UNIT V

NANOELECTRONIC DEVICES

5.1.INTRODUCTION

- Nanoscience is a branch of science which deals with the study of phenomena and manipulation of materials at nanometer scales.
- Nanotechnology is the design, production, characterization and application of structures, devices and systems by controlling shape and size at the nanometer scale.
- **Definition:** Nanomaterials are newly developed materials with grain (particle) size at the nanometer range (1nm = 10^{-9}) ie., in the order of 1 – 100 nm.
- Nano devices are the devices which consists of nano materials, its efficiency is more.
- Nano electronics refers to the use of nanotechnologyin electronic components, especially transistors.
- The unique micro structure provides tremendous strength, hardness, formability and toughness. to this is has tremendous strength, hardness, toughness and high magnetic & chemical properties.
- (Ex: nano copper is 5 times more stronger than ordinary copper)

ELECTRON DENSITY IN BULK MATERIAL

- **Definition:** Electron density is the number of electrons per unit volume in a material. It is determined by using density of energy states.
- In a solid, the total number of electron energy states *'N'* with energies upto *'E'* is determined based on quantum mechanics using the following equation.

$$N = \left(\frac{8\pi}{3}\right)(2mE)^{3/2}\left(\frac{a^3}{h^3}\right) \quad ----(1)$$

- Here, *'a³'* → Volume of the material (*'a'* is the characteristic dimension of the solid)

  E → Maximum energy level *m* → Mass of an electron *h* → Planck"s constant.

∴ Number of energy states per unit volume, $n = \frac{N}{a^3}$

$$= \left(\frac{8\pi}{3}\right)\frac{(2mE)^{3/2}}{h^3} \quad ----(2)$$

- Density of states function, D(E) is obtained after taking the derivative of this expression with respect to energy $\left(\frac{dn}{dE}\right)$.

Number of energy states per unit volume per unit energy, $D(E) = \frac{dn}{dE}$

$$= \frac{d}{dE} * \frac{8\pi}{3}\frac{(2mE)^{3/2}}{h^3} +$$

$$= \frac{8\pi}{3}\frac{(2m)^{3/2}}{h^3}\frac{d(E)^{3/2}}{dE}$$

$$= \frac{8\pi}{3}\frac{2^{3/2}m^{3/2}}{h^3}\left(\frac{3}{2}E^{\frac{3}{2}-1}\right)$$

$$= \frac{8\pi}{3}\frac{2^1 \times 2^{1/2}m^{3/2}}{h^3} \times \left(\frac{3}{2}E^{1/2}\right)$$

$$D(E) = \frac{8\ \sqrt{2}\ m^{3/2}}{h^3} \times \sqrt{E} \qquad ------(3)$$

- In a conductor at *'0 K'*, the electron distribution goes from zero energy upto Fermi energy *'E_F'*
- So, the number of free electrons per unit volume or electron density in a bulk conductor at „0 K"

$$n_e = \frac{8\pi}{3}\left(\frac{(2mE_F)^{3/2}}{h^3}\right) \qquad ------(4)$$

SIZE DEPENDENCE OF FERMI ENERGY

Fermi energy:

It is defined as the highest energy level occupied by the electron at „0K" in metal

$$\text{Fermi energy,}\quad E_F = \frac{h^2}{2m}\left(\frac{3n_e}{8\pi}\right)^{2/3}$$

- Here, n_e is the only variable and all the other terms are constants.
- So, we can write, $E_F \propto n_e$
- Thus, Fermi energy of the conductor just depends on the number of free electrons per unit volume (electron density).
- As the elctron density is a property of the material, Fermi energy does not vary with the material"s size.
- E_F is same for small volume and large volume materials. Also it is same for small size and large size materials.
- But, the average spacing between energy states is inversly proportional to the volume of the solid.

$$\Delta E \propto \frac{1}{V} \quad (\text{or}) \quad \Delta E \propto \frac{1}{a^3}$$

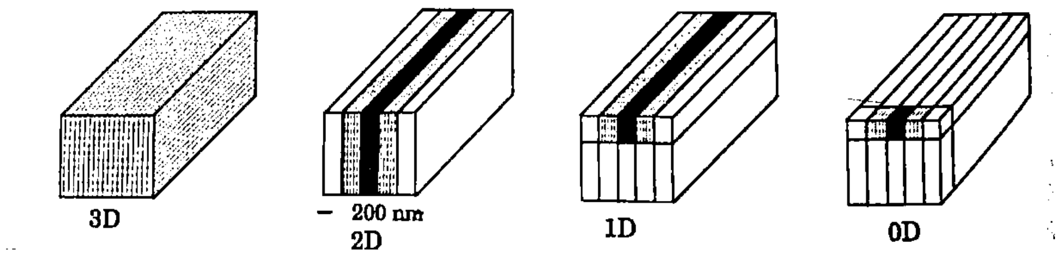
QUANTUM CONFINEMENT

Definition: It is a process of reduction of the size of the solid such that the energy levels inside becomes discrete.

- In this case, small “droplets” of isolated electrons are created.
- Hence, it is possible for us to count few electrons.
- This effect is observed when the size of the particle is too small.
- If we decrease the size of the particle to 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
- Since, the band gap and wavelength are inversely related to each other the wavelength decreases with decrease in size and the proof is the emission of blue radiation.

QUANTUM STRUCTURES

- 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 the confinement direction, quantum confined structure will be classified into three categories as quantum well, quantum wire and quantum dot.



Types of structure

1.Quantum well(2D): When the electrons are confined in onedimension then the structure is known as quantum well

2.Quantum wire(1D): When two dimensions are minimized, then the structure is known as quantum wire.

3.Quantum dots(0D): When three dimension are minimized then itis quantum wire

The classification is shown below in 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

DENSITY OF STATES IN QUANTUM WELL

The two dimensional density of states is the number of states per unit area and unit energy.

Let us consider an electron in a two dimensional potential well. The electron is confined in the well.

We have to find out number of energy levels available in between E and E+dE

The space consists of only X-Y plane

In 2 dimensional space $n^2 = n_x^2 + n_y^2$

$No.\ of\ energy\ states\ within\ the\ circle\ of\ radius\ 'n'$

$$= \quad \pi n^2 \qquad ------(1)$$

$No. \, of \, energy \, states \, within \, the \, circle \, of \, radius \, `n + dn'$

$$= \quad (n + dn)^2 \quad ---- (2)$$

The quantum numbers (n_x and n_y) can have only positive integer values. It will have positive values

at $\frac{1}{4}^{th}$ part of the circle.

No. of energy states within the circle of radius 'n' = $\frac{1}{4} \times \pi n^2$

$$= \frac{1}{4} \pi n^2 \quad ---- (3)$$

No. of energy states within the circle of radius '$n + dn$' = $\frac{1}{4} \times (n + dn)^2$

$$= \frac{1}{4} (n + dn)^2 \quad ---- (4)$$

No. of energy states between energy interval E and E + dE

$$(E)\, dE = \frac{1}{4} \pi \, (n + dn)^2 - \frac{1}{4} \pi n^2$$

$$(E)\, dE = \frac{1}{4} \pi \, [(n + dn)^2 - n^2]$$

$$(E) dE = \frac{1}{4} \pi \, (n^2 + 2ndn + dn^2 - n^2) \quad --- (5)$$

Since „dn" is very small the higher orders of „dn" can be neglected.

$$Z(E)\, dE = \frac{\pi}{4} \times 2ndn$$

$$Z(E) dE = \frac{\pi}{2} \, n \, dn \quad ---- (6)$$

The energy of an electron in a cubical metal piece of sides 'a' is given by, E

$$= \frac{n^2 h^2}{8ma^2} \quad ------------------ (7)$$

$$n^2 h^2 = 8ma^2 E$$

$$n^2 = \frac{8ma^2 E}{h^2} \quad ---- (8)$$

$$n = [\frac{8mE}{h^2}]^{\frac{1}{2}} \, a \quad ---- (9)$$

ifferentiating equation (9)with respect to ‘n’ we get,

$$dn = \left[\frac{8m}{h^2}\right]^{\frac{1}{2}} a \ \frac{1}{2} \ E^{\frac{1}{2}-1} \ dE \qquad ------ \ (10)$$

$$\text{dn} = \frac{1}{2}\left[\frac{8m}{h^2}\right]^{\frac{1}{2}} a \ E^{-\frac{1}{2}} \ dE \qquad ----(11)$$

Substituting (9)& (11) in (6)we get,

$$\text{Z(E)dE} = \frac{\pi}{2}\left[\frac{8mE}{h^2}\right]^{\frac{1}{2}} a \ \frac{1}{2}\left[\frac{8m}{h^2}\right]^{\frac{1}{2}} a \ E^{-\frac{1}{2}} \ dE \qquad ---- \ (12)$$

$$\text{Z(E)dE} = \frac{\pi}{4}\left(\frac{8m}{h^2}\right) a^2E^0dE \qquad --- \ (13)$$

Pauli‟s exclusion principle states that “Two electrons of opposite spin can occupy each state”. Hence, the number of energy states available for electron occupancy is given by,

$$\text{Z(E)dE} = 2 \times \frac{\pi}{4}\left(\frac{8m}{h^2}\right) a^2E^0dE \qquad ----(14)$$

$$\text{Z(E)dE} = \frac{\pi}{2}\left(\frac{8m}{h^2}\right) a^2E^0dE \qquad ----(15)$$

The number of energy states per unit area per unit energy is

$$\text{Z(E)} = \frac{\pi}{2}\left(\frac{8m}{h^2}\right) E^0 \qquad (\therefore a^2 = 1 \, for \ unit \ area)$$

$$\text{Z(E)} \ \text{a} \ E^0$$

$$\text{i.e} \quad \text{Z(E)}^{\text{2D}} \ \text{a} \ E^0 = \text{constant}$$

This is the expression for density of charge carriers in the energy interval E and E+dE in a quantum well

DENSITY OF STATES IN QUANTUM WIRE

The one dimensional density of states is the number of states per unit length and unit energy.

Let us consider an electron in a one dimensional quantum wire. We have to find out number of energy

levels available in between E and E+dE

The space consists of only X plane

In 1 dimensional space $n^2 = n_x^2$

$$No.\ of\ energy\ states\ \text{in}\ the\ wire\ of\ length\ 'n'\ =\ n \qquad -------(1)$$

$$No.\ of\ energy\ states\ \text{in}\ the\ wire\ of\ length\ 'n+dn'$$

$$=\ n + dn \qquad ----(2)$$

The quantum numbers (n_x) can have only positive integer values. It will have positive values at $\frac{1}{2}^{th}$ part

of the wire.

$$\text{No. of energy states within the wire of length } 'n' = \frac{1}{2} \times n$$

$$= \frac{1}{2} n \qquad ----(3)$$

$$\text{No. of energy states within the wire of length } 'n+dn' = \frac{1}{2} \times (n + dn)$$

$$= \frac{1}{2}(n + d\ ) \qquad ----(4)$$

No. of energy states between energy interval E and E + dE

$$Z(E)\ dE\ = \frac{1}{2}\ (n + d\ ) - \ \frac{1}{2}\ n$$

$$(E)\ dE\ = \frac{1}{2}\ [n + dn\ -\ n]$$

$$Z(E)dE = \frac{1}{2}\ (dn) \qquad ---(5)$$

The energy of an electron in a cubical metal piece of sides 'a' is given by, E

$$= \frac{n^2h^2}{8ma^2} \qquad ------ (6)$$

$$n^2h^2 = 8ma^2E$$

$$n^2 = \frac{8ma^2E}{h^2} \qquad ---- (7)$$

$$n = [\frac{8mE}{h^2}]^{\frac{1}{2}} a \qquad ---- (8)$$

Differentiating equation (11)with respect to 'n' we get,

$$dn = [\frac{8m}{h^2}]^{\frac{1}{2}} a \frac{1}{2} E^{\frac{1}{2}-1} dE \qquad ------ (9)$$

$$dn = \frac{1}{2}[\frac{8m}{h^2}]^{\frac{1}{2}} a E^{-\frac{1}{2}} dE \qquad ---- (10)$$

Substituting (10) in (5)we get,

$$Z(E)dE = \frac{1}{2}\frac{1}{2}[\frac{8m}{h^2}]^{\frac{1}{2}} a E^{-\frac{1}{2}} dE \qquad ---- (11)$$

$$Z(E)dE = \frac{1}{4}[\frac{8m}{h^2}]^{\frac{1}{2}} a E^{-\frac{1}{2}}dE \qquad --- (12)$$

Pauli"s exclusion principle states that "Two electrons of opposite spin can occupy each state".

Hence, the number of energy states available for electron occupancy is given by,

$$Z(E)dE = 2 \times \frac{1}{4}[\frac{8m}{h^2}]^{\frac{1}{2}} a E^{-\frac{1}{2}}dE \qquad ---- (13)$$

$$Z(E)dE = \frac{1}{2}[\frac{8m}{h^2}]^{\frac{1}{2}} a E^{-\frac{1}{2}}dE \qquad ---- (14)$$

The number of energy states per unit length per unit energy is

$$Z(E) = \frac{1}{2}[\frac{8^2}{h^2}]^{\frac{1}{2}} E^{-\frac{1}{2}} \qquad (\therefore\ a = 1\ for\ unit\ length\ )$$

$$Z(E)\ a\ E^{-\frac{1}{2}}$$

i.e $Z(E)^{1D} \propto E^{-\frac{1}{2}}$

This is the expression for density of charge carriers in the energy interval E and E+dE in a quantum wire.

DENSITY OF STATES IN QUANTUM DOT

In quantum dot, the electron is confined in all three dimensions and hence no motion of electron is possible. So the density of states is merely a delta function.

$$Z(E)^{1D} = 2\delta$$

2 accounts for spin

Type of structures & No. of non confinement diemensions	**Density of state function**
Bulk (3D)	$D(E) = \frac{8\pi\sqrt{2}\, m^{*3/2}(E - E_c)^{1/2}}{h^3}$
Quantum well (2D)	$D(E) = \frac{4\pi m^*}{h^2}$ $E > E_i,\ i = 1,2,3$
Quantum wire (1D)	$D(E) = \frac{2\sqrt{2}\, m^*\, (E - E_i)^{-1/2}}{h}$; $i = 1,2,3$
Quantum dot (0D)	$D(E) = \delta\,(E - E_i)$; $i = 1,2,3$