}$$

   $$\boldsymbol{\lambda = 2.64 \times 10^{-14}\ m}$$

2. **Calculate the de-Broglie wavelength of an electron of energy 100 eV.**

   Given data:

   Energy of electron (E) = 100 eV =100 x 1.6 x 10^{-19} Joules

   $$E = 1.6 \times 10^{-17} \text{ Joules}$$

   Solution:

   de-Broglie wavelength $\lambda = \frac{h}{\sqrt{2mE}}$

   $$\lambda = \frac{6.63\times10^{-34}}{\sqrt{2\times9.1\times10^{-31}\times1.6\times10^{-17}}}$$

   $$\lambda = 1.227 \times 10^{-10}\ \text{m}$$

   $$\boldsymbol{\lambda = 1.227 A^{\circ}}$$

3. **An electron is accelerated by a potential of 150 V. what is the wavelength of that electron wave?**

   Given data:

   Accelerated potential of an electron (V) = 150 V

   Solution:

   de-Broglie wavelength $\lambda = \frac{h}{\sqrt{2meV}}$

   $$\lambda = \frac{6.63\times10^{-34}}{\sqrt{2\times9.1\times10^{-31}\times1.6\times10^{-19}\times150}}$$

   $$\lambda = 1.0018 \times 10^{-10}\text{m}$$

   $$\boldsymbol{\lambda = 1\ A^{\circ}}$$

4. **Calculate the de-Broglie wavelength corresponding to the root mean square velocity of hydrogen molecules at 27˚C.**

Given data:

Temperature T = 27˚C = 300K

Mass of hydrogen = mass of proton = 1.678 x10^{-27}kg

Solution:

de-Broglie wavelength $\lambda = \frac{h}{\sqrt{3mK_BT}}$

$$\lambda = \frac{6.63\times10^{-34}}{\sqrt{3\times1.678\times10^{-27}\times1.38\times10^{-23}\times300}}$$

λ = 1.451 A˚

5. **An electron is confined to a one dimensional box of side 10^{-10}m. Obtain the first two Eigen values of the electron.**

Given data:

Length of one dimensional box 'l' = 10^{-10}m

Solution:

1st Eigen value,

Eigen Energy of the particle (electron) $E_1 = \frac{1^2(6.63\times10^{-34})^2}{8\times9.1\times10^{-31}\times(10^{-10})^2}$

$E_1 = 6.022 \times 10^{-18}$J

(or) $\boldsymbol{E_1 = \frac{6.022\times10^{-18}}{1.6\times1.6^{-19}}}$ **= 37.63 eV**

2nd Eigen value,

Eigen Energy of the particle (electron) $\boldsymbol{E_2 = 2^2E_1}$ **= 2.408 x 10^{-17}J = 150 eV**

(or) $\mathrm{E}' = \frac{7.8002\times10^{-14}}{1.6\times10^{-19}}$

$$\mathbf{E' = 0.4875 \times 10^6\ eV}$$

6. **Calculate the magnifying power of a microscope. Give that the angle subtended by the final image (β) is 40˚ at eye and the angle subtended by the object at the eye kept at the near point (α) is 10˚.**

Given data:

$\beta = 40^\circ$; $\alpha = 10^\circ$

Solution:

Magnifying power $M = \frac{\beta}{\alpha}$

Or $M = \frac{tan\beta}{tan\alpha}$

$= \frac{tan40^\circ}{tan10^\circ}$

∴ M**agnifying power M = 4.758**

UNIT II
ELECTRONIC MATERIALS

INTRODUCTION

Materials can be broadly classified into three types based on conductivity. They are,

1. Conductors (Example: metals),
2. Semi – conductors (Example: germanium, silicon) and
3. Insulators (Example: wood, mica, glass).

Conductors:

- Conductivity is the ability or power to conduct or transmit heat, electricity, or sound.
- Conductors are materials that electricity easily passes through, that do not resist the flow of electricity.
- Examples are copper, aluminum, steel, silver, gold, electrolytes.
- Low resistive materials are generally called as conducting materials.
- The conducting property of the solid is due to valence electrons or free electrons.

ELECTRON THEORY OF METALS

The electron theory of metals explain the following concepts

- Structural, electrical and thermal properties of materials.
- Elasticity, cohesive force and binding in solids.
- Behaviour of conductors, semi conductors, insulators etc.

So far **three electron theories** have been proposed.

1. Classical Free electron theory

- It is a macroscopic theory.
- Proposed by Drude and Loretz in 1900.
- It explains the free electrons in lattice
- It obeys the laws of classical mechanics.

2. Quantum Free electron theory

- It is a microscopic theory.
- Proposed by Sommerfield in 1928.
- It explains that the electrons move in a constant potential.
- It obeys the Quantum laws.

3. Brillouin Zone theory or Band theory:

- Proposed by Bloch in 1928.
- It explains that the electrons move in a periodic potential.
- It also explains the mechanism of semi conductivity, based on bands and hence called band theory.

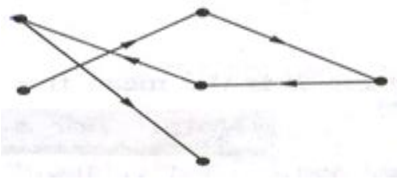
CLASSICAL FREE ELECTRON THEORY OF METALS

After the discovery of electron, Drude and Lorentz attempted for an explanation of electrical and thermal conductivities based on the assumption that metal contains a certain number of free electrons and hence called **free electron theory**. All the free electrons freely move in the crystal like molecules of a gas in a container. Mutual repulsion between electrons is ignored and hence potential energy is taken as zero. Therefore the total energy of the electron is equal to its kinetic energy.

Postulates of Classical free electron theory:

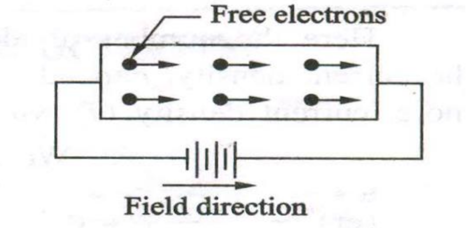
In the absence of Electric field:

All the atoms are composed of atoms. Each atom have central nucleus around which there are revolving electrons. The electrons are free to move in all possible directions about the whole volume of metals. In the absence of an electric field the electrons move in random directions making collisions from time to time with positive ions which are fixed in the lattice or other free electrons. All the collisions are elastic i.e.; no loss of energy.



In the presence of Electric field:

When an external field is applied the free electrons are slowly drifting towards the positive potential. Since the electrons are assumed to be a perfect gas they obey classical kinetic theory of gasses. Classical free electrons in the metal obey Maxwell-Boltzmann statistics.



Drift velocity (V_d):

The average velocity acquired by the free electron in a particular direction due to the application of electric field is called as Drift velocity.

Mobility (μ):

Mobility is defined as the drift velocity acquired by the free electrons per unit electric field (E) applied to it.

$$\mu = \frac{V_d}{E}$$

Where, l is the distance travelled by the electron.

Relaxation time (τ):

It is the time taken by the free electron to reach its equilibrium position from its disturbed position in the presence of applied field.

$$\tau = \frac{l}{V_d}$$

Collision time (τ_c):

It is the average time taken by the free electron between two successive collision.

$$\tau = \frac{\lambda}{V}$$

Where, λ is the mean free path.

Mean free path:

The average distance travelled between two successive collisions is called mean free path.

(i.e) $\lambda = \bar{c}\tau_c$, where $\bar{c}$ is the root mean square velocity of the electron.

QUANTUM FREE ELECTRON THEORY

Classical free electron theory could not explain many physical properties. In 1928, Sommerfeld developed a new theory applying quantum mechanical concepts and Fermi-Dirac statistics to the free electrons in the metal. This theory is called quantum free electron theory. Classical free electron theory permits all electrons to gain energy. But quantum free electron theory permits only a fraction of electrons to gain energy.

According to Classical free electron theory the particles (electrons) of a gas at zero kelvin will have zero kinetic energy and hence all the particles are found to be in rest. But according to quantum theory when all the particles are at rest, all of them should be filled only in the ground state energy level, which is impossible and is controversial to the Pauli’s exclusion principle.

Thus inorder to fill the electrons in a given energy level, we should know the following.

i. Energy distribution of electrons
ii. Number of available energy states
iii. Number of filled energy states
iv. Probability of filling an electron in a given energy state

As the "free electron gas" obeys Fermi-Dirac statistics, all the above can be very easily determined using it.

Fermi energy level (E_F)

Fermi energy level is the maximum energy level upto which the electrons can be filled at 0K.

Importance:

1. Fermi energy level act as a reference level which seperates the vacant and filled states at 0K.
2. It gives the information about the filled electron states and the empty states.
3. At 0K, below Fermi energy level electrons are filled at above Fermi energy level it will be empty.
4. When the temperature is increased, few electron gains the thermal energy and it goes to higher energy levels.

FERMI DISTRIBUTION FUNCTION

Fermi distribution function F (E) represents the probability of an electron occupying a given energy state. To find out the energy states actually occupied by the free electron at any temperature (T) we can apply the Fermi – Dirac statistics. The Fermi – Dirac statistics deals with the particles (Electrons) having half integral spin, named as Fermions.

$$F(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{K_BT}\right)}} \qquad \ldots(1)$$

Where E_F is the Fermi energy

K_B is the Boltzmann constant

EFFECT OF TEMPERATURE ON FERMI FUNCTION

The effect of temperature on Fermi function F (E) can be discussed with respect to equation (1).

(i) At 0 kelvin

At 0 kelvin, the electrons can be filled only upto a maximum energy level called Fermi energy (E_{F_0}), above E_{F_0} all the energy levels will be empty. It can be proved from the following conditions.

(i) When $E < E_F$, equation (1) becomes,

$$F(E) = \frac{1}{1+e^{-\infty}} = \frac{1}{1} = 1$$

[i.e., 100% chance for the electron to be filled within the Fermi energy level]

(ii) When $E>E_F$, equation (1) becomes,

$$F(E) = \frac{1}{1+e^{\infty}} = \frac{1}{\infty} = 0$$

[i.e Zero % chance for the electron not to be filled within the Fermi energy level]

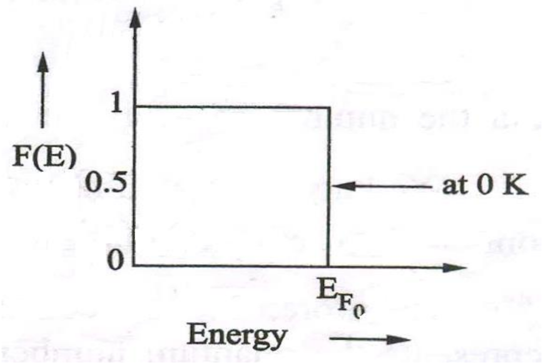
(i) When $E=E_F$, equation (1) becomes,

$$F(E) = \frac{1}{1+1} = \frac{1}{2} = 0.5$$

[i.e 50% chance for the electron to be filled and not to be filled within the Fermi energy level]

This clearly shows that 0 kelvin all the energy states below$E_{F_0}$are filled and all those above it are empty.

The Fermi function at 0 kelvin (E_{F_0}) can also be represented graphically as shown in fig. It is seen from the figure that the curve has step-like character at 0 kelvin.

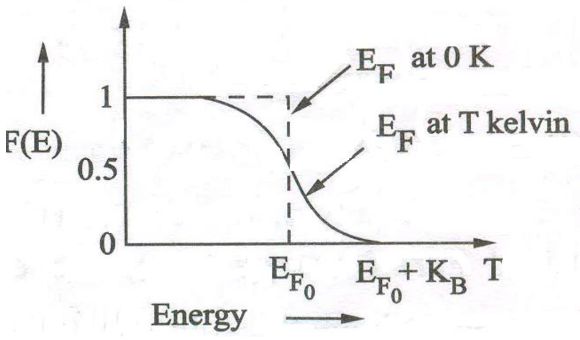


(i.e) F (E) = 1 below (E_{F_0})

and F (E) = above (E_{F_0})

(i) At any temperatue T kelvin:

When the temperature is raised slowly from absolute zero, the Fermi distribution function smoothly decreases to zero as shown in fig.



Explanation:

Due to the supply of thermal energy the electrons within the range of K_BT below the Fermi level (E_{F_0}) alone takes the energy (=K_BT) and goes to higher energy state. Hence at any temperature (T), empty states will also be available belowE_{F_0}.

DENSITY OF STATES AND CARRIER CONCENTRATION IN METALS

The Fermi Function F (E) gives only the probability of filling up of electrons in a given energy state, it does not gives the information about the number of electrons that can be filled in a given energy state. To know that we should know the number of available energy states so called density of states.

Definition:

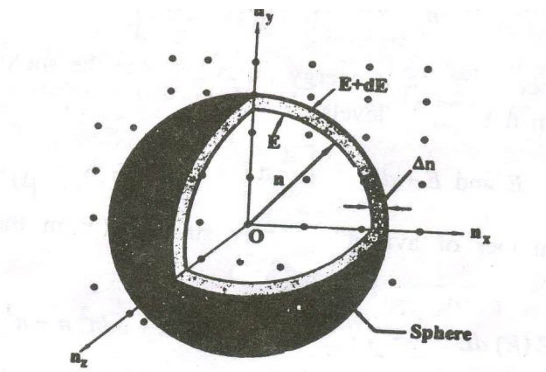
Density of States Z (E) dE is defined as the number of available energy states per unit volume in an energy interval.(dE).

Explanation:

In order to fill the electrons in an energy state we have to first find the number of available energy states within a given energy interval.

We know that a number of available energy levels can be obtained for various combinations of quantum numbers n_x, n_y and n_z ((i.e) $n^2 = n^2{}_x+n^2{}_y+n^2{}_z$)

Therefore, let us construct a three dimensional space of points which represents the quantum numbers as shown in fig. In this space each point represents an energy level.



Number of energy levels in a cubical metal piece:

To find the energy levels in a cubical metal piece and to find the number of electrons that can be filled in a given energy level, let us construct a sphere of radius ‘n’ in the space.

The sphere is further divided into many shells and each of this shell represents a particular combination of quantum numbers (n_x, n_y and n_z) and therefore represents a particular energy value.

Let us consider two energy values E and E+dE. The number of energy states between E and E+dE can be found by finding the number of energy states between the shells of radius n and n+, from the origin.

The number of available energy states within the sphere of radius

$$\text{‘ n ‘} = \left[\frac{4}{3}\pi n^3\right]$$

Since will have only positive values, we have to take only one octant of the sphere (i.e) 1/8th of the sphere volume.

The number of available energy states within the sphere of radius

$$\text{‘ n ‘} = \frac{1}{8}\left[\frac{4}{3}\pi n^3\right]$$

Similarly, the number of available energy states within the sphere of radius

$$n + dn = \frac{1}{8}\left[\frac{4}{3}\pi\,(n + dn)^3\right]$$

Therefore, the number of available energy states between the shells of radius n and n + dn (or) between the energy levels E and E + d E

$$= \frac{1}{8}\left[\frac{4}{3}\pi(n+dn)^3 - \frac{4}{3}\pi n^3\right]$$

(i.e) The number of available energy states between the energy interval d E is

$$Z(E)\,d\,E = \frac{1}{8}\,\frac{4\pi}{3}\left(n^3 + dn^3 + 3n^2dn + 3dn^2dn - n^3\right)$$

Since the higher powers of dn is very small, dn2 and dn3 terms can be neglected.

$$Z(\,E\,)\,d\,E = \frac{\pi}{6}\,3n^2dn$$

(or)

$$Z(E)\,dE = \frac{\pi}{2} n^2 dn \qquad \ldots (1)$$

We know the energy of the electron in a cubical metal piece of sides ‘l’,

$$E = \frac{n^2h^2}{8ml^2}$$

$$\text{(or)} \quad n^2 = \frac{8ml^2E}{h^2} \qquad \ldots(2)$$

$$n = \left[\frac{8ml^2E}{h^2}\right]^{1/2} \qquad \ldots(3)$$

Differentiating equation (2) we get

$$2ndn = \frac{8ml^2}{h^2}\,dE$$

$$ndn = \frac{8ml^2E}{2h^2}\,dE \qquad \ldots(4)$$

Equation (1) can be written as

$$Z(E)\,dE = \frac{\pi}{2} n(ndn)$$

Substituting equation (3) and (4) in the above equation we have

$$Z(E)\,dE = \frac{\pi}{2}\left[\frac{8ml^2E}{h^2}\right]^{1/2}\left[\frac{8ml^2}{2h^2}\right] dE$$

$$= \frac{\pi}{2}\cdot\frac{1}{2}\left[\frac{8ml^2E}{h^2}\right]^{1/2}\left[\frac{8ml^2}{2h^2}\right] dE$$

$$= \frac{\pi}{4}\left[\frac{8ml^2}{h^2}\right]^{3/2} E^{1/2}\,dE$$

$$Z(E)\,dE = \frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{3/2} E^{1/2}\, l^3 dE$$

Here l^3 represents the volume of the metal piece.

If $l^3 = 1$, then we can write that

The number of available energy states per unit volume (i.e) Density of states.

$$Z(E)\,dE = \frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{3/2} E^{1/2}\,dE \qquad \ldots (5)$$

Since each energy level provides 2 electron states one with spin up and another with spin down (pauli’s exclusion principle), we have

Density of states

$$Z(E)dE = 2.\frac{\pi}{4}\left[\frac{8m}{h^2}\right]^{3/2} E^{1/2}\,dE$$

$$Z(E)dE = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{3/2} E^{1/2}\, dE \qquad \ldots(6)$$

CARRIER CONCENTRATION IN METALS

Let N (E) d E represents the number of filled energy states between the interval of energy d E. Normally all the energy states will not be filled. The probability of filling of electrons in a given energy state is given by Fermi Function F (E).

$$N(E)\, dE = Z(E)\, dE \,.\, F(E) \qquad \ldots(7)$$

Substituting equation (6) in equation (7), we get

Number of filled energy states per unit volume

$$N(E)\, dE = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{3/2} E^{1/2}\, d\,E \,.F(E) \qquad \ldots(8)$$

N (E) is known as carrier distribution function (or) Carrier concentration in metals.

Fermi Energy at 0 Kelvin:

We know at 0K maximum energy level that can occupied by the electron is called Fermi energy level (E_{F_0})

(i.e) at 0 Kelvin for E< EF and

Therefore F (E) = 1

Integrating equation (8) within the limits 0 to E_{F_0} we can get the number of energy states electrons (N) within the Fermi energy E_{F_0}

$$\int N(E)d\,E = \frac{\pi}{2}\left[\frac{8m}{h^2}\right]^{3/2} \int_0^{E_{F_0}} E^{\frac{1}{2}}\, E.dE$$

$$= \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} \frac{{E_{F_0}}^{\frac{3}{2}}}{\frac{3}{2}}$$

(or) Number of filled energy states at zero $= \frac{\pi}{3}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} {E_{F_0}}^{\frac{3}{2}}$ ...(9)

(or)

$${E_{F_0}}^{\frac{3}{2}} = \frac{3N}{\pi}\left(\frac{h^2}{8m}\right)^{3/2}$$

Fermi energy $$E_{F_0} = \frac{h^2}{8m}\left(\frac{3N}{\pi}\right)^{2/3} \qquad \ldots(10)$$

Average energy of an electron at 0K:

Average energy of an electron

$$(E_{ave}) = \frac{\text{Total energy of the electrons at 0K } (E_T)}{\text{Number of energy states at 0K (N)}} \qquad \ldots(11)$$

Here, the total energy of the electrons at 0K = $(Number\ of\ energy\ states\ at\ 0K)$ X $(Energy\ of\ the\ electron)$

(i.e) $E_T = \int_0^{EF_0} N(E)dE\ .E$

$$= \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} \int_0^{E_{F_0}} E^{\frac{1}{2}}\ \text{E.dE} \qquad [F(E) = 1]$$

$$= \frac{\pi}{2}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} \frac{{E_{F_0}}^{\frac{5}{2}}}{\frac{5}{2}}$$

$$E_T = \frac{\pi}{5}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} {E_{F_0}}^{\frac{5}{2}} \qquad \ldots(12)$$

Substituting equation 9 and 12 in 11 we get

$$E_{ave} = \frac{\frac{\pi}{5}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} {E_{F_0}}^{\frac{5}{2}}}{\frac{\pi}{3}\left(\frac{8m}{h^2}\right)^{\frac{3}{2}} {E_{F_0}}^{\frac{3}{2}}}$$

$$E_{ave} = \frac{3}{5} {E_{F_0}}^{\frac{5}{2}} {E_{F_0}}^{\frac{-3}{2}}$$

The average energy of an electron at 0K is $E_{ave} = \frac{3}{5} E_{F_0}$

ENERGY BAND THEORY OF SOLIDS

Energy band theory of solids plays a very important role in determining whether a solid is a conductor, insulator or a semiconductor. This theory explains how an energy band occurs in a solid.

i. FREE AND BOUND ELECTRONS

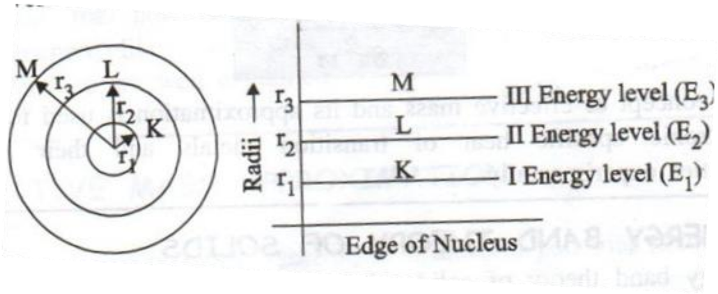
In an isolated atom all the electron are tightly bounded within the central positive nucleus and revolves around various orbits. The number of electrons at outer most orbit are called valence electrons. In the outer most orbits, the attractive force between the nucleus and electrons will be very less, so that electrons can be easily detached from the nucleus. These detached electrons from the outer shell orbits are called free electrons. But in innermost orbits electrons are tightly bound to the nucleus, and hence they are called as bound electrons. The free and bound electrons as shown in figure.

ii. **ENERGYLEVELS**

We know that each orbit of an atom has fixed amount of energy associated with it. The electrons moving in a particular orbit possess the energy of orbit. The larger the orbit, the greater is its energy. So, the outermost orbit of electrons possess more energy than inner orbit electrons.

The energy of different orbits are called energy levels. As shown in figure.

Let E_1 be the energy level of K-shell, E_2 be the energy level of M-shell, E_3 be the energy level of L-shell and so on.

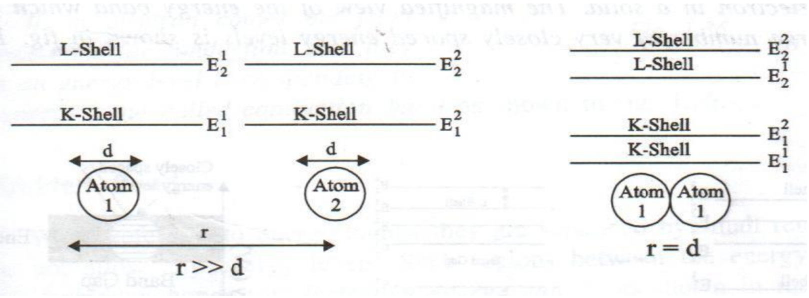


From the figure, it is clear that the electrons can revolve only in certain permitted orbits of radii r_1, r_2, r_3 .... and not in arbitrary orbit.

1. Therefore the electrons cannot filled in spacing of energy levels.
2. Electrons fill the lowest energy levels first. A specific quantity of energy must be supplied to move an electron to the next higher level.
3. Pauli Exclusion Principle states that no two electrons can occupy the same quantum state. Not more than two electrons can occupy any one energy level.

iii. ENERGY BANDS:

A set of closed spaced energy levels is called an energy band. let us consider two identical atoms of diameter (d) separated at a diatance (r), so that leletronic energy levels of one atom [E_1^1(K-shell) and E_2^1 (L-shell)] do not affect the electronic energy levels of the other atom [E_1^2(K-shell) and E_2^2 (L-shell)] as shown in figure.



Now, when we bring the atoms close together, some force of attraction occurs between them and according to quantum mechanics, their wave functions will start overlapping, therefore the two atoms are brought closer, it does not remain as two independent atoms, rather it forms a single two-atom system with two different energy levels to form energy band as shown in figure.

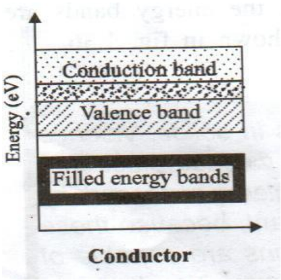
CLASSIFICATION OF MATERIALS INTO METALS, SEMICONDUCTORS AND INSULATORS ON THE BASIS OF BAND THEORY:

Based on band theory, and on the basis of presence of forbidden band gap the materials are classified into three catogories,viz.

i. Metals (or) Conductors
ii. Semiconductors
iii. Insulators

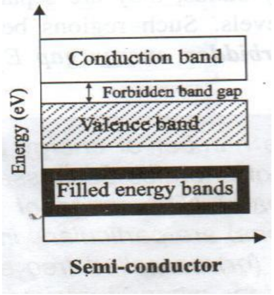
i. Metals (or) Conductors

In conductors, there is no forbidden energy gap. Here the valence band and conduction band overlap each other as shown in figure a. In metals the availability of free electrons will be very high due to the overlapping of conduction band and valence band. Hence even small field is applied to it, the electrons in valence band freely enters in to the conduction band and produces current. **EX. Copper, Aluminium, Iron.,**



ii. Semiconductors

In Semiconductors, the forbidden energy gap is very small, in the order 0.5ev to 1.5ev and hence there will be a very small gap between the valence and conduction band as shown in figure b. **Ex. Ge, Si.**

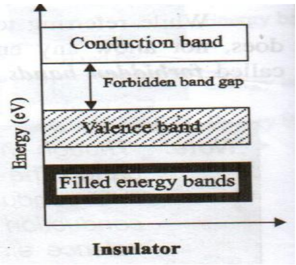


Generally, in Semiconductors the availability of free electrons in conduction band will be less compared to metals, due to the presence of forbidden band gap between the valence band and conduction band. Therefore, when external field of energy, equal to (or) greater than forbidden band gap energy (E_g) is applied to a semiconductor, immediately the conduction will take place.

iii. Insulators

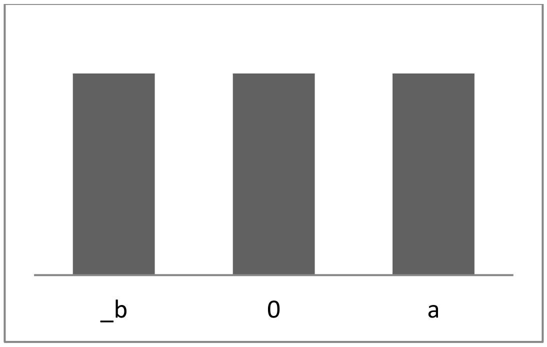
Insulators, the forbidden band gap is very wide, in the range of 3 ev to 5.47 ev and hence there will be very large gap between the valence band and conduction band as shown in figure c. Since the forbidden band gap is very very high in the case of insulators, so that very large amount of external field is required for conduction to occur.

Ex: Diamond, Dielectrics etc..



KRONIG PENNY MODEL

The Kronig Penny model is simplified model for an electron in one dimensional periodic potential the possible states that the electron can occupy are determined by Schrodinger equation.



The corresponding Schroedinger equation for the two regions I and II

$$\frac{d^2\Psi}{dx^2} + \frac{8\pi^2 m}{h^2} E\Psi = 0 \quad , \; 0 < x < a$$

$$\frac{d^2\Psi}{dx^2} + \alpha^2\Psi = 0 \qquad \_\_\_\_\_\_\_(1)$$

$$\alpha^2 = \frac{8\pi^2 m}{h^2}\,\mathrm{E} \qquad \_\_\_\_\_\_\_(2)$$

$$\frac{d^2\Psi}{dx^2} + \frac{8\pi^2 m}{h^2}(E - V_0)\,\Psi = 0 \qquad -b < x < 0$$

$$\frac{d^2\Psi}{dx^2} + \beta^2\,\Psi = 0 \qquad \_\_\_\_\_\_\_(3)$$

$$\beta^2 = \frac{8\pi^2 m}{h^2}\,(\mathrm{E} - V_0) \qquad \_\_\_\_\_\_\_(4)$$

The general solution of the above equation (1) , (3)

$$\Psi_1(x) = Ae^{i\alpha x} + Be^{-i\alpha x} \qquad \_\_\_\_\_\_\_(5)$$

$$\Psi_2(x) = Ce^{\beta x} + De^{-\beta x} \qquad \_\_\_\_\_\_\_(6)$$

Where A, B, C, D are arbitrary constants. The expected solution of the above Schroedinger equation must have the same form as that of Bloch function.

Now applying boundary condition we obtain the following modified equation

A + B = C + D

$i\alpha$ (A – B) = β (C- D)

$$Ce^{\beta b} + De^{-\beta b} = e^{ik(a+b)}[Ae^{i\alpha a} + Be^{-i\alpha a}]$$

$$\beta Ce^{\beta b} + \beta De^{-\beta b} = i\alpha\, e^{ik(a+b)}[Ae^{i\alpha a} - Be^{-i\alpha a}]$$

The solution of above equation can be found by following determinant.

$$\begin{vmatrix} 1 & 1 & -1 & -1 \\ i\alpha & -i\alpha & -\beta & \beta \\ -e^{ik(a+b)+\,i\alpha a} & -e^{ik(a+b)-\,i\alpha a} & e^{-\beta b} & e^{\beta b} \\ -i\alpha e^{ik(a+b)+\,i\alpha a} & iae^{ik(a+b)-i\alpha a} & \beta e^{-\beta b} & \beta e^{\beta b} \end{vmatrix} = 0 \qquad \_\_\_\_\_\_\_(7)$$

On simplifying this determinant we obtain

$$\cos ka = \left(\frac{\beta^2 - \alpha^2}{2\alpha\beta}\right)\beta b \sin\alpha a \sinh\beta b + \cos\alpha a \cosh\beta b \qquad \_\_\_\_\_\_\_(8)$$

In order to simplify above equation Kronig Penny assumes that the potential energy is 0 at lattice sites and equals to V₀ inbetween them hence equation (8) becomes

$$\cos ka = \left(\frac{\beta^2 - \alpha^2}{2\alpha\beta}\right)\beta b \sin\alpha a + \cos\alpha a \qquad \_\_\_\_\_\_\_(9)$$

$$\begin{aligned} \beta^2 - \alpha^2 &= \frac{8\pi^2 m}{h^2}\,(\mathrm{E} - V_0) - \frac{8\pi^2 m}{h^2}\,E \\ &= \frac{8\pi^2 m V_0}{h^2} \qquad \_\_\_\_\_\_\_(10) \end{aligned}$$

Sub. Eqn (10) in (9)

$$coska = \frac{8\pi^2 mV_0}{2\alpha\beta h^2}\beta bsin\alpha a + cos\alpha a$$

$$coska = Pb\frac{sin\alpha a}{\alpha a} + cos\alpha a \quad \_\_\_\_\_\_(11)$$

Where $P = \frac{4\pi^2 mV_{0\,b}}{h^2}$

$$P\frac{sin\alpha a}{\alpha a} = 0$$

$$\frac{sin\alpha a}{\alpha a} = 0$$

$$sin\alpha a = 0$$

$$\alpha a = sin^{-1}(0) = n\pi$$

$$\alpha = \frac{n\pi}{a}$$

$$\alpha^2 = \frac{n^2\pi^2}{a^2} \quad \_\_\_\_\_\_(12)$$

Comparing equations (2) and (12)

$$\frac{n^2\pi^2}{a^2} = \frac{8\pi^2 m}{h^2}\,E \quad \_\_\_\_\_\_(13)$$

$$E = \frac{n^2\pi^2}{8a^2 m}$$

Effective mass of electron:

The mass acquired by an electron when it is accelerated in a periodic potential is called effective mass of an electron.

When an electron is accelerated by an electrical or magnetic field in a periodic potential, the mass of an electron is not a constant. But, it varies with respect to the field applied. This varying mass is called effective mass (m*).

Consider a crystal subjected to an electric field of intensity ‘E’. Due to this applied field , the electron gains a velocity which can be

PROBLEMS

1. Energy required to remove an electron from sodium metal is 2.3e V. Does Sodium exhibit photoelectric effect from an orange light having wavelength 2800Å?

   Solution:

   Given: 2800 Å, $E_g = 2.3$

   Energy required to remove an electron from sodium = 2.3

$$E = h\nu = \frac{hc}{\lambda}$$

$$= \frac{6.625\times10^{-34}\times3\times10^{8}}{2800\times10^{-10}\times1.6\times10^{-19}}$$

   By using orange light having wavelength 2800 the energy produced is

   Since, the above calculated energy 4.4 e V i.e energy produced is greater than the required (i.e) 2.3e V. **Sodium exhibits photo-electric effect** from an orange light having wavelength 2800 Å

2. Calculate the drift velocity of electrons in copper and current density in wire of diameter 0.16cm which carries a steady current of 10A.Given $n = 8.46 \times 10^{28}/\text{m}^3$

   Solution:

   Current density $J = \frac{\text{Current}}{\text{Area of cross section}}$

$$= \frac{10}{\frac{\pi\times(0.16\times10^{-2})^2}{4}}$$

$$J = 497.3 \times 10^{4}\ \text{A/m}^2$$

UNIT III

SEMICONDUCTORS

INTRODUCTION

The materials are classified on the basis of conductivity and resistivity. The resistivity of a semiconductor is in the order of 10^{-4} to 0.5 ohm-metre. A semiconductor is a solid which has the energy band similar to that of an insulator. It acts as an insulator at absolute zero and as a conductor at high temperatures and in the presence of impurities.

PROPERTIES OF SEMICONDUCTOR

1. The resistivity of semiconductors lies between conducting and insulating materials. (i.e.,) 10^{-4} to 0.5 ohm-metre.
2. At 0K they behave as insulators.
3. When the temperature is raised or when impurities are added, their conductivity increases.

   i.e., $\rho \propto 1/T$
4. They have negative temperature co-efficient of resistances.
5. Total conductivity $(\sigma) = \sigma_e + \sigma_h$

   Where, σ_e – conductivity due to electrons

   σ_h - Conductivity due to holes
6. They are formed by covalent bond.
7. They have empty conduction band at ok.
8. They have almost filled valence band.
9. They small energy gap.
10. If impurities add in semiconductor, the electrical conductivity increases. When the temperature is increased, electrical conductivity is decreases.

CLASSIFICATION OF SEMICONDUCTORS

There are two types

i. Elemental Semiconductors

ii. Compound Semiconductors

Elemental semiconductors

Elemental semiconductors are made up of single element and are called as indirect band gap semiconductors. Heat is produced during recombination process. Ex: Ge, Si

Compound semiconductors

Compound semiconductors are made up of compounds and are called as direct band gap semiconductors. Photons are emitted during recombination process.

Ex: GaP, MgO

TYPES OF SEMICONDUCTORS

Based on the purity, semiconductors are classified into the following two types:

i. Intrinsic semiconductor
ii. Extrinsic semiconductor

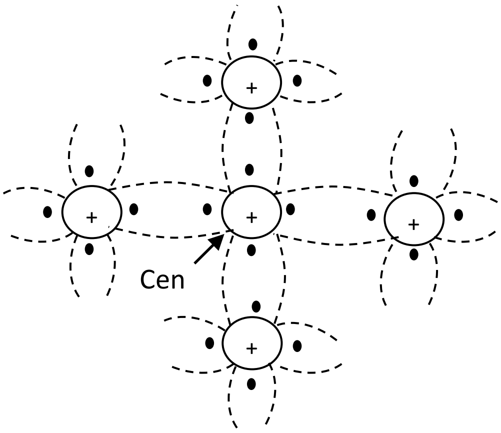
INTRINSIC SEMICONDUCTOR

A semiconductor in a extremely pure form is called as intrinsic semiconductors.

Ex: Ge, Si

Let us consider two atoms of Germanium brought closer to each other. Now the positive core of one atom interacts with one of the electrons from the other atom and the two electrons are shared by two atoms. These electrons are called Electron Pairs. When the attractive force is balanced, by the repulsive force between the two positive cores, a covalent bond is formed.

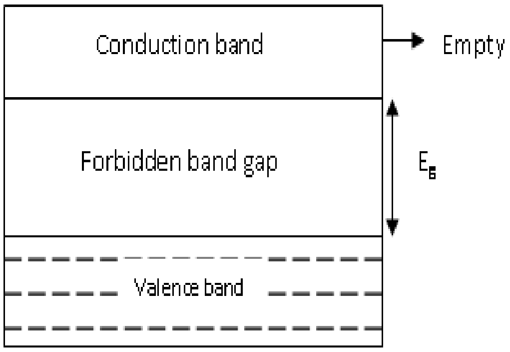
Explanation



- In the case of Ge or Si we have 4 valence electrons.
- It is the tendency of each germanium atom to have 8 electrons in the outer most shell.
- To do so, each germanium atom arranges itself between four other germanium atoms as shown in fig.
- Here neighbouring atoms share one valence electron with the central atom.
- So, by this sharing, the central atom completes its last orbit by having 8 electrons.
- Hence all the four valence electrons of the central atom gets tightly bound to the nucleus.
- Similar such bonding occurs among all the other atoms giving rise to extremely stable structure and hence has low conductivity.
- In these semiconductors the electrons and holes can be created only by thermal agitation.
- As there are no impurities the number of free electrons must be equal to the number of holes.

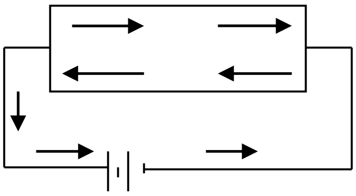
Effect of Temperature on intrinsic semiconductors

i. **At absolute zero**:



- At absolute zero, all the electrons are tightly bound to the nucleus.
- The inner orbit electrons are bound, whereas the valence electrons are bonded, with covalent bond, with other atoms.
- Hence at absolute zero, no valence electron can reach the conduction band to become free electron.
- So the valence band is completely filled and the conduction band is empty.

ii. **At absolute zero**:



- At absolute zero, all the electrons are tightly bound to the nucleus.
- The inner orbit electrons are bound, whereas the valence electrons are bonded, with covalent bond, with other atoms
- Hence at absolute zero, no valence electron can reach the conduction band to become free electron.
- So the valence band is completely filled and the conduction band is empty.

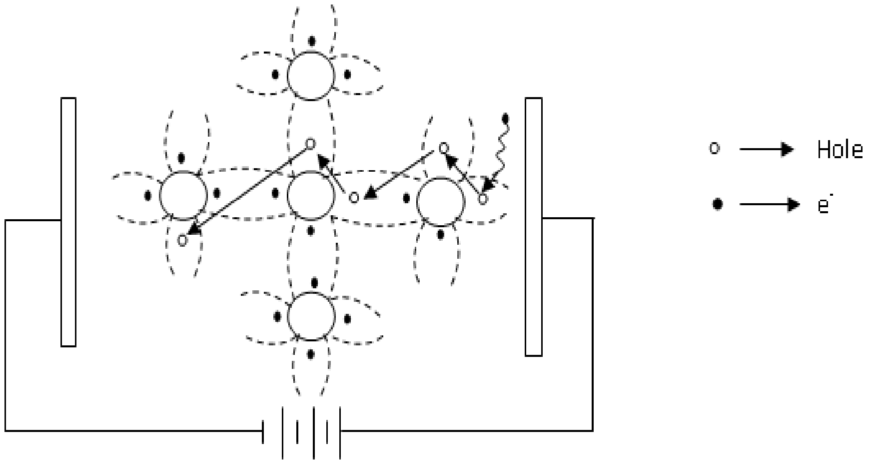
iii. **Above absolute zero**:

- When the temperature is raised some of the covalent bonds break due to thermal energy supplied.
- Due to the breaking of bonds the electrons are released from the covalent bonds and become free electrons.
- Now if a potential difference is applied across the semiconductor, these free electrons move with respect to field direction and produce a tiny electric current as shown in fig.
- This shows that the resistance of semiconductor decreases with the rise in temperature. i.e., it has **Negative temperature co efficient of resistance**.
- The no. of free electrons that move to conduction band will be exactly equal to the number of holes created in the valence band.

Hole Current

- Similar to the normal current which is due to free electrons another current called the hole current also flows in the semiconductor.

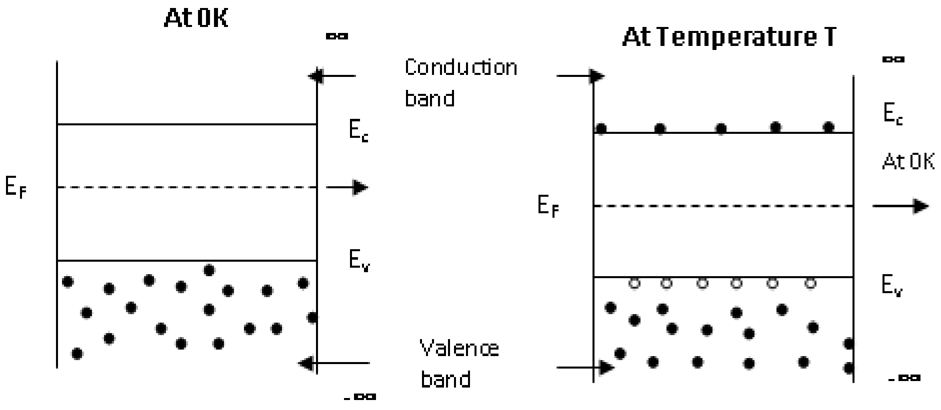
- Due to thermal energy if one electron enters conduction band from valence band, one hole is created in the valence band. Due to thermal energy hole- electron pairs are created.



- Definition: It is noted that hole current is due to the movement of valence electrons from one covalent bond to another bond.

CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTORS

- We know at 0 K intrinsic pure semiconductor behaves as insulator.
- But as temperature increases some electrons move from valence band to conduction band as shown in figure.
- Therefore both electrons in conduction band and holes in valence band will contribute to electrical conductivity.
- Assume that electron in the conduction band is a free electron of mass m_e^* and the hole in the valence band behaves as a free particle of mass m_h^*.
- The electrons in the conduction band have energies lying from E_e to ∞ and holes in the valence band have energies from -∞ to E_v as shown in figure.



- Here E_c represents the energy of the bottom (or) lowest level of conduction band and E_v represents the energy of top (or) the highest level of the valence band.

Density of electrons in conduction band

Density of electrons in conduction band $n_e = \int_{E_c}^{\infty} Z(E).F(E)dE$ ………. (1)

From Fermi-Dirac statistics we can write

$$Z(E)dE = 2.\frac{\pi}{4}\left[\frac{8m_e^*}{h^2}\right]^{\frac{1}{2}} E^{\frac{1}{2}}\, dE \qquad ……….\ (2)$$

Considering minimum energy of conduction band as E_c and the maximum energy can go upto ∞ we can write eqn (2) as

$$Z(E)dE = \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}}\, dE \qquad ………..\ (3)$$

We know Fermi function, $F(E) = \frac{1}{1+e^{(E-E_F)/TK_B}}$ ………… (4)

Sub. Eqn (4) and (3) in eqn (1) we have Density of electrons is conduction band within the limits E_c to ∞

$$n_e = \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{\frac{3}{2}} \int_{E_c}^{\infty} \frac{(E-E_c)^{\frac{1}{2}}}{1+e^{(E-E_F)/TK_B}}.dE \qquad ……….\ (5)$$

Since to move an electron from valence band to conduction band the energy required is greater than $4K_B$ T. (i.e) $e^{(E-E_F)/TK_B} \gg 1$ & $1 + e^{(E-E_F)/TK_B} = e^{(E-E_F)/TK_B}$

Eqn. (5) becomes

$$n_e = \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{\frac{3}{2}} \int_{E_c}^{\infty} (E - E_c)^{\frac{1}{2}}.\, e^{(E-E_F)/TK_B}\ dE \qquad ……….\ (6)$$

Let us assume that $E\text{-}E_c = xK_BT$ Differentiating we get $dE = K_BT.dx$,

Limits: when $E=E_c$; x=0, when E=∞; x=∞ Therefore limits are 0 to ∞

By solving Eqn (6) using this limits we can get,

Density of electrons in conduction band is $n_e = 2\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{\frac{3}{2}}.\ e^{(E-E_F)/TK_B}$ ……….. (7)

Density of holes in valence band

- We know, F(E) represents the probability of filled state.
- As the maximum probability will be 1, the probability of unfilled states will be [1-F(E)]
- Example, if F(E) = 0.8, then 1-F(E) = 0.2
- Let the maximum energy in valence band be E_v and the minimum energy be -∞. So density of holes in valence band n_h is given by

$$n_h = \int_{-\infty}^{E_v} Z(E).[1 - F(E)]dE \qquad …………\ (8)$$

We know $Z(E)dE = \frac{\pi}{2}\left[\frac{8m_e^*}{h^2}\right]^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}}\, dE$ ………….. (9)

$$1\text{-}F(E) = e^{(E-E_F)/TK_B} \qquad …………\ (10)$$

Sub eqn (10) and (9) in (8), we get

$$n_h = \frac{\pi}{2}\left[\frac{8m_h^*}{h^2}\right]^{\frac{3}{2}} \int_{-\infty}^{E_v} (E-E_c)^{\frac{1}{2}}.\, e^{(E-E_F)/TK_B}\, dE \qquad \text{……………. (11)}$$

Let us assume that E_v-E = xK_BT Differentiating we get dE = -K_BT.dx,

Limits: when E=-∞; we have E_v –(-∞) = x Therefore x= ∞

When E=E_v; x=0,

Therefore limits are ∞ to 0

Using these limits we can solve eqn (11) and we can get the Density of holes.

Density of holes in valence band is

$$n_h = 2\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{\frac{3}{2}}.\; e^{(E_v-E_F)/TK_B} \qquad \text{……………… (12)}$$

VARIATION OF FERMI ENERGY LEVEL AND CARRIER CONCENTRATION WITH TEMPERATURE IN AN INTRINSIC SEMICONDUCTOR

For an intrinsic semiconductor number of electrons (i.e.,) electron density will be the same as that of number of holes (i.e.,) hole density.

(i.e.,) $n_e = n_h$

Equating equns (7) and (12), we can write

$$[m_e^*]^{\frac{3}{2}}.\; e^{(E-E_F)/TK_B} = [m_h^*]^{\frac{3}{2}}.\; e^{(E_v-E_F)/TK_B}$$

By solving this equn and taking log on both sides we can get

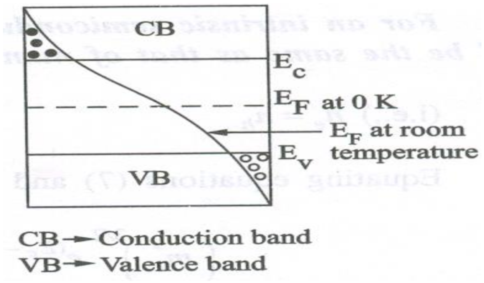
$$E_F = \frac{E_c+E_v}{2} + \frac{3}{4} K_B T \log\left(\frac{m_h^*}{m_e^*}\right) \qquad \text{………………… (13)}$$

If $m_h^* = m_e^*$, then $\log\left(\frac{m_h^*}{m_e^*}\right) = 0$

and equn (13) becomes

$$E_F = \frac{E_c+E_v}{2} \qquad \text{……………….. (14)}$$

The Fermi energy level lies in the midway between E_c and E_v as shown in figure. But in actual case $m_h^* > m_e^*$ and Fermi energy level slightly increases with the increase in temperature as shown in figure.



Density of electrons and holes interms of E_g

In terms of energy gap (E_g) where $E_g = E_c - E_v$ we can get the expression of n_e and n_h by substituting the value of E_F in terms of E_c and E_v.

Substituting equation (13) in (7) we get

$$n_e = 2\left(\frac{2\pi\, m_e^*\, K_B T}{h^2}\right)^{3/2} \exp\left[\frac{\dfrac{E_c + E_v}{2} + \dfrac{3}{4} K_B T \log_e\left(\dfrac{m_h^*}{m_e^*}\right) - E_c}{K_B T}\right]$$

$$= 2\left(\frac{2\pi\, K_B T}{h^2}\right)^{3/2} (m_e^*)^{3/2} \exp\left[\frac{2E_c + 2E_v + 3K_B T \log_e\left(\dfrac{m_h{}^*}{m_e^*}\right) - 4E_c}{4K_B T}\right]$$

$$= 2\left(\frac{2\pi\, K_B T}{h^2}\right)^{3/2} (m_e^*)^{3/2} \exp\left[\frac{2(E_v - E_c)}{4K_B T} + \frac{3}{4}\log_e\left(\frac{m_h^*}{m_e^*}\right)\right]$$

Since $E_g = E_c - E_v$, we can write

$$n_e = 2\left\{\frac{2\pi\, K_B T}{h^2}\right\}^{3/2} (m_e^*)^{3/2} \exp\left[\frac{-E_g}{2K_B T} + \log_e\left(\frac{m_h^*}{m_e^*}\right)^{3/4}\right]$$

(or) $$n_e = 2\left\{\frac{2\pi\, K_B T}{h^2}\right\}^{3/2} (m_e^*)^{3/2} \frac{(m_h^*)^{3/4}}{(m_e^*)^{3/4}}\, e^{-E_g/2K_B T}$$

(or) $$n_e = 2\left\{\frac{2\pi\, K_B T}{h^2}\right\}^{3/2} (m_e^*)^{3/4} (m_h^*)^{3/4}\, e^{-E_g/2K_B T}$$

$$\boxed{n_e = 2\left\{\frac{2\pi\, K_B T}{h^2}\right\}^{3/2} (m_e^*\, m_h^*)^{3/4} e^{-E_g/2K_B T}} \quad ...(15)$$

Similarly by substituting equation (13) in (12) we get

$$\boxed{n_h = 2\left\{\frac{2\pi\, K_B T}{h^2}\right\}^{3/2} (m_h^* \cdot m_e^*)^{3/4}\, e^{-E_g/2K_B T}} \quad ...(16)$$

Thus, it is found that $n_e = n_h = n_i$ where n_i is the ***intrinsic carrier concentration.***

Results

- In an intrinsic semiconductor the density of electrons in conduction band is equal to the density of holes in valence band. (i.e.,) $n_e = n_h$
- n_e and n_h increases exponentially as the temperature increases.

Intrinsic Carrier Concentration

We know that, $n_i = n_e = n_h$ and $n_i^2 = n_e \cdot n_h$

Substituting from equations (15) and (16), we have

$$n_i^2 = 2^2 \left[\left\{ \frac{2\pi K_B T}{h^2} \right\}^{3/2} \right]^2 \left[(m_h^* \cdot m_e^*)^{3/4} e^{-E_g/2K_B T} \right]^2$$

$$n_i^2 = 4 \left[\frac{2\pi K_B T}{h^2} \right]^3 (m_e^* m_h^*)^{3/2} e^{-E_g/K_B T}$$

$$\text{(or)} \quad n_i = 2 \left[\frac{2\pi K_B T}{h^2} \right]^{3/2} (m_e^* m_h^*)^{3/4} e^{-E_g/2K_B T} \qquad \ldots(17)$$

Therefore for intrinsic semiconductor even if impurity is added to increase n_e there will be decrease in n_h and hence the product $n_p n_h$ will remain constant. This is called ***law of mass action.***

MOBILITY AND ELECTRICAL CONDUCTIVITY OF INTRINSIC SEMICONDUCTORS

The electrical conductivity of an intrinsic semiconductor in terms of mobility of charge carriers is given by,

The electrical conductivity $\boldsymbol{\sigma_i = n_i e(\mu_e + \mu_h)}$ ……………..(1)

Where

n_i is intrinsic carrier concentration

e is charge of electron

μ_e is mobility of electrons

μ_h is mobility of holes.

According to intrinsic carrier concentration

$$\sigma = 2e \left\{ \frac{2\pi K_B T}{h^2} \right\}^{\frac{3}{2}} \left(m_h^* . m_e^* \right) e^{-\frac{E_g}{2K_{BT}}} (\mu_e + \mu_h)$$

Here the electrical conductivity depends on the exponential of forbidden energy gap between valence band and conduction band and on the mobility of charge carriers, both μ_e and μ_h.

But the term ($\mu_e + \mu_h$) has temperature dependence and it will cancel with the $T^{3/2}$ term and hence we can write

$$\sigma_i = Ce^{-E_g/2K_BT} \quad \ldots\ldots\ldots\ldots (2)$$

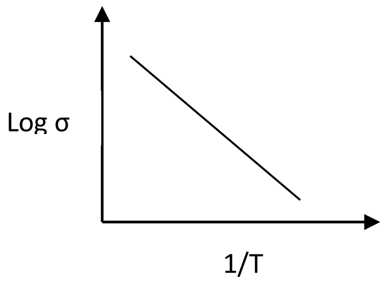
Where, C is a constant.

Taking log on both sides we have

$$\log\sigma_i = \log C - (E_g/2K_BT)$$

If a plot is made between log σ_i and 1/T we get a straight line.

Here σ_i increases with temperature as shown in figure.



DETERMINATION OF BAND GAP ENERGY

We know for intrinsic semiconductor $\sigma_i = Ce^{-E_g/2K_BT}$

We know resistivity ρ_i = 1/ Conductivity

$$P_i = \frac{1}{C} e^{E_g/2K_BT} \quad \ldots\ldots\ldots\ldots (1)$$

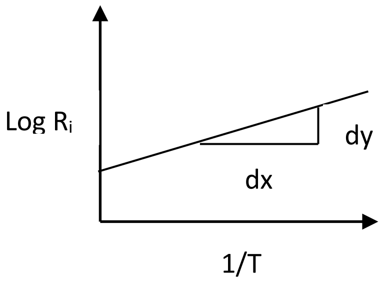
We know resistivity is resistance per unit area per unit length

$$\rho_i = \frac{R_i a}{l} \quad \ldots\ldots\ldots\ldots (2)$$

Where ρ_i – Resistance,

a – Cross sectional area,

l – Length



Equating eqns (1) and (2) and Taking log on both sides we get,

$$\log R_i = \log C_1 + (E_g/2K_BT)$$

The resistance can be found using meter bridge or carey fosters bridge or post office box experiments at various temperatures.

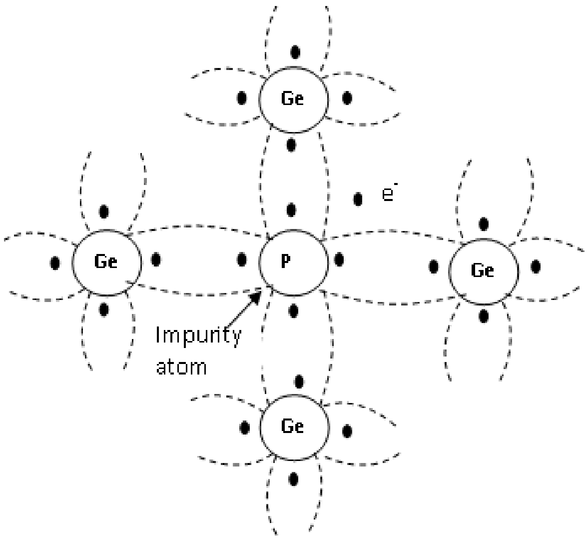
If a graph is plotted between 1/T and log R_i a straight line is obtained as shown in figure, with a slope dy/dx = $E_g/2K_B$.

Therefore by finding the slope of line we can calculate the energy band gap E_g with the following expression.

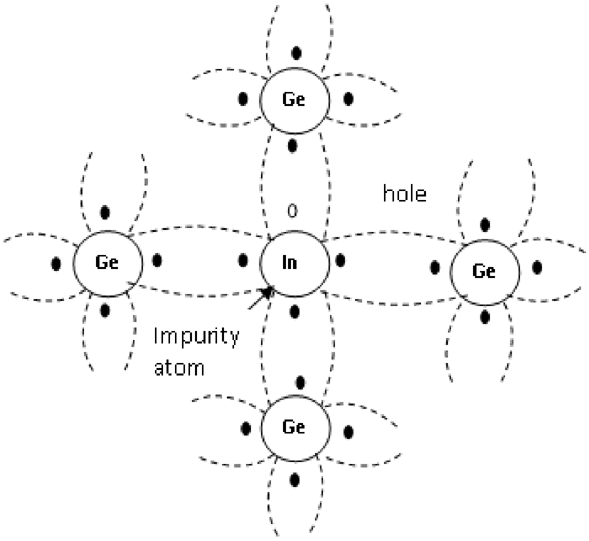
$$\mathbf{E_g = 2K_B(dy/dx)\ \ Joules}$$

EXTRINSIC SEMICONDUCTOR

- Impure semiconductors in which the charge carriers are produced due to impurity atoms are called extrinsic semiconductors.
- They are obtained by doping an intrinsic semiconductor with impurity atoms.
- Based on the type of impurity added they are classified into n-type semiconductor and p-type semiconductor.



n-type semiconductor



p-type semiconductor

(i) n-type semiconductor

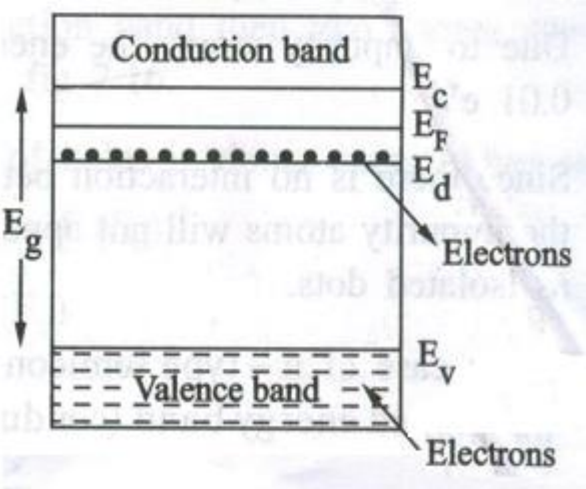
- N-type semiconductor is obtained by doping as intrinsic semiconductor with pentavalent impurity atoms like phosphorus, arsenic, antimony, etc.,
- The four valence electrons of the impurity atoms bond with 4 valence electrons of the semiconductor atom and the remaining 1 electron of the impurity atom is left free as shown in figure.
- Since electrons are donated in this type of semiconductor the energy level of these donated electrons is called donor energy level (E_d) as shown in figure.
- E_d is very close to conduction band and hence even at room temperature the electrons are easily excited to conduction band.
- The current flow in this type of semiconductor is due to electrons.

(ii) P-type semiconductor

- P-type semiconductor is obtained by doping an intrinsic semiconductor with trivalent impurity atoms like boron, Gallium, Indium, etc.,
- The three valence electrons of the impurity atom pairs with three valence electrons of semiconductor atom and one position of the impurity atom remains vacant, this is called hole as shown in figure.
- Therefore the no. of holes is increased with the impurity atoms added to it.
- Since holes are produced in excess, they are the majority charge carriers in p-type semiconductor and electrons are the minority charge carriers.
- Since the impurity can accept the electrons this energy level is called acceptor energy level (E_a) and is present just above the valence band as shown in figure.
- Here the current conduction is mainly due to holes.

CARRIER CONCENTRATION IN N-TYPE SEMICONDUCTOR

- The energy band structure of n-type semiconductor is as shown in figure.



- At 0 K, E_F will lie exactly between E_c and E_d, but even at low temperature some electrons may go from E_d to E_c.
- Let us assume that $E_c - E_F > K_B T$.
- Then the density of electrons in conduction band can be written as

$$n_e = 2\left[\frac{2\pi m_e^* K_B T}{h^2}\right]^{\frac{3}{2}} .\ e^{(E-E_F)/TK_B} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- Let N_d be the number of donor energy levels per cm^3 (i.e.,) density of state $Z(E_d)dE$, which has energy E_d below the conduction band.
- If some of the electrons are donated from donar energy level to conduction band say for example if two electrons go to conduction band then two vacant sites will be created in E_d levels as shown in figure.
- Thus in general we can write the density of holes in donar energy level as

$$N(E_d)dE = Z(E)dE.(1-F(E_d))$$

$$n_h = N_d\,(1-F(E_d)) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

we know

$$F(E_d) = \frac{1}{1+e^{(E_d-E_F)/TK_B}}$$

And

$$1 - F(E_d) = \frac{e^{(E_d-E_F)/TK_B}}{1+e^{(E_d-E_F)/TK_B}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$e^{(E_d-E_F)/TK_B} << 1$$

$$1 + e^{(E_d-E_F)/TK_B} = 1$$

Equation (3) becomes

$$1 - F(E_d) = e^{(E_d-E_F)/TK_B} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Substituting equn (4) in (2)

$$n_h = N_d e^{(E_d - E_F)/TK_B} \qquad \text{…………… (5)}$$

At equilibrium condition

No. of electrons per unit volume In conduction band	=	No. of holes per unit volume in donar energy level

Equating equn (1) & equn (5) and taking log on both sides we get

$$E_F = \frac{E_c + E_d}{2} + \frac{K_B T}{2} \log \left[\frac{N_d}{2\left\{\frac{2\pi m_e^* K_B T}{h^2}\right\}} \right] \qquad \text{……………. (6)}$$

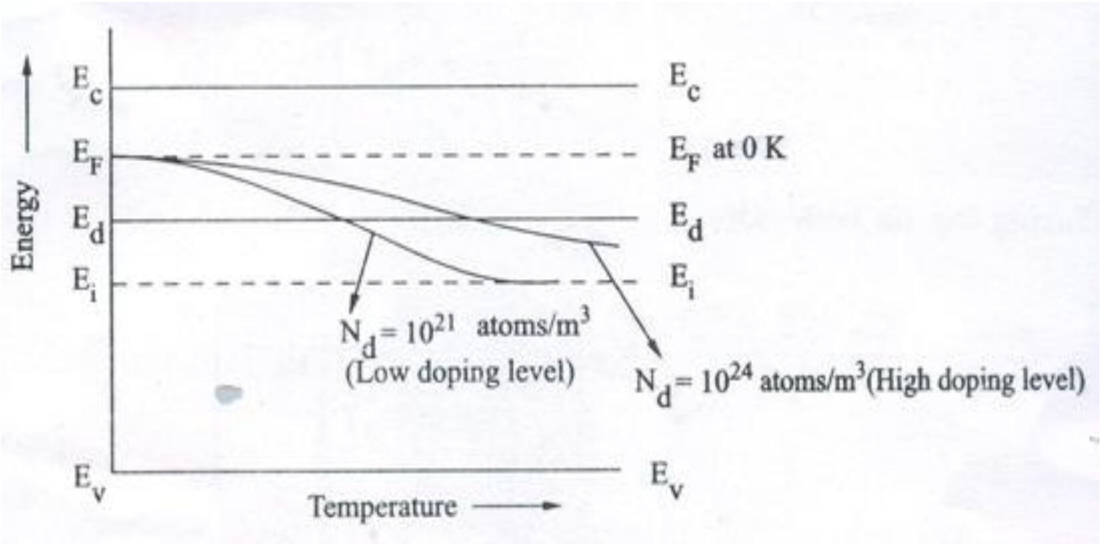
At 0K when T=0,

we can write the above equation as $E_f = (E_c + E_d)/2$ ………….. (7)

Eqn (7) shows that, at 0 K, E_F will lie exactly in the midway between E_c and E_d.

VARIATION OF FERMI ENERGY LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION IN n-TYPE SEMICONDUCTOR

- When the temperature is increased some electrons in E_d level may be shifted to conduction band and hence some vacant sites will be created in E_d levels.
- Therefore the Fermi level shifts down to separate that empty levels and the filled valence band level as shown in figure, for the doping level of $N_d = 10^{21}$ atoms/m^3.



- From the figure it can be seen that for the same temperature, if the impurity atoms i.e., doping level is increased, the electron concentration increases and hence the Fermi level increases.

Expression for Density of Electrons in Conduction Band in terms of N_d

Substituting equation (6) in (1) we get

$$n_e = 2\cdot\left\{\frac{2\pi m_e^* K_B T}{h^2}\right\}^{3/2}\cdot\exp\left\{\frac{\dfrac{(E_c+E_d)}{2}+\dfrac{K_B T}{2}\log\left(\dfrac{N_d}{2\cdot\left\{\dfrac{2\pi m_e^* K_B\,T}{h^2}\right\}^{3/2}}\right)-E_c}{K_B T}\right\}$$

$$\text{(or)}\quad n_e = 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}\exp\left[\frac{E_c+E_d-2E_c}{2K_B T}+\frac{1}{2}\log\left(\frac{N_d}{2\left(\dfrac{2\pi m_e^*\,K_B T}{h^2}\right)^{3/2}}\right)\right]$$

$$n_e = 2\cdot\left\{\frac{2\pi\,m_e^* K_B T}{h^2}\right\}^{3/2}.\exp\left(\frac{(E_d-E_c)}{2K_B T}+\log\left\{\frac{N_d^{1/2}}{(2)^{1/2}\left[\left(\dfrac{2\pi\,m_e^* K_B T}{h^2}\right)^{3/2}\right]^{1/2}}\right\}\right]$$

$$\text{(or)}\ n_e = 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}\exp\left[\frac{E_d-E_c}{2K_B T}\right]\exp\left[\log\left\{\frac{N_d^{1/2}}{2^{1/2}\left[\dfrac{2\pi m_e^* K_B T}{h^2}\right]^{3/4}}\right\}\right]$$

$$n_e = 2\left\{\frac{2\pi m_e^* K_B T}{h^2}\right\}^{3/2} e^{(E_d-E_c)/2K_B T}\left(\frac{N_d^{1/2}}{2^{1/2}\left\{\dfrac{2\pi m_e^* K_B T}{h^2}\right\}^{3/4}}\right)$$

$$\text{(or)}\qquad n_e = (2N_d)^{1/2}\left[\frac{2\pi m_e^*\,K_B\,T}{h^2}\right]^{3/4} e^{(E_d-E_c)/2\,K_B T}$$

Here $E_c - E_d = \Delta E$ is called as ***Ionisation energy of donors*** (i.e.) ΔE *represents the amount of energy required to transfer an electron from donar energy level* (E_d) *to conduction band* (E_c).

∴ We can write

$$\boxed{n_e = (2N_d)^{1/2}\left(\frac{2\pi\,m_e^*\,K_B\,T}{h^2}\right)^{3/4} e^{-\Delta E/2K_B T}} \qquad \text{...(8)}$$

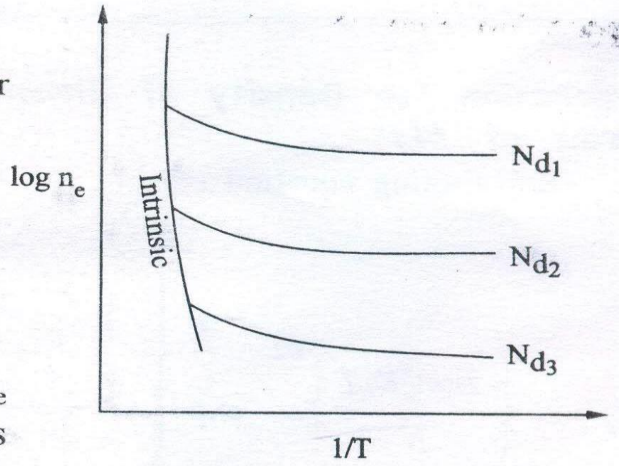
Ionisation Energy of Donor

To find the ionisation energy of donor equation (8) can be written as

$$n_e = C\, e^{-\Delta E/2K_BT}, \text{ where C is a constant}$$

$$\text{(or)} \quad \frac{\log n_e}{1/T} = -\Delta E/2K_B$$

If a graph is plotted between log n_e and 1/T we get lines (fig) for various values of donor impurity levels. From the slope $-\Delta E/2K_B$, the value of ionisation energy of donor can be calculated.



Results

- Density of electrons (n_e) in conduction band is proportional to the square root of donor concentration (N_d).
- When temperature is increased the Fermi level falls below the donor level and may approach only upto E_i (Fermi level of the intrinsic semi conductor).

Electrical Conductivity of n-type

We know the electrical conductivity (σ) is given by

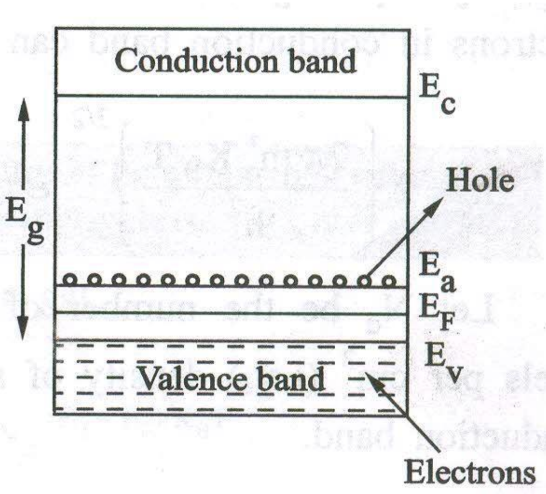
$$\sigma = n_e\, e\, (\mu_e + \mu_h)$$

For n-type semiconductor the acceptors are at the most zero. Therefore the mobility of charge carriers (holes) is zero. i.e., $\mu_h = 0$.

$$\boxed{\therefore\ \sigma = n_e\, e\, \mu_e}$$

CARRIER CONCENTRATION IN P-TYPE SEMICONDUCTOR

- For p-type at absolute zero E_f will be exactly between E_a and E_v.
- At low temperatures some electron from valence band fills the holes in the acceptor energy levels as shown in figure.



- We know the density of holes in the valence band,

$$n_h = 2\left[\frac{2\pi m_h^* K_B T}{h^2}\right]^{\frac{3}{2}} .\ e^{(E_v - E_F)/TK_B} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- Let N_a be the number of acceptor energy levels per cm^3 (i.e.,) density of state $Z(E_a)dE$, which has energy E_a below the conduction band.
- If some of the electrons are accepted by the acceptor energy level from valence band say for example if two electrons are accepted to fill the hole sites in the acceptor levels, then two holes will be created in valence band as shown in figure.
- Thus in general we can write the density of holes in donar energy level as

$$N(E_a)dE = Z(E_a)dE.F(E_a)$$

$$n_e = N_a .F(E_a) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

we know

$$F(E_a) = \frac{1}{1+e^{(E_a-E_F)/TK_B}}$$

And

$$e^{(E_a-E_F)/TK_B} >> 1$$

$$1 + e^{(E_a-E_F)/TK_B} = e^{(E_a-E_F)/TK_B}$$

$$F(E_a) = \frac{1}{e^{(E_a-E_F)/TK_B}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Substituting equn (3) in (2)

$$n_e = N_a\frac{N_a}{e^{(E_a-E_F)/TK_B}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

At equilibrium condition

No. of holes per unit volume = No. of electrons per unit volume
In valence band in acceptor energy level

Equating equn (1) & equn (4) and taking log on both sides we get

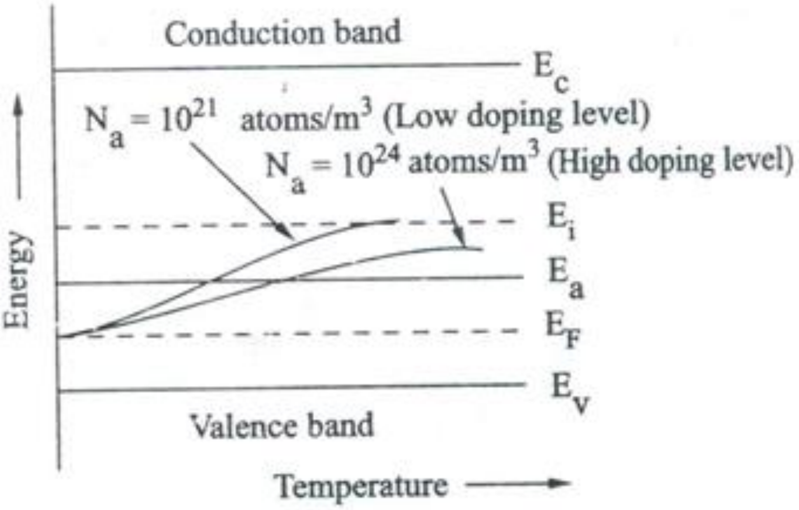
$$E_F = \frac{E_v+E_a}{2} + \frac{K_B T}{2}\log\left[\frac{N_a}{2\left\{\frac{2\pi m_h^* K_B T}{h^2}\right\}}\right] \qquad \ldots\ldots\ldots\ldots\ldots (5)$$

At 0K when T=0K,

We can write the above equation as $E_f = (E_v+E_a)/2$ ………….. (6)

VARIATION OF FERMI ENERGY LEVEL WITH TEMPERATURE AND IMPURITY CONCENTRATION IN P-TYPE SEMICONDUCTOR

- When the temperature is increased, some of the electrons in the valence band will go to acceptor energy levels by breaking up the covalent bonds and hence the Fermi level is shifted in upward direction for doping level of $N_d = 10^{21}$ atoms/m^3 as shown in figure.



- From the figure it can be seen that for the same temperature, if the impurity atoms doping level is increased say $N_a = 10^{24}$ atoms/m^3, the hole concentration increases and hence the Fermi level decreases.
- Therefore at low temperature the Fermi energy level may be increased upto the level of intrinsic energy level (E_i)

Expression for Density of Holes in Terms of N_a

Substituting equation (5) in (1) we get

$$n_h = 2 \cdot \left\{ \frac{2\pi\, m_h^*\, K_B T}{h^2} \right\}^{3/2} \cdot \exp \left\{ \frac{E_v - \left[\frac{(E_v + E_a)}{2} - \frac{K_B\, T}{2} \log \left(\frac{N_a}{2 \cdot \left\{ \frac{2\pi\, m_h{}^*\, K_B T}{h^2} \right\}^{3/2}} \right) \right]}{K_B\, T} \right\}$$

$$\text{(or)} \quad n_h = 2 \left(\frac{2\pi m_h^* K_B T}{h^2} \right)^{3/2} \exp \left[\frac{2E_v - E_v - E_a}{2K_B T} + \frac{1}{2} \log \left(\frac{N_a}{2 \left(\frac{2\pi m_h^* K_B T}{h^2} \right)^{3/2}} \right) \right]$$

$$n_h = 2 \cdot \left\{ \frac{2\pi\, m_h^*\, K_B\, T}{h^2} \right\}^{3/2} \cdot \exp \left\{ \frac{(E_v - E_a)}{2\, K_B\, T} + \frac{1}{2} \log \left(\frac{(N_a)}{2 \left\{ \frac{2\pi\, m_h^*\, K_B\, T}{h^2} \right\}^{3/2}} \right) \right\}$$

$$n_h = 2 \left[\frac{2\pi m_h^* K_B T}{h^2} \right]^{3/2} \exp \left[\frac{E_v - E_a}{2K_B T} \right] \exp \left[\log \left(\frac{N_a^{1/2}}{(2)^{1/2} \left[\left(\frac{2\pi m_h^* K_B T}{h^2} \right)^{3/2} \right]^{1/2}} \right) \right]$$

$$\text{(or)} \quad n_h = 2 \cdot \left\{ \frac{2\pi\, m_h^*\, K_B T}{h^2} \right\}^{3/2} \cdot e^{(E_v - E_a)/2K_B T} \cdot \left(\frac{N_a^{1/2}}{2^{1/2} \cdot \left\{ \frac{2\pi\, m_h^*\, K_B T}{h^2} \right\}^{3/4}} \right)$$

$$\mathbf{n_h = (2N_a)^{1/2} \cdot \left[\frac{2\pi\, m_h^*\, K_B T}{h^2} \right]^{3/4} \cdot e^{(E_v - E_a)/2K_B T}} \qquad \text{...(7)}$$

Here $E_a - E_v = \Delta E$ is known as ***ionisation energy of acceptors*** *i.e., ΔE represents the energy required for an electron to move from valence band* (E_v) *to acceptor energy level* (E_a).

Therefore equation (7) becomes

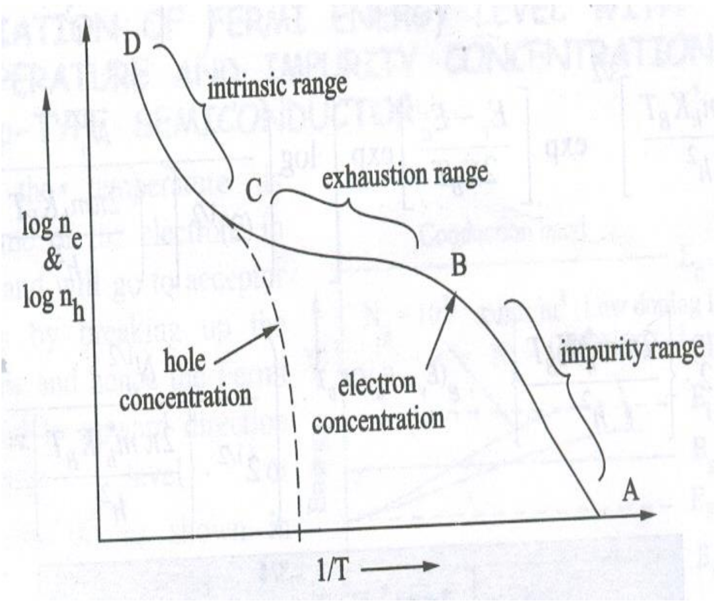
$$\mathbf{n_h = (2N_a)^{1/2} \cdot \left[\frac{2\pi\, m_h^*\, K_B T}{h^2} \right]^{3/4} \cdot e^{-\Delta E/2K_B T}} \qquad \text{...(8)}$$

VARIATION OF CARRIER CONCENTRATION WITH TEMPERATURE

- The carrier concentration in n-type semiconductor varies with the increase in the temperature.

Electron concentration

- At very low temperature at 0 K, 1/T is high, the Fermi level will be exactly in the middle between E_c and E_d and the carrier concentration is at the most zero in the conduction band and hence point A is obtained in the graph.



- Now when the temperature is slowly increased, the donar atom gets ionized and the electrons move towards conduction band.
- Hence the carrier concentration increases slowly in the conduction band for electrons.
- Since this range is obtained due to impurity atoms, it is called impurity range shown by curve AB in figure.
- The range is obtained due to exhaustion of donor atoms it is called exhaustion range, shown by curve BC in figure.
- Since the number of available electrons in donor energy level is almost exhausted, many number of electrons are shifted from valence band to conduction band and thus the carrier concentration increases rapidly, tracing the curve CD.
- Since the material practically becomes intrinsic in this range, this range is known as intrinsic range.

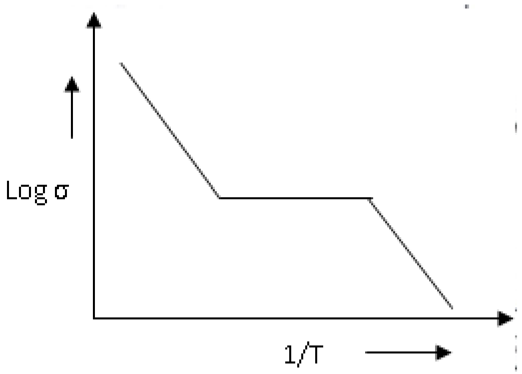
Hole Concentration

- At 0K electrons concentration is zero in conduction band.
- Now when temperature is increased slowly the electrons will move from donor energy level to conduction band.

- Now when temperature is very high the electrons are transferred from valence band to conduction band and holes are created in valence band.
- The electron concentration in conduction band equalizes the hole concentration in valence band.
- So electron concentration curve and hole concentration curve overlaps only in the intrinsic region.

Conductivity of Extrinsic semiconductor

- The variation in the conductivity of an extrinsic semiconductor, with the increase in temperature is as shown in figure.



- When the temperature is slowly increased from 0K impurity atoms are slowly ionized and goes to conduction band and hence conductivity increases.
- When all the impurities are ionized the mobility of charge carriers decreases slightly and therefore logσ becomes constant (or) may slightly decrease.

Carrier tansport

In semiconductor electrons and holes are called carriers, which moves from one position to another and this movement of charge carriers is called Carrier tansport.

In the absence of field (Random Motion)

In the absence of external field, the charge carrier moves in random direction due to its thermal energy. The path of the charge carrier changes due to scattering by the vibration of the lattice points and by the coulomb force of ionised donar and acceptor atoms in the semiconductor.

In the presence of field (Drift)

Now when the charge carriers are subjected to external fields, then they move with a velocity called drift velocity, and reaches steady state.

At steady state

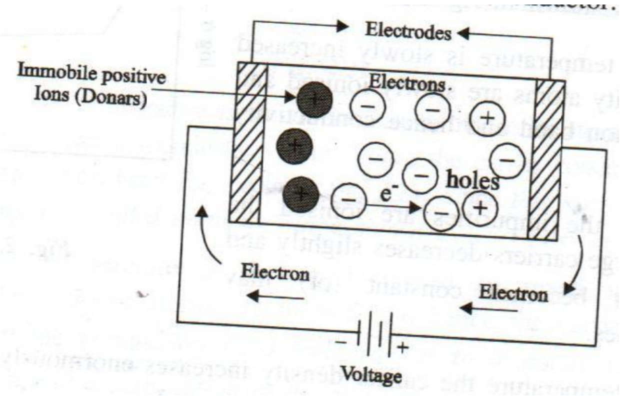
The rate of momentum gained due to external field = The rate of momentum lost due to scattering

Thus during steady state a steady current flows due to the carrier transport in semiconductors.

i. Carrier transport in n -type semiconductor

We know that in n -type semiconductor the electrons are majority charge carriers and holes are minority charge carriers. Apart from this, there will be equal number of immobile positive ions (grey shaded) in n -type semiconductor.

Let us consider an n -type semiconductor placed between a pair of electrodes, for which a voltage is applied as shown in figure.



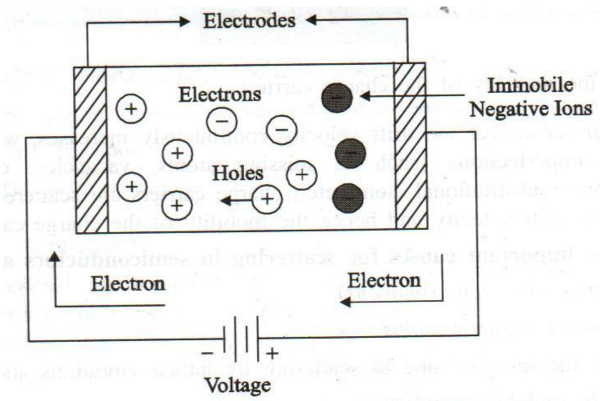
Due to the field applied the electrons in the semiconductor move towards the positive terminal and they disappear. At the same time equal numbers of electrons are generated at the negative terminal. These electrons are attracted by the immobile positive ions present in the semiconductor and therefore a continuous flow of electrons from one terminal to other terminal takes place through the semiconductor.

The net current flow in the semiconductor depends on the biasing voltage.

ii. Carrier transport in p -type semiconductor

We know that in p -type semiconductor the holes are majority charge carriers and electrons are minority charge carriers. Apart from this, there will be equal number of immobile negative ions (grey shaded) in p -type semiconductor.

Let us consider a p -type semiconductor placed between a pair of electrodes, for which a voltage is applied as shown in figure.



Due to the field applied the holes in the semiconductor move towards the negative terminal and they combine with the electrons coming out from the negative terminal and disappears. At the same time equal numbers of holes are generated near the positive terminal. These holes are attracted by the immobile negative ions present in the semiconductor towards the positive terminal and thus current to continuous flow.

During this process an electron is lost by the acceptor atom and therefore it try to get back an electron from the adjacent atom to fill that hole in the semiconductor. This process continues and hole current occurs inside the semiconductor.

PROBLEMS

1. Find the resistance of an intrinsic Ge rod 1cm long, 1mm wide and 1mm thick at 3000k.

For Ge $n_i = 2.5 \times 10^{19}/m^3$
$\mu_e = 0.39\ m^{-2}\ V^{-1}\ s^{-1}$
$\mu_h = 0.19\ m^2\ V^{-1}\ s^{-1}$

Solution

Conductivity of an intrinsic semiconductor is $\boldsymbol{\sigma_i = n_i e(\mu_e+\mu_h)}$

$\sigma = 2.5 \times 10^{19} \times 1.6 \times 10^{-19}\ (0.39+0.19)$
$\boldsymbol{\sigma = 2.32}$

Resistance $R=\rho l/A$

$R = 1\times10^{-2} / 2.32 \times(1 \times 10^{-3} \times 1 \times 10^{-3})$

R= 4310 ohm.

2. The sample of silicon is doped with 10^{16} phosphor atoms / m^3. Find the hall voltage in a sample with thickness 500 mm, area of cross section 2.25×10^{-3} m^2, current 1A and magnetic field 10×10^4 Wb/m^2.

Solution

Given data:

$n_e = 10^{16}$ m^3 , $B = 10^4$ Wb/m^2

$J_x = ½2.55 \times 10^{-3}$

$= 444.44$ A/m^2

T= 500mm

$R_H = 1/n_e e$

$R_H = 1/10^{16} \times 1.6 \times 10^{-19}$

$R_H = 625$

Hall Voltage $V_H = R_H J_x Bt$

$V_H = 625 \times 444.44 \times 10 \times 10^4 \times 5000\ 10^{-3}$

$\mathbf{V_H = 1.3888 \times 10^{10}}$ **Volts**

UNIT-IV

LOSSES IN OPTICAL FIBERS- ATTENUATION

When light propagates through an optical fiber, a small percentage of light is lost through different mechanisms. The loss of optical power is measured in terms of decibels per kilometer for attenuation losses.

Attenuation

It is defined as the ratio of the optical power output (P_{out}) from a fiber of length 'L' to the power input (p_{in})

$$\text{ie. Attenuation } (\alpha) = \frac{-10}{L}\log\frac{P_{in}}{P_{out}} \text{ dB/km}$$

Since attenuation plays a major role in determining the transmission distance, the following attenuation mechanisms are to be considered in designing an optical fiber.

(1) Absorption

(2) Scattering

(3) Radiative losses.

1. Absorption

Usually absorption of light occurs due to imperfections of the atomic structure such as missing molecules, (OH^-) hydroxyl ions, high density cluster of atoms etc., which absorbs light.

Absorption also depends on the wavelength of the light used. The three bands of wavelength at which the absorption increases drastically is 950 nm, 1250 nm and 1380 nm. For example, at the wavelength say 850 nm the absorption is 1.5 dB/Km and for 1500 nm, it is 0.5 dB/Km.

2. Scattering

Scattering is also a wavelength dependent loss, which occurs inside the fibers. Since the glass is used in fabrication of fibers, the disordered structure of glass will make some variations in the refractive index inside the fiber. As a result, if is passed through the atoms in the fiber, a portion of the light is scattered (elastic scattering). This type of scattering is called Rayleigh scattering. i.e., Rayleigh scattering loss $\alpha \frac{1}{\lambda^4}$

3. **Radiative losses**

Radiative loss occurs in fibers, due to bending of finite radius ofc curvature in optical fibers.

PRINCIPLE OF SPONTANEOUS AND STIMULATED EMISSION EINSTEIN'S QUANTUM THEORY OF RADIATION

When light is absorbed by the atoms or molecules, then it goes from the lower energy level (E_1) to the higher energy level (E_2) and during the transition from higher energy level (E_2) to lower energy level (E_1), the light is emitted from the atoms or molecules.Let us consider an atom exposed to (light) photons of energy E_2-E_1= h^{γ}, three distinct processes takes place.

i. Absorption

ii. Spontaneous emission

iii. Stimulated emission

i. Absorption

An atom in the lower energy level or ground state energy level E_1absorbs the incident photon radiation of energy (h^{γ}) and goes to the higher energy level or excited energy state E_2 as shown in fig 5.1. This process is called as absorption.

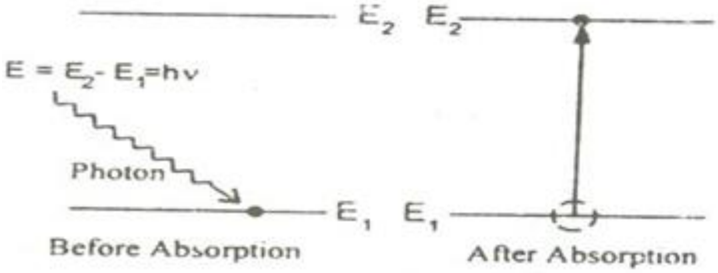


Fig. 5.1

If there are many number of atoms in the ground state then each atom will absorb the energy from the incident photon and goes to the excited state then,

The rate of absorption (R_{12}) is proportional to the following factors.

i.e. R_{12} α Energy density of incident radiation (ρ_v)

α No of atoms in the ground state (N_1)

i.e. $R_{12} \alpha \rho_v N_1$

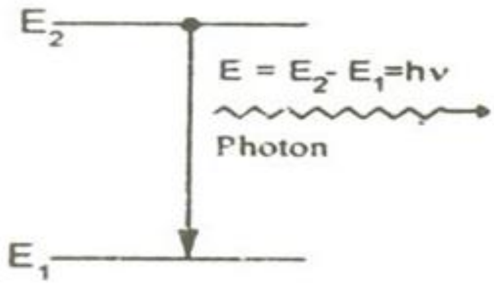
or $R_{12} = B_{12} \rho_v N_1$ ----(1)

Where, B_{12} is a constant which gives the probability of absorption transition per unit time.

ii. Spontaneous emission

The atom in the excited state returns to the ground state by emitting a photon of energy E= (E_2– E_1) = h^{γ}, spontaneously without any external triggering as shown.

This process is known as spontaneous emission. Such an emission is random and is independent of incident radiation.



If N_1 and N_2 are the numbers of atoms in the ground state (E_1) and excited state (E_2) respectively, then

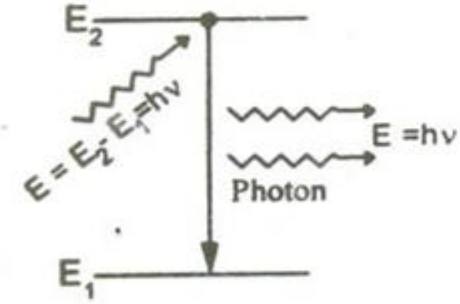
The rate of spontaneous emission is R_{21} (Sp) α N_2

$$\text{(or) } R_{21}\text{ (Sp)} = A_{21}N_2 \qquad \text{-----(2)}$$

Where, A_{21} is a constant which gives the probability of spontaneous emission transition per unit time.

iii. Stimulated emission

The atom in the excited state can also return to the ground state by external triggering (or) inducement of photon there by emitting a photon of energy equal to the energy of the incident photon, known as stimulated emission. Thus results in two photons of same energy, phase difference and of same directionality as shown.



The rate of stimulated emission is R_{21} (St) α ρ_v N_2

$$\text{(or)} \qquad R_{21}\text{ (St)} = B_{21}\,\rho_v\,N_2 \qquad \text{----(3)}$$

Where, B_{21} is a constant which gives the probability of stimulated emission transition per unit time.

Einstein's theory

Einstein's theory of absorption and emission of light by an atom is based on Planck's theory of radiation. Also under thermal equilibrium, the population of energy levels obeys the Boltzmann's distribution law.

i.e. under thermal equilibrium

The rate of absorption = The rate of emission

$$B_{12}\,\rho_v\,N_1 = A_{21}N_2 + B_{21}\,\rho_v\,N_2$$

$$\rho_v\,[B_{12}\,N_1 - B_{21}\,N_2\,] = A_{21}N_2$$

$$\therefore \rho_v = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}$$

$$\therefore \rho_v = \frac{A_{21}}{B_{12}(^{N_1}/_{N_2}) - B_{21}} \qquad \text{----(4)}$$

We know from Boltzmann distribution law

$$N_1 = N_0 e^{-E_1/K_BT}$$

Similarly

$$N_2 = N_0 e^{-E_2/K_BT}$$

Where

K_B - Boltzmann Constant

N_0 - Number of atoms at absolute zero

T- Absolute temperature

At equilibrium, we can write the ratio of population levels as follows,

$$\frac{N_1}{N_2} = e^{(E_2 - E_1)/K_BT}$$

Since $E_2 - E_1 = h\vartheta$, we have

$$\frac{N_1}{N_2} = e^{h\vartheta/K_BT} \qquad \text{----(5)}$$

Sub eqn (5) in (4), we get

$$\rho_v = \frac{A_{21}}{B_{12}(e^{h\vartheta/K_BT}) - B_{21}}$$

$$\rho_v = \frac{A_{21}}{B_{21}} \frac{1}{(B_{12}/B_{21})e^{h\vartheta/K_BT} - 1} \qquad \text{----(6)}$$

This equation has a very good agreement with plank’s energy distribution radiation law

$$\rho_v = \frac{8\pi h\vartheta^3}{C^3} \frac{1}{e^{h\vartheta/K_BT} - 1} \qquad \text{---(7)}$$

Therefore comparing (6) and (7), we have

$$B_{12} = B_{21} = B$$

and $$\frac{A_{21}}{B_{21}} = \frac{8\pi h\vartheta^3}{C^3} \qquad \text{----(8)}$$

Taking $A_{21} = A$

The constants A and B are called as Einstein Coefficients, which accounts for spontaneous and stimulated emission probabilities. Ratio of magnitudes of stimulated and spontaneous emission rates are as follows,

From eqn (2) and (3) we have

$$\frac{R_{21}(st)}{R_{21}(sp)} = \frac{B_{21}\rho_v N_2}{A_{21}N_2}$$

$$\frac{R_{21}(st)}{R_{21}(sp)} = \frac{B_{21}\rho_v}{A_{21}} \qquad \text{---(9)}$$

Rearranging eqn (6) we can write

$$\frac{B_{21}\rho_v}{A_{21}} = \frac{1}{(B_{12}/B_{21})e^{h\vartheta/K_BT}-1}$$

Since$B_{12} = B_{21}$, we have

$$\frac{1}{e^{h\vartheta/K_BT}-1} = \frac{B_{21}\rho_v}{A_{21}} \qquad \text{--- (10)}$$

Comparing (9) and (10) we get

$$\frac{R_{21}(st)}{R_{21}(sp)} = \frac{1}{e^{h\vartheta/K_BT}-1} = \frac{B_{21}\rho_v}{A_{21}}$$

In simpler way the ratio can be written as

$$R = \frac{B_{21}\rho_v}{A_{21}}$$

Generally spontaneous emission is more predominant in the optical region (ordinary light). To increase the number of coherent photons stimulated emission should dominate over spontaneous emission.

5.4 DIFFERENCE BETWEEN SPONTANEOUS AND STIMULATED EMISSION OF RADIATION

S. No	**Stimulated emission**	**spontaneous emission**
1.	An atom in the excited state is induced to return to ground state, thereby resulting in two photons of same frequency and energy is called stimulated emission.	The atom in the excited state returns to ground state thereby emitting a photon, without any external inducement is called spontaneous emission.
2.	The emitted photons move in same direction and is highly directional	The emitted photons move in all directions and are random.
3.	The radiation is high intense, monochromatic and coherent.	The radiation is less intense and is incoherent.
4.	The photons are in phase (i.e.) there is a constant phase difference.	The photons are not in phase (ie.) there is no phase relationship between them.
5.	The rate of transition is given by $R_{21}(St) = B_{21}\,\rho_v\,N_2$	The rate of transition is given by $R_{21}(Sp) = A_{21}N_2$

1. **Calculation of wavelength**

Band gap of GaAs = 1.44ev

$$E_g = h\,\gamma = h\frac{c}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

$$= \frac{6.625 \text{ x } 10^{-34} \text{ x } 3 \text{ x } 10^{8}}{1.44 \text{ x } 1.6 \text{ x } 10^{-19}}$$

$$= 8626 \text{ A}^{\circ}$$

The wavelength is near IR region.

Advantages

(i) It is easy to manufacture the diode.

(ii) The cost is low.

Disadvantages

(i) It produces low power output.

(ii) The output wave is pulsed and will be continuous only for some time.

(iii) The beam has large divergence.

(iv) They have high threshold current density.

Light Emitting Diodes

It is a semiconductor p-n junction diode which emits light when it is forward biased.

Principle:

The electrons injected into the p- region make a direct downward transition from the conduction band into valence band and they recombine with holes and emit photons of energy Eg.

We know that the forbidden gap energy is given by

$$E_g = h\nu \qquad \longrightarrow \qquad (1)$$

Where h = Planck’s constant

ν = frequency of the emitted radiation

But we know $\nu = \dfrac{c}{\lambda} \qquad \longrightarrow \qquad (2)$

Substituting (2) in (1)

$$E_g = \frac{hc}{\lambda}$$

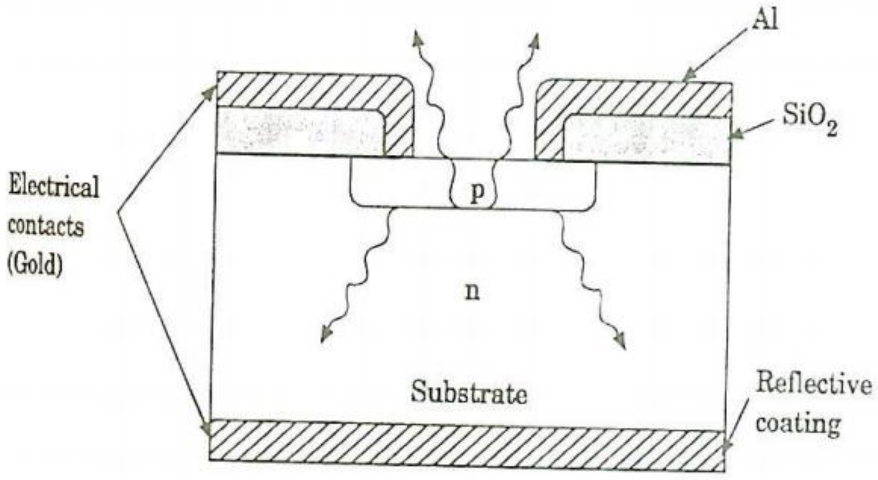
Hence, the wavelength of the emitted photon is given by relation

$$\lambda = \frac{hc}{E_g}$$

Therefore, the wavelength of the light emitted purely depends on the band gap energy.

Construction:

A n- type layer is grown on a substrate and a p- type layer is deposited on it by diffusion. Since carrier recombination takes place in the p-layer, it is deposited upper most. For maximum light emission, a metal film anode is deposited at the outer edges of the p-layer. The bottom of the substrate is coated with metal (gold) film for reflecting most of the light surface of the device and also to provide connection with n-type layer.

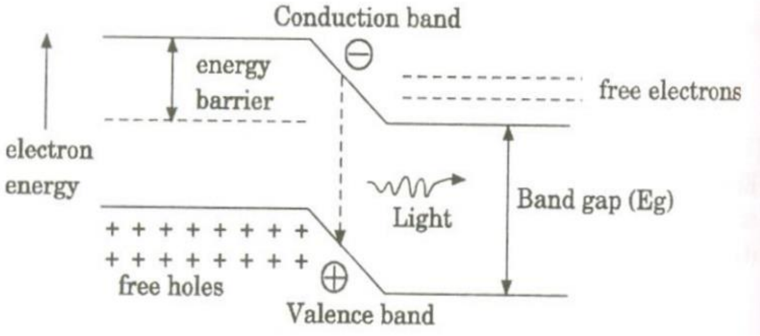


Working:

When the p –n junction diode is forward biased, the barrier width is reduced, raising the potential energy on the n-side and lowering that on the p-side.

The free electrons and holes have sufficient energy to move into the junction region. If a free electron meets a hole, it recombines with each other resulting in the release of a photon

Thus light radiation of the LED is caused by the recombination of holes and electrons that are injected into the junction by forward bias voltage.



Advantages:

1. Light output is proportional to the current. Hence, the light intensity of LEDs can be controlled easily by varying the current flow.
2. LEDs are rugged and therefore withstand shocks and vibrations.
3. Varieties of LEDs are available which emit in different colours like red, green, yellow etc.
4. It has long life time and high degree of reliability.
5. It has low drive voltage and low noise.
6. It is easily interfaced to digital logic circuits.
7. It can be operated over a wide range of temperatures.

Disadvantages:

1. It requires high power.
2. Its preparation cost is high.
3. LED is not suitable for large area display because of its high cost.
4. It cannot be used for illumination purposes.

UNIT – V

ENGINEERED SEMICONDUCTOR MATERIALS

NANO PHASE MATERIALS

Nanophase materials are materials with a grain size in the 1 to 100 nm range and these atoms will not move away from each other.

Ex: ZnO, Cu- Fe alloys

Nanophase materials exhibit greatly altered mechanical properties compared to their normal, large-grained counterparts with the same chemical composition. For example, nanophase metals are up to five times harder than the normal materials. While nanophase metals generally become harder and more brittle, nanophase ceramics become more ductile. In a typical nanophase material, 10 to 50% of the atoms are in grain boundary regions. These new materials are called nano materials and the developed technology is called nano technology.

Quantum Confinement

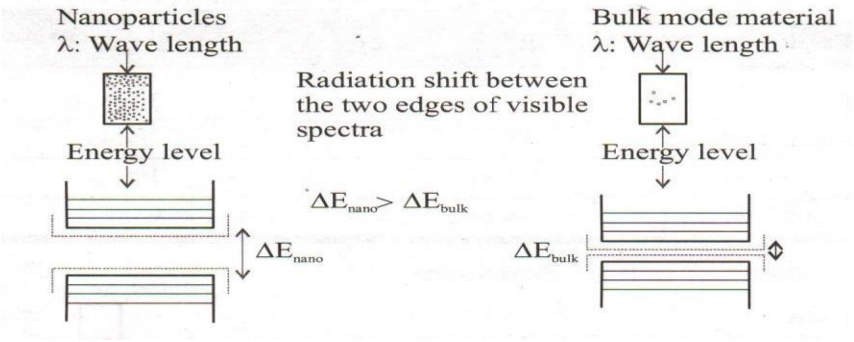
Definition

The effect achieved by reducing the volume of a solid so that the energy levels with in it becomes is called quantum confinement.

Explanation

The quantum confinement effect is observed when the size of the particle is too small to be comparable to the wavelength of the electron.

The word confinement means to confine the motion of randomly moving electron to restrict its motion in specific enrgy levels (discreteness) and quantum reflects the atomic dimension of particles.



If we decrease the size of the particle to the nano size, the decrease in confining size creates the energy levels discrete. The formation of discrete energy levels increases or widens up the band gap and finally the band gap energy also increases as shown in figure.

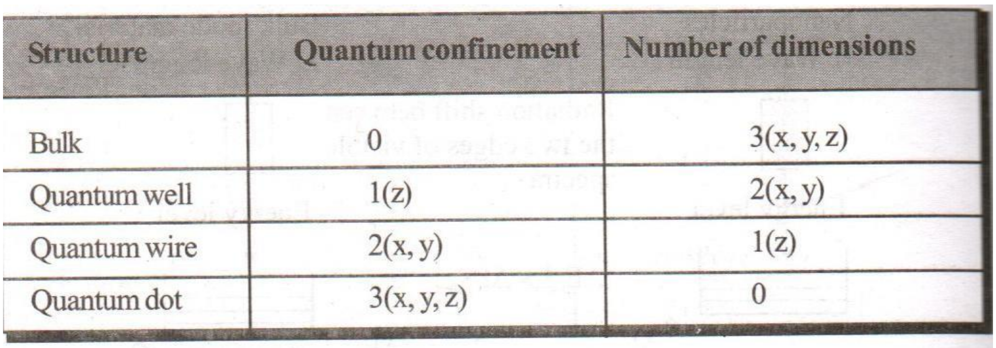
Due to this, there is significant change in the electronic and optical materials of nano dimensions as compared to the bulk materials.

Quantum Structures

Volume is a three dimensional quantity. To reduce the volume of the box, we can shorten its length, its width or its height.

A quantum confined structure is one in which the motion of the electrons or holes are confined in one or more directions by potential barriers.

Based on confinement direction, a quantum confined structure will be classified into three categories as quantum well, quantum wire and quantum dot. The classification of quantum confined structures is shown in below table.



Structure	Quantum confinement	Number of dimensions
Bulk	0	3(x, y, z)
Quantum well	1(z)	2(x, y)
Quantum wire	2(x, y)	1(z)
Quantum dot	3(x, y, z)	0

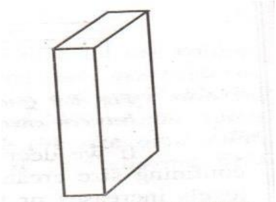
i) Quantum well (2 dimension)

Definition

When we constrain electrons inside a region of minimal width, we create a quantum well.

In other words, if one dimension is reduced to the nano range while other two dimensions remain large, then we get a structure known as quantum well.

Figure shows a 2-D structure or quantum well.



quantum Well (2D)

Construction

Quantum wells are made from alternative layers of different semiconductors or by deposition of very thin metal films.

Explanation

The well is like a cage in which the carrier particles (the excitons) are trapped. These trapped particles can be considered to be quantum confinement.

Due to this quantum confinement, the motion of charge carriers is reduced. In a quantum well, the excitons can move freely sideways in the plane of thin layers, but they might like to move in the forward and backward directions as well. Due to confinement charge carriers, the structure quantum well has important applications in making useful devices.

Use

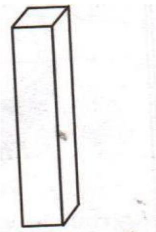
Quantum wells are widely used to make semiconductor layers and other important devices.

ii. Quantum wire (1 dimension)

Definition

If we constrain width and depth of electrons domain, we create a quantum wire.

In other words, if two dimensions are so reduced and remains large, the resulting structure is quantum wire.



Quantum wire

The above figure shows a 1-D structure or quantum wire.

Explanation

The carriers trapped in such structures can be considered to be in 1-D quantum confinement. In this case, an exciton is only free to choose its trajectory along the wire. However, for each motion of its movement, the exciton can have various ways of being confined.

Example

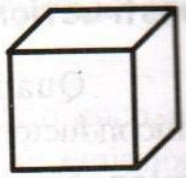
Examples of quantum wire structures are nanowires, nanorod and nanotube.

iii) Quantum Dots (0-dimension)

Definition

When all three dimensions are minimized the resulting structure is quantum dot.

The dot can be particle located inside a larger structure or on its surface. It can also be a place where electrons have been trapped using electric fields.



Quantum dot

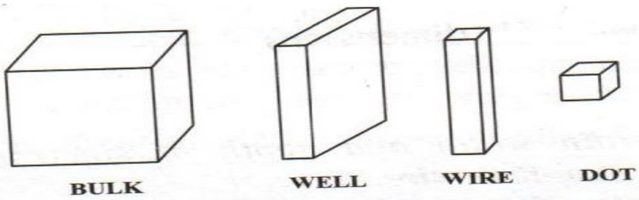
The above figure shows the 0-D structure or quantum dot.

Explanation

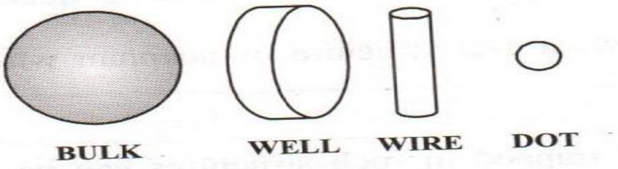
Hence in this situation, the exciton only has confined states i.e. there are no freely moving excitons. Although a quantum dot has many thousands of atoms, but due to its peculiar properties, it is considered more like a single atom rather than many atoms.

Use

Quantum Dot may be used as a basic building block in making quantum computer.

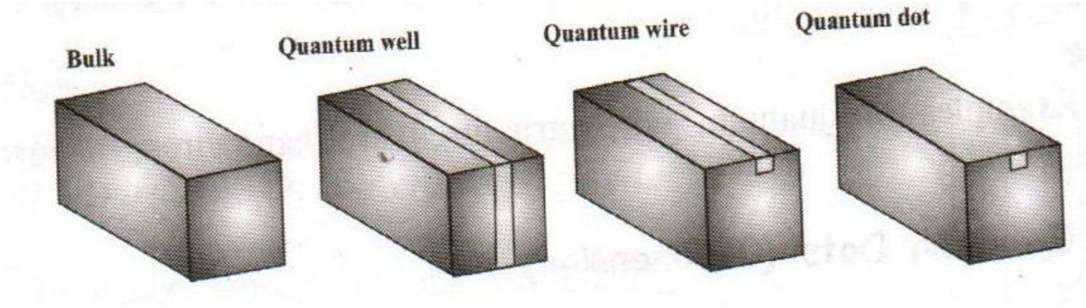


Progressive generation of rectangular nanostructures.



Progressive generation of curvilinear nanostructures.

The above figure shows the processes of diminishing the size for the case of rectilinear geometry and curvilinear geometry respectively.



Three quantum structures

The above figure shows the comparison of three quantum confined structures with bulk material.

SYNTHESIS OF NANO PHASE MATERIALS

Nanophase materials can be synthesised in any of the two ways viz.,

- **Top down approach** in which bulk materials are broken into nanosized materials.
- **Bottom up approach** in which nano materials are made by building atom by atom.

VARIOUS TECHNIQUES

- Plasma – arching
- Chemical vapour deposition
- Sol – gel technique
- Electro – deposition
- Ball milling
- Laser synthesis
- Inert gas condensation etc.,

Using the above techniques it is possible to produce nano phase materials in the form of nano – particles, nano – powders, nano – crystals, nano – films, nano – wires, nano – tubes, nano – dots etc.,

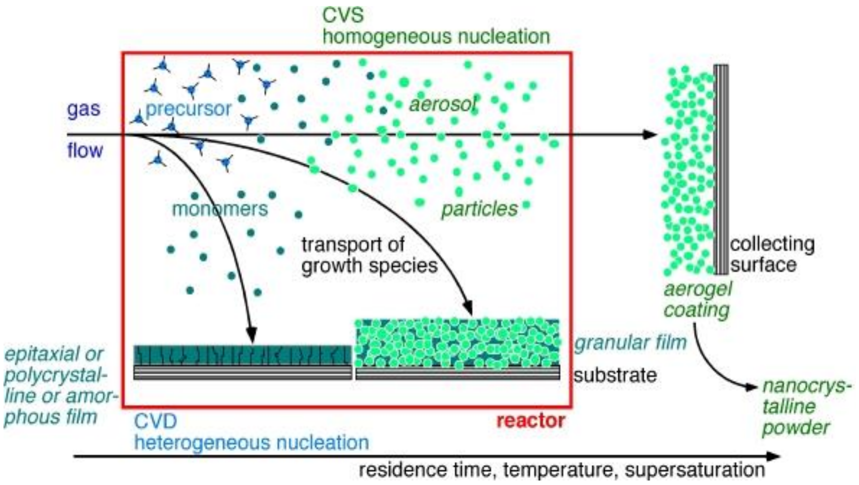
CHEMICAL VAPOUR DEPOSITION

This method is used to prepare nano – powder. In this method, the material is heated to form a gas and is allowed to deposit on a solid surface under vacuum condition, which forms nano – powders on the surface of the solid. This method can also be used to grow surfaces, i e., suppose if an object has to be coated with nano – powders, then the object has to be introduced inside the chemical vapour deposition area so that the nano – powders can be deposited all over the object.

Examples: (i) Nano – powders of oxides and carbides

(ii) Pure metal nano – powders

Chemical Vapor Synthesis of Nanocrystalline Powders



Chemical Vapor Deposition (CVD) method is used to form nanoparticles. In CVD, precursors are metalorganics, carbonyls, hydrides, chlorides and other volatile compounds in gaseous, liquid or solid state are used. The major limitation of the CVD process is the availability of appropriate precursor materials. The energy for the conversion of the reactants into nanoparticles is supplied in hot wall (external furnace), flame (reaction enthalpy), plasma (microwave or radio frequency) and laser (photolysis or pyrolysis) reactors.

The most important process parameters determining the quality of the nanopowders are the total pressure (typical range from 100 to 100000 Pa), the precursor material (decomposition kinetics and ligands determining the impurity level), the partial pressure of the precursor (determining the production rate and particle size), the temperature or power of the energy source, the carrier gas (mass flow determining the residence time) and the reactor geometry.

The nanoparticles are extracted from the aerosol by means of filters, thermophoretic collectors, electrostatic precipitators or scrubbing in a liquid. A typical laboratory reactor (shown schematically in the figure below) consists of a precursor delivery system, a reaction zone, a particle collector and a pumping system. Modifications of the precursor delivery system and the reaction zone allow the synthesis of pure oxides, doped oxides, coated nanoparticles, functionalized nanoparticles and granular films.

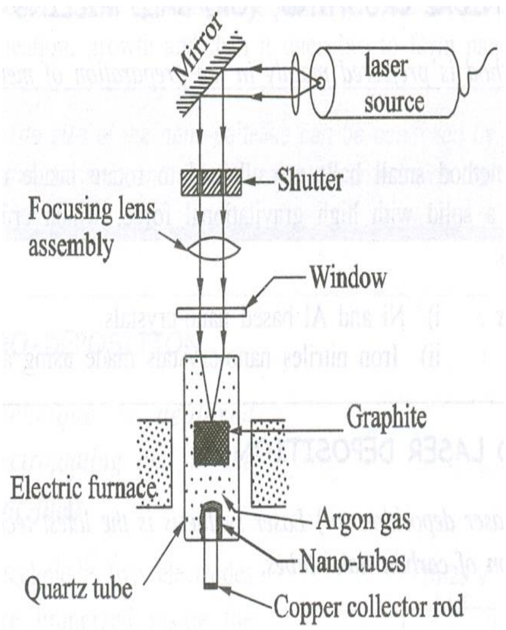
PULSED LASER DEPOSITION

Pulsed laser deposition is the latest technique adopted for the preparation of carbon nano tubes.

Principle

The technique of laser heat treatment is used in the preparation of carbon nano tubes. Ruby laser, Nd – YAG laser and CO_2 laser are used for this purpose.

Instrumentation



The Instrumentation for the fabrication of carbon nano tubes consists of a quartz tube containing a graphite target kept in argon gas region. The tube is surrounded by an electric furnace in order to heat the target. A colder copper collector rod is used to collect the nano carbons emitted by the graphite. Along with this it also consists of a pulsed laser source to produce laser beam, shutter to control the intensity of the laser beam and an assembly of lenses to effectively focus the laser onto the graphite.

Synthesis

Initially the graphite is heated upto 1200°C with the help of the electric furnace. An intense laser beam can be used to evaporate carbon from the graphite and thus now the laser source is switched ON. The light reflected by the plane mirror is made to pass through the shutter and hence the intensity is controlled. Then the beam is made to fall on the focussing lens assembly. This lens assembly focuses the light effectively onto the window and is made to incident on the graphite.

Due to laser heating the graphite gets heated and evaporates carbon atoms. The argon gas present inside the quartz tube is used to sweep the carbon atoms towards the colder copper collector rod. Thus, due to the movement of carbon atoms from a higher temperature to a lower temperature region it gets condensed and hence carbon nano tubes are formed over the collector rod. The cobalt and nickel present in the graphite act as catalytic nucleation sites for the formation of carbon nano tubes.

PROPERTIES OF NANO MATERIALS

(i) **Physical Properties**

  a) Interparticle spacing is very less in nano materials
  b) They have high strength and super hardness because it does not have any dislocation in it.

c) The melting point of nano materials will be very less.

(ii) Electronic Properties

a) Energy bands in these materials will be very narrow.
b) The ionization potential is very high for nano materials.
c) They have more localized molecular bonds.

(iii) Magnetic Properties

a) The atoms will have less co-ordination number and hence possess local magnetic moment within themselves.
b) They exhibit spontaneous magnetisation.
c) Ferro – magnetic and anti - ferro magnetic multi layer nano materials has GMR (Giant Magneto Resistance) effect.
d) The nano materials shows variation in their magnetic property, when they change from bulk state to cluster state.

(iv)**Mechanical Properties**

a) The hardness of nano phase materials varies from material to material. This may be due to the phase transformation, stress relief, density and grain boundaries.
b) They exhibit super plastic behaviour.

APPLICATIONS OF NANO MATERIALS

They have applications almost in all Engineering fields as follows.

(i) **Mechanical Engineering**

a) Since they are stronger, lighter etc., they are used to make hard metals.
b) Smart magnetic fluids are used in vacuum seals, magnetic separators, etc.,
c) They are also used in GMR spin valves.
d) Nano – MEMS are used in ICs, optical switches, pressure sensors, mass sensors etc.,

(ii) Electrical, Electronics and Communication Engineering

a) Orderly assembled nano materials are used as quantum electronic devices and photonic crystals.
b) They are also used as sensing elements.
c) They are also used in energy storage devices such as hydrogen storage devices, magnetic refrigeration and in ionic batteries.
d) Dispersed nano materials are used in magnetic recording devices, rocket propellant, solar cells, fuel cells, etc.,
e) Recently nano robots were designed, which are used to remove the damaged cancer cells and also to modify the neuron network in human body.

(iii) **Computer Science Engineering and IT**

a) They are used to make CD’s and semiconductor laser.
b) They are also used to store the information in smaller chips.
c) They are used in mobiles and lap – tops.
d) They are used in chemical/optical computers.
e) Nano – dimensional photonic crystals and quantum electronic devices plays a vital role in the recently developed computers.

(iv) **Bio – medical and Chemical Engineering**

a) Consolidated state nano – particles are used as catalyst, electrodes in solar and fuel cells.
b) They are also used in the production of DNA – chips and bio – sensors.
c) Nano – structured ceramic materials are used in synthetic bones.
d) Few nano materials are also used in adsorbents, self cleaning glass, fuel additives, drugs, ferrofluids, paints etc.,
e) Nano – metallic colloids are used as film precursors.

questions

A perfect black body is one which ________________ all the radiations.

The classical theory was not able to explain the ___________.

The discrete energy values in the form of quantum of definite frequency are called_________.

Which of the following are not affected by the magnetic field?

The relation between energy and the momentum of the photon is ___________.

The wave associated with a material particle are called as __________.

De-Broglie wavelength in terms of energy is _________.

De-Broglie wavelength in terms of voltage is __________.

According to ___________ theory the hydrogen spectrum is a continuous spectrum.

According to ___________ theory the hydrogen spectrum is a discrete spectrum.

The de-Broglie wavelength of an electron of energy 100 eV is ________.

In one dimensional potential box,the potential energy of the electron inside the box is ___________.

According to quantum mechanics, the energy levels of an electron are_________.

Source used in the SEM is ___________.

energy and other characteristics to be calculated. In classical physics, what is analogue of the wave function?

The speed of propagation of an electromagnetic wave in vacuum is:

The expression of the momentum of a photon is :

If the uncertainty of a proton accelerated in a laboratory is 400 m/s, that of its position is:

Planck's constant has the same units as______________.

Which of the following is known as the Schrodinger equation ?

particle:

In the probabilistic interpretation of wave function Ψ, the quantity |Ψ| ^2 is:

Quantum Mechanics is also called as _________.

Classical Mechanics failed to explain _________.

Quantum Theory was indtroduced by _________.

As temperature increase, the peak wavelength emitted by the black body___________.

As temperature increase, the total energy emitted by black body ______________.

________________.

Speed of Light ___________.

A particle in one dimensional box at the walls of the box potential Energy will be _____________.

Photons propagate with ______________ speed of light.

According to de-broglie wave equation, when mass of the particle increases wavelength will be

Black body emits radiation in ____________.

According to plancks quantum theory,electrons in the black body radiator are assumed to be ____________.

The black body radiator emits energy in ____________.

The term kB represents ____________.

Expression for momentum is ____________.

(Delta)^2 represents ____________.

Relation between angular and linear frequencies is ____________.

Which one of the following is true?

For a free particle, potential energy is ____________.

According to de-broglie wave equation, when velocity of the particle increases wavelength will be __________.

A particle in one dimensional box at the walls of the box wave function will be _____________.
Energy of photon is directly related to the _____________.
Calculate the minimum uncertainty in velocity of an electron trapped in 30.3nm wide?
Frequency below which no electrons are emitted from metal surface is ____________.
Loss of energy of an electron results in ___________.
Electrons show diffraction effects because their de Broglie wavelength is similar to _____________.
Wavelength of ultraviolet region of electromagnetic spectrum is ______________.
A perfect black body is a perfect absorber and radiator of ____________ radiation.

opt1	opt2	opt3
Absorbs	emits	absorbs and emits
diffraction	interference	emission of black body radiation
phonons	photons	neutrons
electrons	protons	photons
P=EC	E=P/C	C=EP
standing wave	progressive wave	transverse wave
h/2mE	h/sqrt(2mE)	h/2mEe
h/2mV	h/2mE	h/2m
classical	quantum	Electro magnetic
classical	quantum	electro magnetic
12.27 Angstrom	122.7 Angstrom	1.227 Angstrom
maximum	minimum	zero
continuous	discrete	scattering
electrical enregy	chemical source	electron gun
particle’s momentum.	particle’s energy	particle’s mass
3 x (10)^ 6 m/s	3 x (10)^8 m/s	3 x (10)^8 km/s
p = h * lamda	p = h / lamda	p = c/lamda
7.88 nm	9.70 nm	112 nm
angular momentum	the Hamiltonian	frequency
E = h* nu	E = m* (c)^2	H* Psi = E* Psi
singularity	duality	triality
a probability density	a probability amplitude.	1
Classical Mechanics	Wave mechanics	Statistical mechanics
Thermodynamics of maths	Electromagnetic Theroy	Atomic Spectra
Max Planck	De-Broglie	Newton
Increases	No Change	Decreases
No Change	Decreases	Saturates
Decreases	Increases	Doubles
3× (10)^8 m/s	(2.5)×(10)^8 m/s	(3.5)×(10)^8 m/s
Increases	Decreases	Zero
smaller	greater	equal
Decreases	Increases	Doubles
visible region	single wavelengths	Discrete wavelengths
electric oscillators	harmonic oscillators	simple pendulum
discrete	continuos	pulse
Bohr radius	Plancks constant	Boltzmann constant
p = 2 m v	p = m v	p = h *nu
Hermition operator	Laplacian operator	Energy operator
omega = nu/2π	omega = 2*pi/nu	omega = 2*pi*nu
nu= p/lamda	nu= c/lamda	lamda = nu*c
0	1	2
Doubles	Increases	Decreases

Increases	Decreases	Zero
wavelength	wave number	frequency
1.20 x 10^4 m/s	2.87 x 10^4 m/s	1.20 x 10^ 6 m/s
minimum frequency	angular frequency	maximum frequency
absorption of photon	emission of photon	destruction of photon
spacing between atomic layers	no. of atomic layers	nature of atomic layers
121 nm	120 nm	119 nm
monochromatic	all wavelengths of	coherent

opt4	opt5	opt6	answer
reflects			absorbs and emits
scattering			emission of black body radiation
scattering			photons
positive ions			photons
E=PC			E=PC
matter wave			matter wave
h/2m			h/sqrt(2mE)
h/sqrt(2meV)			h/sqrt(2meV)
wave			classical
electro magnetic			quantum
0.1227 Angstrom			1.227 Angstrom
infinity			zero
diffraction			discrete
neutron gun			electron gun
The sum of the forces on the particle			particle's mass
3 x (10)^ (-8) km/s			3 x (10)^8 km/s
p = c*lamda			p = c/lamda
115nm			7.88 nm
de Broglie wavelength			angular momentum
lamda = h/p			H* Psi = E* Psi
infinality			duality
0			a probability density
Newtonian mechanics			Wave mechanics
Velocity of Particle			Atomic Spectra
Einstein			Max Planck
Saturates			Decreases
Increases			Increases
Zero			Increases
2×(10)^8 m/s			3× (10)^8 m/s
infinity			infinity
same			same
Zero			Decreases
All wavelengths			All wavelengths
non-linear oscillators			harmonic oscillators
wave			discrete
Stefans constant			Boltzmann constant
p = h*(nu)/c			p = m v
Hamiltonion operator			Laplacian operator
nu= 2*pi*omega			omega = 2*pi*nu
lamda = 1/nu			nu= c/lamda
3			0
Zero			Decreases

infinity	Zero
amplitude	frequency
1.20 x 10^5 m/s	1.20 x 10^4 m/s
threshold frequency	threshold frequency
formation of photon	emission of photon
positioning of atomic layers	spacing between atomic layers
130 nm	121 nm
polychromatic	all wavelengths of

questions
What does conductivity of metals depend upon?
What happens to the free electrons when electric field is applied?
Which of the following theories cannot be explained by classical theory?
Which of the following theories can be adopted to rectify the drawbacks of classical theory?
Calculate the drift velocity of the free electrons with mobility of 3.5×10^-3 m^2/Vs in copper for an electric field
Electrons in the outer shell are called __________ electrons.
Which of the following has least number of valence electrons?
A good conductor has how many electrons?
What principle states that each electron in an atom must have an different set of quantum numbers?
The temperature coefficient of resistance of conductors is ___________.
The temperature coefficient of resistance of conductor ___________ with an increase in temperature.
A positively charged body has ___________.
Electrons flow assumes charges flow from ______________.
Which of the following has negative temperature coefficient?
Which orbit controls the electrical property of the atom?
Which of the following statements correctly describes a metal within band theory?
Which is the correct ordering of the band gaps energy?
The energy required to break a covalent bond in a semiconductor _____________.
Fermi level for a metal is_____________.
The probability of occupation of an energy level E, when E- EF = kT, is given by _____________.
The Fermi level is _____________.
Mobility of electron is_____________.
Fermi level represents the energy level with probability of its occupation of_____________.
At absolute zero temperature, the probability of finding an electron at an energy level E is zero when__________
Substances which allow electric current to pass through them are called _____________.
The probability that an electron in a metal occupies the Fermi level, at any temperature (>0 K) is:
The mobility is given by :
Fermi energy level for n type extrinsic semiconductors lies_____________.
Fermi energy level for intrinsic semiconductors lies_____________.
Not an example for intrinsic semiconductor_____________.
In intrinsic semiconductors, number of electrons __________ number of holes.
In p type semiconductors, number of holes __________ number of electrons.
Mobility of holes is ___________ mobility of electrons in intrinsic semiconductors.
Electronic current in the wire is the flow of ___________ electrons.
The highest energy band of an atom which can be filled with electrons is _______________.
An energy band in which electrons can move freely _________________.
Which type of material usually has one valence electron ?
Which of the following is considered as best conductor?
The eight electrons which are tightly held by the atom are called_____________.
The amount of time between creation and disappearance of a free electron is _____________.
Density of states is defined as the number of available electron states per unit volume in an energy interval _____
Phonon is the quantum of __________ wave.
The effective mass of an electron ______________.
Einstein's theory of lattice vibration is based on the quantum theory of ________________.
A phonon interacts with ____________.
_______________ is defined as the number of available energy states per unit volume in an energy interval.

When the effective mass of an electron is positive then the curve of E(k) will be ________________.
Classical free electron theory was proposed by _______________.
In the kronig - Penney model , if there exists no potential barrier, then _____________.
The density of allowed states between E and E + dE is proportional to ____________.
The average time taken by a free electron between any two successive collisions is known as ____________.
In an electric field, the electron moves away from the field with a constant velocity, known as ____________.

opt1	opt2	opt3	opt4	opt5	opt6	answer
The nature	Number of	Resistance	Number of electrons			Number of free electrons
They move	They move	They rema	They move in the direction oppos			They move in the direction of the
Electron th	Lorentz th	Photo-elec	Classical free electron theory			Photo-electric effect
Compton t	Quantum t	Band theo	Electron theory			Quantum theory
3.5 m/s	1.75×10^3	11.5 m/s	1.75×10^-3 m/s			1.75×10^3 m/s
outer shell	inner shell	Semicondu	valence			valence
conductor	semicondu	insulator	semi-insulator			conductor
8	4	2	1			1
inclusion pr	exclusion p	electron pr	quantum principle			exclusion principle
positive	negative	zero	infinite			positive
increases	decreases	remains sa	becomes negative			decreases
excess of n	excess of e	deficit of el	deficit of protons			deficit of electrons
positive to	positive to	negative to	negative to negative			negative to positive
Nickel	Carbon	Brass	Constantan			Carbon
first orbit	fourth orb	M shell	valence orbit			valence orbit
A material	A material	A material	A material with infinite band gap			A material possesses a large band
Diamond >	Diamond <	Diamond <	Diamond < silicon < copper			Diamond > silicon > copper
is equal to	is equal to	is greater i	is the same in Ge and Si			is equal to the width of the forbid
Highest en	Highest en	Average va	Highest energy level occupied by			Highest energy level occupied by
0.73	0.63	0.5	0.27			0.27
an average	an energy l	the highest	the highest occupied energy level			the highest occupied energy level
Average flo	Average ap	Average dr	Reciprocal of conductivity per unit			Average drift velocity per unit fiel
0 %.	25 %.	50 %.	1			50 %.
E < EF	E > Ef	2E - E = f	2E + E = f			E > Ef
Conductors	insulation	semi condu	superconductors			Conductors
0	1	0.75	0.5			0.5
muo = V / E	muo = V - E	muo = V +	muo = V X E			muo = V / E
At middle c	Close to co	Close to va	Close to forbidden band			Close to conduction band
At middle c	Close to co	Close to va	Close to forbidden band			Close to valence band
Si	Al	Ge	Sn			Si
Equal	Greater tha	Less than	Can not define			Less than
Equal	Greater tha	Less than	Can not define			Equal
Equal	Greater tha	Less than	Can not define			Can not define
free	valence	bound	loose			free
energy leve	valence ba	conduction	insulation band			valence band
energy leve	valence ba	conduction	insulation band			conduction band
Conductors	insulation	semi condu	superconductors			Conductors
Gold	Silica	Germaniun	Mica			Gold
valence ele	outermost	bound elec	covalent electrons			bound electrons
recombinat	lifetime	propagatio	bonding			lifetime
E + dE	E - dE	E * dE	E / dE			E + dE
electromag	elastic	polarizatio	magnetization			elastic
positive	negative	infinity	positive, negative and infinity			positive, negative and infinity
Schrodinge	Planck	Dirac	Heisenberg			Planck
another ph	fermion	boson	muon			another photon
E + dE	F(E)	dE	Z(E)dE			Z(E)dE

Concave u	Concave d	parabola	hyperbola	Concave up
Bloch	Drude	De-Broglie	Schrodinger	Drude
there exist	there exist	E is not a c	all values of E are not allowed	there exists no forbidden energy r
E^ (1/2)	E^ (-1/2)	E^ (3/2)	E^ (-3/2)	E^ (1/2)
mean free	collision ti	drift veloci	relaxation time	collision time
mean free	collision ti	drift veloci	relaxation time	drift velocity

electrons at 0

questions
How does a semiconductor behave at absolute zero?
How is the resistance of semiconductor classified?
Which of the following is known as indirect band gap semiconductors?
What are the charge carriers in semiconductors?
How is charge carriers produced in intrinsic semiconductors?
Majority carriers in P-type semiconductor are ____________.
Minority carriers produced by thermal agitation or vibration in a semiconductor are ____________.
The cause of a potential barrier in a P - N diode is the ____________.
A Zener diode is always used ____________.
How does a semiconductor behave at absolute zero?
How is the resistance of semiconductor classified?
Which of the following is known as indirect band gap semiconductors?
What are the charge carriers in semiconductors?
How is charge carriers produced in intrinsic semiconductors?
The probability that an electron in a metal occupies the Fermi-level, at any temperature (>0 K) is ____________.
n-type semiconductors are ____________.
If the energy gap of a semiconductor is 1.1 e V it would be ____________.
In an intrinsic semiconductor, the mobility of electrons in the conduction band is ____________.
The electron and hole concentrations in a intrinsic semiconductor are ni and pi respectively. When doped with a
If the temperature of an extrinsic semiconductor is increased so that the intrinsic carrier concentration is
At room temperature, the current in an intrinsic semiconductor is due to ____________.
The mobility is given by ____________.
A good ohmic contact on a p-type semiconductor chip is formed by introducing ____________.
The width of the depletion region is ____________.
The Fermi energy in p–n junction at thermal equilibrium is ____________.
Germanium has _________ protons
One eV equals to _________.
An electron volt is a unit of _______.
Which one has four valence electrons?
The temperature coefficient of resistance of semiconductors is ___________.
A negatively charged body has____________.
The value of temperature coefficient is dependent upon _________________ of the material.
Semiconductor in pure form is called______________ semiconductor.
__________ and ___________ are the two carrier transport mechanism in Si crystal.
Semiconductor in impure form is called______________ semiconductor.
___________ is associated with random motion due to the thermal agitation in the movement of holes and
Silicon that has been doped with trivalent impurity is called _________semiconductor.
Silicon that has been doped with pentavalent impurity is called _________semiconductor.
What is the another name for a pn crystal?
An acceptor atom is also called ________.
Which is a donor atom?
What is the barrier potential of germanium at 25 degree Celsius ?
What is the barrier potential of silicon at 25 degree Celsius?
When temperature increases , barrier potential _______________.
The most important application of Schottky diodes is in _____________.

Typical leakage current in a pn junction is in the order of ___________.
The resistance of a forward biased pn junction is in the order of __________.
Doping materials are called impurities because they _______________.
The method of adding impurities to a pure semiconductor is known as ___________.
The merging of a free electron and a hole is called _____________.
A donor atom has how many valence electrons?

opt1
Conductor
High resistance
Germanium
Electrons and holes
By pure atoms
electrons
holes in N-type & free electrons in P-type
concentration of positive charges near the junction
with forward bias
Conductor
High resistance
Germanium
Electrons and holes
By pure atoms
0
Negatively charged
Opaque to the visible light
Less than the mobility of holes in the valence band
n + p = ni + pi
The majority carrier density doubles
Holes
μ = V/E
Gold as an impurity below the contact
Directly proportional to doping
Proportional to distance
30
1.6 x 10 ^(-19)
momentum
conductor
positive
excess of neutrons
length
good
covalent bond and recombination
pure
Diffusion
N-type
N-type
lattice
Minority carrier
Pentavalent atom
0.3 V
0.4 V
remains the same
Digital computers

micrometer
ohm
decrease number of charge carriers
etching
covalent bonding
1

opt2
Insulator
Positive temperature co-efficient
Nickel
Electrons
By electrons
neutrons
holes in N-type & P-type
depletion of negative charges near the junction
with reverse bias
Insulator
Positive temperature co-efficient
Nickel
Electrons
By electrons
1
Produced when Indium is added as an impurity to Germanium
Transparent to the visible light
Zero
n + ni = p + pi
The minority carrier density doubles
Electrons
μ = V^2/E
A high concentration of acceptors below the contact
Inversely proportional to doping
Directly increases with the temperature
32
2.6 x 10 ^(-19)
potential difference
semiconductor
negative
excess of eletrons
nature and temperature
intrinsic
forward and reverse bias
intrinsic
Drift
P-type
P-type
diode
Majority carrier
trivalent atom
0.4 V
0.5 V
decreases
Voltage regulators

millimeter
milliohm
change the chemical properties of semiconductors
morping
lifetime
2

opt3
Semiconductor
Negative temperature co-efficient
Platinum
Holes
By impure atoms
holes
free electrons in N-type & P-type
concentration of positive and negative charges near the junction
as a rectifier
Semiconductor
Negative temperature co-efficient
Platinum
Holes
By impure atoms
0.5
Produced when phosphorous is added as an impurity to silicon
Transparent to the ultraviolet radiation
Greater than the mobility of holes in the valence band
np = nipi
Both majority and minority carrier densities double
Holes and electrons
µ = V/E^2
A high concentration of donors below the contact
Independent of doping
Invariant with respect to distance
34
1.4 x 10 ^(-19)
energy
insulator
zero
deficit of electrons
volume
extrinsic
drift and diffusion
extrinsic
Recombination
intrinsic
intrinsic
junction diode
trivalent atom
Aluminium
0.5 V
0.6 V
increases
Power supplies

nanometer
microohm
makes semiconductors less than 100 %
doping
recombination
4

opt4	opt5	opt6
Protection device		
Low resistance		
Carbon		
Charges		
By holes		
neutrinos		
free electrons in N-type & holes in P-type		
depletion of positive charges near the junction		
as a switch		
Protection device		
Low resistance		
Carbon		
Charges		
By holes		
0.75		
None of the above		
Transparent to the infrared radiation		
1		
n - ni = p - pi		
No change in charge carriers		
phonons		
µ = V^2/E^2		
None of the above		
Directly proportional to square of doping		
Proportional to temperature		
36		
1.2 x 10 ^(-19)		
charge		
semi-insulator		
infinite		
deficit of protons		
cross-sectional area		
doped		
free and charged		
bad		
Doping		
extrinsic		
extrinsic		
pn junction		
pentavalent atom		
Boron		
0.6 V		
0.7 V		
depends on material		
amplifier circuits		

picometer
kiloohm
alter the crystal structure of pure semiconductors
annealing
thermal energy
5

answer
Insulator
Negative temperature co-efficient
Germanium
Electrons and holes
By impure atoms
holes
holes in N-type & free electrons in P-type
concentration of positive and negative charges near the junction
with reverse bias
Insulator
Negative temperature co-efficient
Germanium
Electrons and holes
By impure atoms
0.5
Produced when phosphorous is added as an impurity to silicon
Opaque to the visible light
Greater than the mobility of holes in the valence band
np = nipi
Both majority and minority carrier densities double
Holes and electrons
μ = V/E
A high concentration of donors below the contact
Inversely proportional to doping
Invariant with respect to distance
32
1.6 x 10 ^(-19)
energy
semiconductor
negative
excess of eletrons
nature and temperature
intrinsic
drift and diffusion
extrinsic
Diffusion
P-type
N-type
junction diode
trivalent atom
Pentavalent atom
0.3 V
0.7 V
decreases
Digital computers

micrometer
ohm
alter the crystal structure of pure semiconductors
doping
recombination
5

questions	opt1	opt2	opt3	opt4	opt5	opt6	answer
The workin	Photo conc	Photo emis	Photo volta	Photo caloric effect			Photo voltaic effect
The efficier	15-20%	40%	50%	75%			40%
In spontane	atoms are i	transitions	transitions	none			transitions are without
To form sti	ground stat	excited sta	forbidden s	metastable state			excited state
The switchi	1 second	I millisecon	1 microsec	1 nanosecond			1 nanosecond
The colour	type of ma	type of bias	recombinat	environmental conditions			type of material used
Compared	longer wav	shorter wa	medium wa	all wavelengths			longer wavelength
An LED is m	Phosphores	Silicon	Germaniun	Gallium arsenide			Gallium arsenide
Emission of	Photovolta	emission of	generation	conversion of heat			emission of electrons
Germaniun	5 mA	10 mA	15 mA	20 mA			10 mA
The colour	varying bar	varying sen	varying dop	varying intensity			varying doping level
LEDs fabric	visible	ultraviolet	infrared	ultrasonic			infrared
A photodio	forward	reverse	forward or	light			reverse
When the l	increases	decreases	unaffected	doubly increases			increases
In photodi	dark currer	Zener curr	photo curre	PIN current			dark current
As forward	become ze	become inf	will increas	will decrease			will increase
For satellite	Edison cell	fuel cell	solar cell	cryogenic storage			solar cell
The output	0.25 W	0.5 W	0.75 W	1.0 W			1.0 W
The region	Depletion J	Depletion r	Depletion s	Depletion boundary			Depletion region
The stimula	nuclear ene	optical pun	population	heat energy			population inversion
In spontane	Higher ene	Moderate e	Lower ener	forbidden energy			Lower energy
For a photo	3 µA	6 microam	9 microam	12 microammeter			6 microammeter
Depletion	only free el	only free h	both the fr	photons			both the free electrons
The symbo	LED	diode	transistor	BJT			LED
The barrier	diffusion o	thermally g	flow of drif	migration of minority carriers acro			diffusion of majority ca
The excite	proton	photon	exciton	phonon			exciton
In a forwar	Increases	Remains cc	Decreases	doubly increases			Increases
In a diode c	Cut-in poin	Cut-out poi	Knee point	Cut-off point			Cut-in point
When a dic	wave	muon	Radiation	regulator			Radiation
Silicon is nc	An indirect	A direct ba	A wide ban	elemental semiconductor			An indirect band gap se
If the junct	Decreases	Increases	Remains th	doubly increases			Decreases
The creatio	avalanche	thermionic	low-field	high-field			high-field
Zener effec	high-speed	high-speed	intensity of	intensity of magnetic field			intensity of electric fiel
What temp	junction te	ambient te	absolute te	internal temperature			junction temperature
An LED and	thermocou	FET	optocouple	regulator			optocoupler
When the s	Photo diod	Photo volta	Photo dete	Photo transmitter			Photo detector
Solar cells a	120-180 m	120-220 m	180-220 m	180-240 micrometer			180-240 micrometer
_________	Crushed sil	Crystalline	Powdered s	Silicon			Crystalline silicon
_________	Cadmium T	Cadmium c	Cadmium s	Cadmium sulphate			Cadmium Telluroide
Quantum d	Gratzel cell	Solar cell	Voltaic cell	Galvanic cell			Gratzel cell
The term p	Spanish	Greek	German	English			Greek
The volt is t	Alessandro	Alxender vo	Alexa volta	Alexandro volta			Alessandro volta
The term p	1840	1844	1849	1850			1849
The amoun	Temperatu	Photons	Diode curre	Shunt current			Temperature
_________	Copper Ind	Copper Sel	Copper Gal	Copper Indium Gallium Diselenide			Copper Indium Gallium
Dye-sensiti	Ruthium m	Aniline	Safranine	Induline			Ruthium melallo

To measur	LED with f	LED with r	photodiod	photodiode with forward bias	photodiode with rever
The photo	forward bi	reverse bia	both forwa	scattering	reverse bias
Compound	LED	diode	transistor	BJT	LED
In metal-s	Ohmic	Schottky	Fermi	Boltzmann	Ohmic
________ c	Solar cell	Photodiod	LED	LASER	Solar cell

any aid of an external agency

rriers across the junction

questions	opt1	opt2	opt3	opt4	opt5	opt6	answer
Which of t	Size distrib	viscosity	pressure	tension			Size distribution
Nanotechn	the design	size	shape	structure			the design
The interat	decreases	increases	remain sa	None of the above			decreases
Nanopartic	sol-gel met	thermal m	vapour me	deposition method			sol-gel method
The length	several mic	millimetre	centimetre	nanometer			several micrometres t
The diame	1 to 20 nm	20 to 50 n	50 to 100	100 to 200 nm			1 to 20 nm
Carbon na	tetragonal	pentagonal	hexagonal	triangle			pentagonal
The differe	arm chair	I shape	griders	Y - shape			arm chair
Vapour-liq	hybrid gro	liquid gro	solid grow	vapour phase growth			hybrid growth
In modifie	halide and	halide and	halide and	hydroxides and oxygen			halide and oxygen
Complete t	2HCl	2Cl2	4HCl	4Cl_2			4HCl
_________	PVCVD	MCVD	VAD	OVPO			PVCVD
Fullerene o	100	20	75	60			60
"There is p	Eric Drexle	Richard Fe	Harold Cro	Richard Smalley			Richard Feynmann
Who coine	Eric Drexle	Richard Fe	Harold Cro	Richard Smalley			Richard Feynmann
Nanoscien	quantum m	Newtonian	macro-dyn	geophysics			quantum mechanics
The diame	50,000	75,000	90,000	1,00,000			50,000
Which rati	Weight/vol	Surface are	Volume/w	Pressure/volume			Surface area/volume
The two im	pressure a	sticking an	sticking an	temperature and friction			sticking and friction
The size of	5	10	50	100			5
The wavel	40-70	400-700	4000-7000	40000-70000			400-700
Nanopartic	Gold	Lead	Carbon	Silicon			Carbon
Nano parti	Tumour	Fever	Infection	Cold			Tumour
Nanostruct	Creating i	Creating	decreased	Keeping same surface area per un			Creating increased sur
The size of	2 - 5 micro	7 - 10 micr	10 - 17 mic	5 - 7 micrometer			2 - 5 micrometer
Who had i	Eric Drexle	Buckminst	Richard Sm	Faraday			Buckminster Fuller
Nano parti	Copper	Aluminiu	Carbon	Lead			Aluminium
The therm	100	1000	2200	3100			1000
The therm	100	1000	2200	3100			3100
What does	Fine	Front	Force	Flux			Force
The smalle	75	60	20	15			20
The compr	is less than	is greater t	is equal to	may be greater than			is less than
The size of	50	90	2,000	5,000			5,000
The full for	Scanning T	Scientific T	Systematic	Super Tensile Microscope			Scanning Tunneling Mi
The width	1	1.3	2.5	10			1.3
nanotubes	aerogel	sol gel	colloid	sputtering			sputtering
One nanom	1 / 10 ^9o	1 / 10 ^10	1 / 100 of	1 / 1000 of meter			1 / 10 ^9of meter
_________	diborane	Arsine	phosphin	silane			diborane
The flow o	300ml/mi	250ml/mi	200ml/mi	100ml/min			200ml/min
The thickn	10 - 20nm	30 - 40nm	1 - 2nm	50 - 100nm			10 - 20nm

face area per unit volume