②

Unit -V

crystal physics

CRYSTAL PHYSICS

① classification of solids

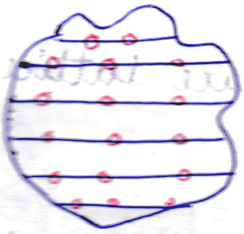
1. crystalline material
2. Non - crystalline (or) Amorphous materia

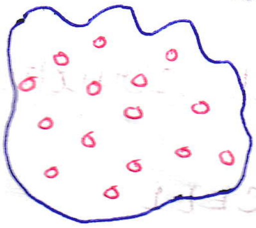
crystalline material

The materials in which the atoms are arranged in a regular pattern ar called as crystalline material.

Non - crystalline material

The materials in which the atom are arranged in a irregular pattern are called as non - crystalline materia


crystalline


Non - crystalline.

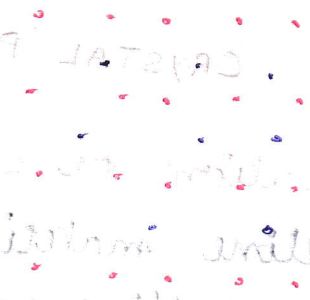
② crystal

A crystal is a three - dimensional solid which consists of a periodic arrangement of atoms.

Definition :

Lattice is an array of points in space in which the environment about each point is the same. i.e every point has identical surrounding to that every other point in the array

2-D space lattice



Not space lattice

Lattice points:

The points in a space lattice are called lattice points.

Lattice lines:

The lattice points are joined with lines are called lattice lines.

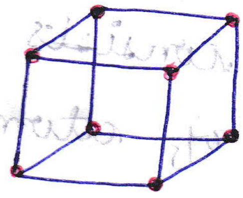
Lattice plane:

A plane containing lattice points are called lattice plane.

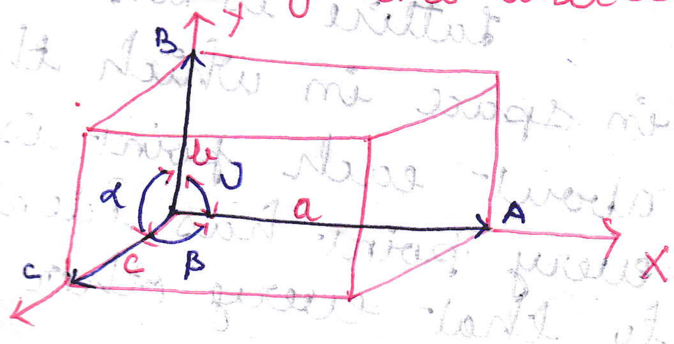
crystal structure → space lattice + Basis.

③. UNIT CELL

The unit cell is defined as the smallest geometric figure which is repeated to derive the actual crystal structure.



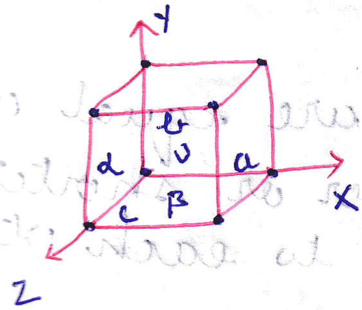
Lattice parameters of the unitcell.



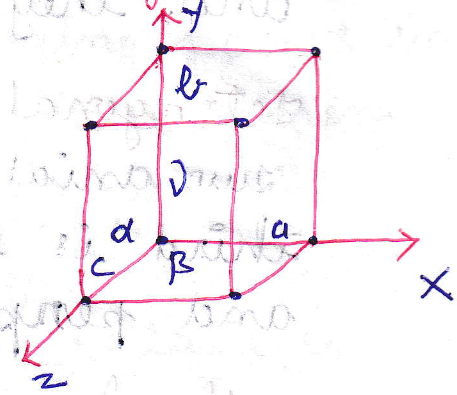
Crystal System	Intercepts	Interfacial angles	Bravais lattice	Types	Examples
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$	3	Simple, Body, Face	Nacl
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	2	Simple, Body	Indium
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90^\circ$	4	Simple, Body, Base Face	$BaSO_4$
Monoclinic	$a \neq b \neq c$	$\alpha = \beta = 90^\circ$ $\gamma \neq 90^\circ$	2	Simple, Base	$FeSO_4$
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma \neq 90^\circ$	1	Simple	$CuSO_4$
Rhombhohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90^\circ$	1	Simple	$CaSO_4$
Hexagonal.	$a = b \neq c$	$\alpha = \beta = 90^\circ$ $\gamma = 120^\circ$	1	Simple	Quartz,

Diagrams :

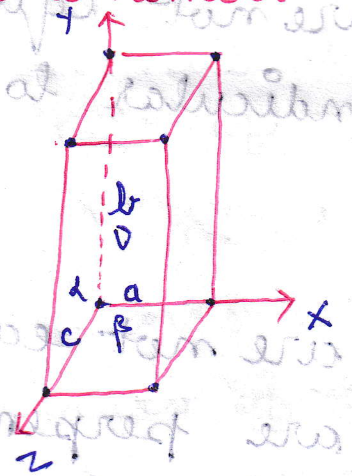
① Simple cubic



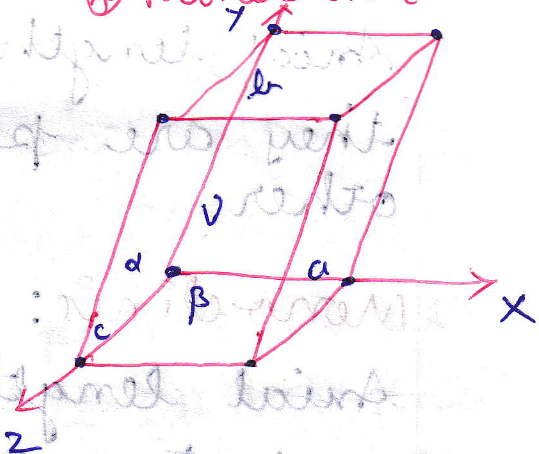
② Tetragonal



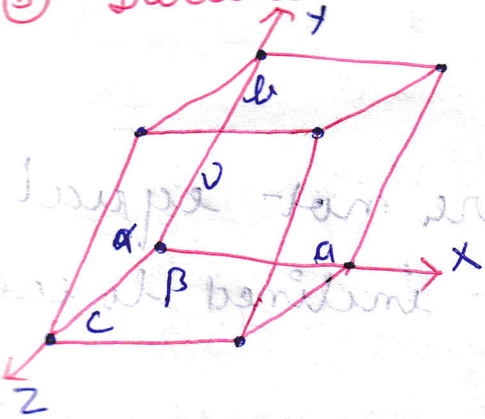
③ orthorhombic



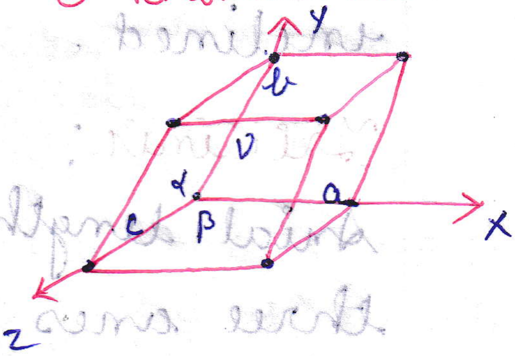
④ Monoclinic



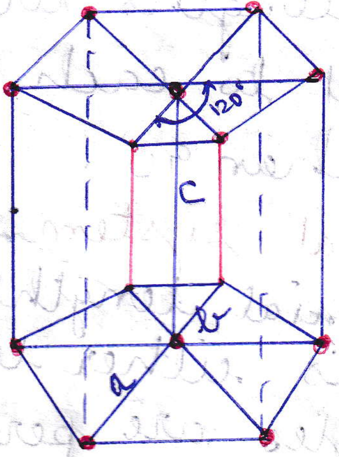
⑤ Triclinic



⑥ Rhombohedral



⑦ Hexagonal



The three axial lengths are equal and they are pendicial to each other

Tetragonal :

Two axial lengths are equal and third is either longer or shorter and perpendicular to each other

orthorhombic :

Axial lengths are not equal and they are perpendicular to each other

Monoclinic :

Axial lengths are not equal and two axes are perpendicular to each other & third is obliquely inclined.

Triclinic :

Axial lengths are not equal & three axes are inclined to each other

Rhombohedral :

Axial lengths are equal and inclined to each other at an angle other than 90°.

Hexagonal system :

Two axial lengths are equal & third is either longer or shorter two angles are perpendicular to each other.

Primitive cell :

The unit cell which contains only one lattice point is called primitive cell.

Non - primitive cell :

The unit cell which contains more than one lattice point is called as non - primitive unit cell.

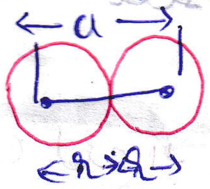
Properties (or) characteristics of unit cell :

1. No. of atoms per unit cell.

No. of atoms possessed by the unit cell is called as no. of atoms per unit cell.

2. Atomic radius :

It is the half distance between the centres of two nearest neighbouring atoms in a crystal



3. Co-ordination number :

It is the number nearest atoms directly surrounding a perticular atom in a crystal.

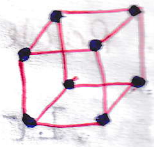
4. Packing factor (PF):

It defined as the ratio of total volume occupied by the atoms in a unit cell to the total volume of a unit cell.

Packing factor : $\frac{v}{V}$

It is also known as density of packing.

Crystal structures:



Simple cubic structure

It has lattice points at all eight corners of the unit cell. These atoms touch each other along cube edges.

1. No. of atoms per unit cell:

Each corner atom is shared by 8 adjuscent unit cell.

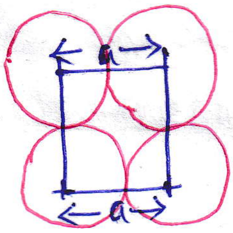
Share of each unit cell $= \frac{1}{8}$ of corner

$$= \frac{1}{8} \times 8 = 1$$

∴ Total no. of atoms in one unit cell is 1 atom.

2. Atomic radius:

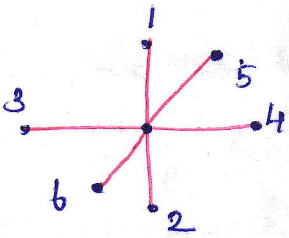
It is the distance between the centres of two nearest atoms is equal to the cube edge a.



$$2r = a$$

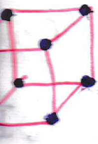
$$\boxed{r = \frac{a}{2}}$$

3. Co-ordination number



No. of nearest atoms directly surrounding that particular atom.

Hence the coordination no. for sc 6.



at all

cell.

r along

by 8

corner atom

it cell is

the

is equal

→ Packing factor (Pf) :

No. of atoms per unit cell = 1

Volume of the atoms in the unit cell

$v = 1 \times \frac{4}{3}\pi r^3$

Atomic radius, $r = \frac{a}{2}$

Total volume of the unit cell, $V = a^3$

$$Pf = \frac{v}{V}$$

$$Pf = \frac{4/3\,\pi r^3}{a^3}$$

$$= \frac{4\pi a^3}{8 a^3 \times 3}$$

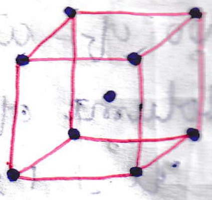
$$= \frac{\pi}{6} = \frac{3.14}{6} = 0.52$$

$$\boxed{Pf = 52\%}$$

Thus, 52% of the volume of the unit cell is occupied by atoms and the remaining 48% volume is vacant.

Example : polonium (Po) element at certain temperature range exhibits this crystal structure.

Body - centred cubic structure:



It has lattice points at all 8 corners of unit unit and one lattice point at the centre of the body of the unit cell is called Body centred cubic lattice.

1. No. of atoms per unit cell.

Each corner atom is shared by 8 adjacent unit cell.

Share of each unit cell $= \frac{1}{8}$ of corner ato

$$= \frac{1}{8} \times 8 = 1$$

In addition it has one lattice packed inside the unit cell.

∴ Total no. of atoms in one unit cell is 2 atoms.

2. Atomic radius:

The corner atoms do not touch each other. However, each corner atom touches the central atom. The corner atom and body centre atoms are lie in a straight line along the body diagonal of the cube.

Δ ABC

$$AC^2 = AB^2 + BC^2$$

$$AC^2 = a^2 + a^2 = 2a^2$$

$AG = r + r + 2r = 4r$

$AG^2 = (4r)^2$

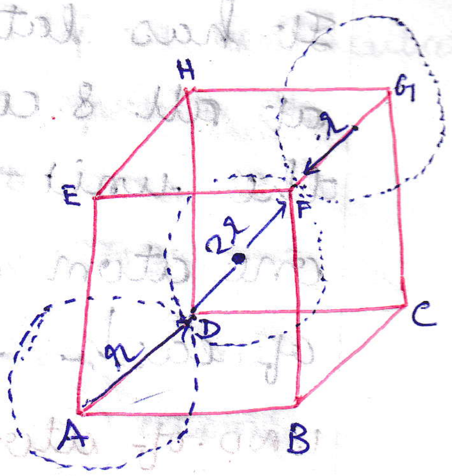
$AG^2 = AC^2 + CG^2$

$(4r)^2 = 2a^2 + a^2 = 3a^2$

$16r^2 = 3a^2$

$r^2 = \frac{8a^2}{16}$

$r = \frac{\sqrt{3}a}{4}$



∴ Hence the atomic radius for BCC is $\boxed{r = \frac{\sqrt{3}a}{4}}$

3. Coordination number:

The corner atoms do not touch each other. However, each corner atom touches the central atom. Thus, the coordination number for BCC is 8.

4. Packing factor:

No. of atoms per unit cell = 2

$v = 2 \times \frac{4}{3}\pi r^3$

$\Rightarrow r = \frac{\sqrt{3}a}{4}$

$V = a^3$

$Pf = \frac{v}{V}$

$Pf = \frac{8\pi r^3}{3a^3}$

$= \frac{8\pi(\sqrt{3}a)^3}{64 \times 3a^3}$

$= \frac{\pi\sqrt{3}}{8}$

$\Rightarrow P.f = 0.68 \times 100$

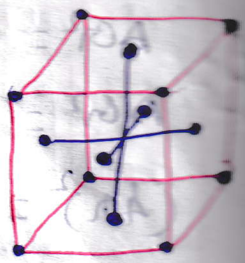
$\boxed{P.f = 68\%}$

Example: Cr, Tungsten.

68% of the volume of unit cell is occupied and the 32% is vacant.

Face centred cubic structure:

It has lattice points at all 8 corners of the unit cell and one atom at the centre of each face.



1. No. of atoms per unit cell.

Share of each unit cell $= \frac{1}{8}$ of corner ato

$$= \frac{1}{8} \times 8 = 1 \text{ atom}$$

similarly each face centred atom is shared 2 adjacent unit cell.

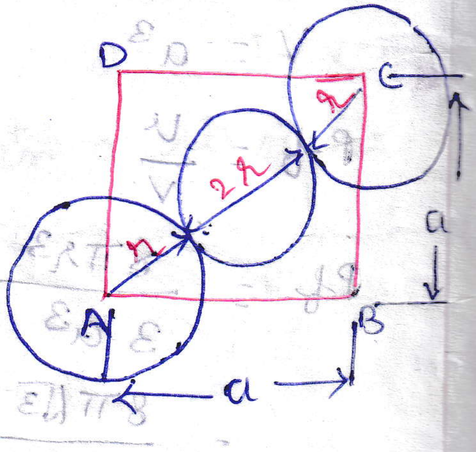
$$= \frac{1}{2} \times 6 = 3 \text{ atoms}.$$

∴ Total no. of atoms in FCC unit cell is 4 atoms.

2. Atomic radius

The atoms touch each other along the face diagonal of the cube.

ΔABC



$$AC^2 = AB^2 + BC^2$$

$$(r+2r+r)^2 = a^2 + a^2$$

$$(4r)^2 = 2a^2$$

$$16r^2 = 2a^2$$

$$\boxed{r = \frac{\sqrt{2}\,a}{4}}$$

3. co-ordination number :

There are three mutually perpendicular planes with a common point of intersection on the atom x.

In I plane, it has 4 Fcc atoms

in II plane, it has 4 Fcc atoms

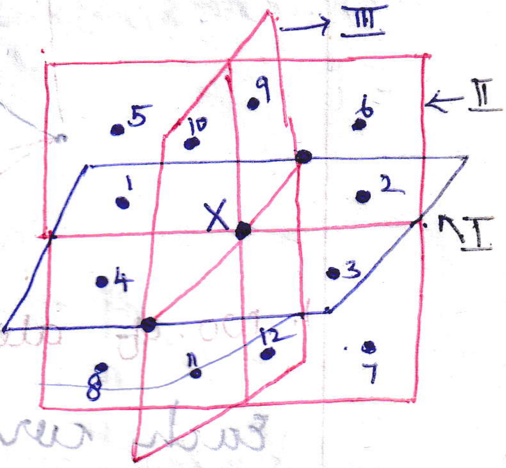
in III plane, it has 4 Fcc atoms

∴ Hence, the coordination number is 12.

4. Packing factor :

No. of atoms per unit cell = 4

$$v = 4 \times \frac{4}{3}\pi r^3$$



$$r = \frac{\sqrt{2}\,a}{4}$$

$$V = a^3$$

$$P.f = \frac{4 \times 4/_3 \pi r^3}{a^3}$$

$$= \frac{4 \times 4\pi\left(\frac{\sqrt{2}a}{4}\right)^3}{3a^3}$$

$$= \frac{16\pi\, 2\sqrt{2}\, a^3}{64 \times 3 a^3}$$

$$= \frac{\pi\sqrt{2}}{6}$$

$$= 0.74 \times 100$$

$$\boxed{P.f = 74\%}$$

Ex - copper, aluminium

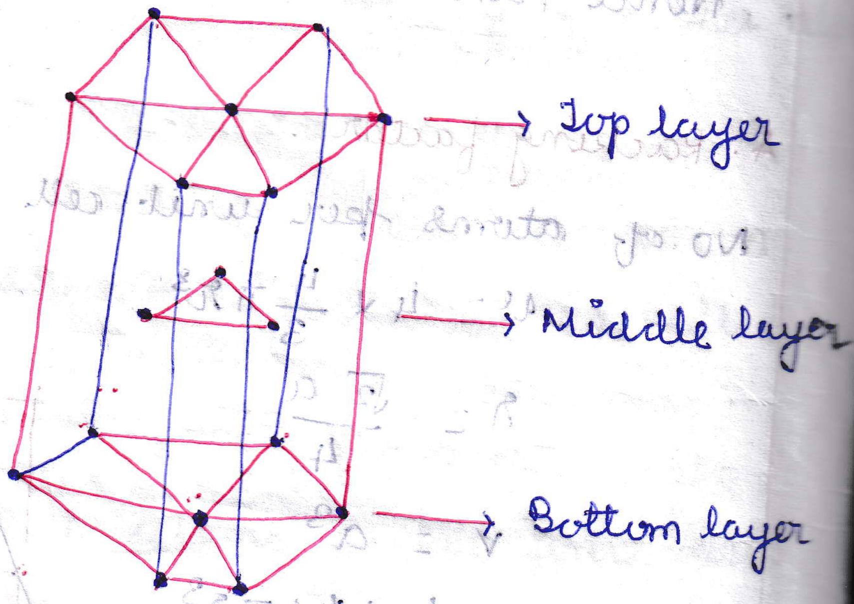
74% of the volume of unit cell is occupied by atoms & 26% is vacant.

Hexagonal close-packed structure:

The intercepts and interfacial angles of HCP are $a = b \neq c$; $\alpha = \beta = 90^\circ$, $\gamma =$

It has three layers, they are top, Bottom and middle layers.

It has 12 corner atoms, 2 face centre atom and 3 atoms packed inside the cell.



1. No. of atoms per unit cell:

Each corner atom is shared by 6 adjacent unit cells (Top layer)

$$= \frac{1}{6} \times 6 = 1$$

For bottom layer, the sharing is

$$= \frac{1}{6} \times 6 = 1$$

each fcatom is shared by 2 unit cells

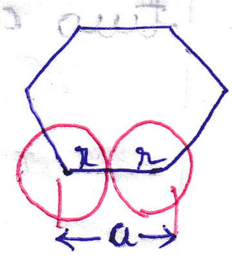
$$= \frac{1}{2} \times 2 = 1$$

In addition it has three middle layer atoms.

∴ Total no. of atoms are $= 1+1+1+3$

$= 6$ atoms.

2. Atomic radius:



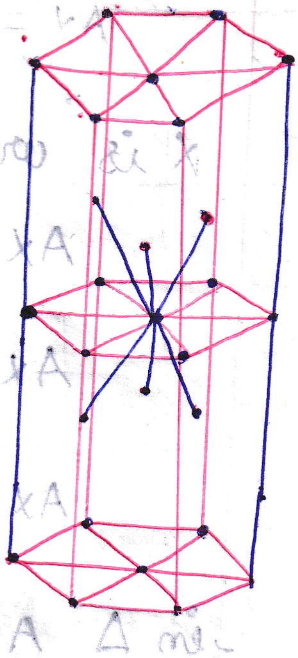
Atoms touch each other along the edges of the hexagon. The nearest neighbouring distance is $a = 2r$

Atomic radius $\boxed{r = \frac{a}{2}}$

3. co-ordination number:

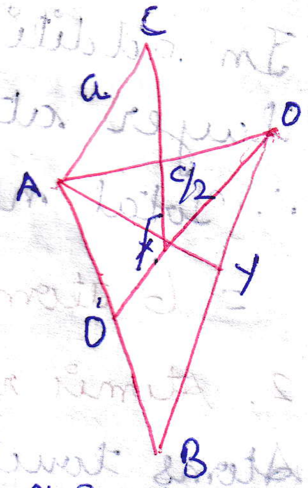
When a unit cell is placed one above the another, we get the following arrangement.

The Bottom layer has 6 neighbouring atoms. At a distance $c/2$ from the bottom layer, there are two layers, one above & the other below the bottom layer containing 3 atoms in each layer



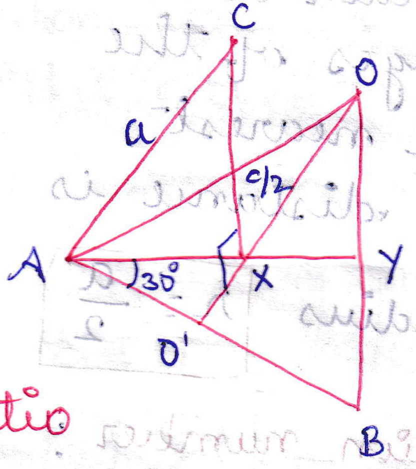
∴ The coordination number for HCP is 12.

4. Packing factor (P.f)



Triangle ABO

Let c be the height of the unit cell of HCP, a is the distance b/w two adjacent atoms



c/a ratio

$$\cos 30^\circ = \frac{AY}{AB}$$

$$AY = AB \cos 30^\circ$$

$$AY = \frac{a\sqrt{3}}{2}$$

X is orthocentre for ΔABO

$$AX = \frac{2}{3} AY$$

$$AX = \frac{a\sqrt{3}}{2} \times \frac{2}{3}$$

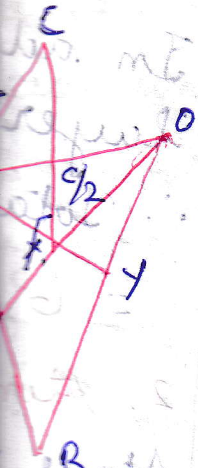
$$AX = \frac{a}{\sqrt{3}}$$

in Δ AXC

$$AC^2 = AX^2 + CX^2$$

$$AC = a, \quad AX = \frac{a}{\sqrt{3}}$$

$$a^2 = \left(\frac{a}{\sqrt{3}}\right)^2 + \left(\frac{c}{2}\right)^2$$



ngle ABO

$$a^2 = \frac{a^2}{3} + \frac{c^2}{4}$$

$$\frac{c^2}{4} = a^2 - \frac{a^2}{3}$$

$$\frac{c^2}{4} = \frac{3a^2 - a^2}{3}$$

$$\frac{c^2}{4} = \frac{2a^2}{3}$$

$$\frac{c^2}{a^2} = \frac{2 \times 4}{3} = \frac{8}{3}$$

$$\frac{c}{a} = \sqrt{\frac{8}{3}}$$

$$\boxed{\frac{c}{a} = 1.633}$$

4. Packing factor

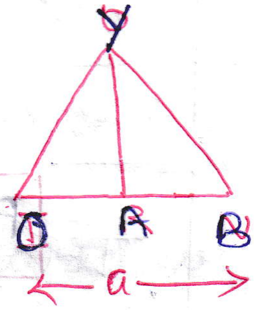
No. of atoms per unitcell = 6, Atomic radius $r = \frac{a}{2}$

$$v = 6 \times \frac{4}{3} \pi r^3$$

$$= \frac{24}{3} \pi \left(\frac{a}{2}\right)^3$$

$$= \frac{24 \pi a^3}{24}$$

$$v = \pi a^3$$



V = Base × height

Base = Area of 6 triangles $= 6 \times \frac{1}{2} bh$

ΔONI

$$= \frac{6}{2} OB \times AY$$

$$= \frac{6}{2} \times a \times AY$$

$$= 6 \quad \sqrt{3}\,a$$

$$\boxed{V = \frac{3\sqrt{3}\,a^2}{2} \times c}$$

$$P.f = \frac{v}{V}$$

$$= \frac{\pi a^3 \times 2}{3\sqrt{3}\,a^2 \times c}$$

$$= \frac{2\pi a}{3\sqrt{3}\,c}$$

$$= \frac{2\pi}{3\sqrt{3}} \times \frac{a}{c}$$

$$= \frac{2\pi}{3\sqrt{3}} \times \frac{\sqrt{3}}{\sqrt{8}}$$

$$= \frac{\cancel{2}\pi}{\cancel{2}\sqrt{2}\,3}$$

$$= \frac{\pi}{3\sqrt{2}}$$

$$= 0.74 \times 100$$

$$\boxed{P.f = 74\%}$$

Ex - Quartz

74% of the volume of unit cell is occupied by atoms & 26% is vacant. Hence, the given crystal system is tightly packed structure.

Diamond Structure :

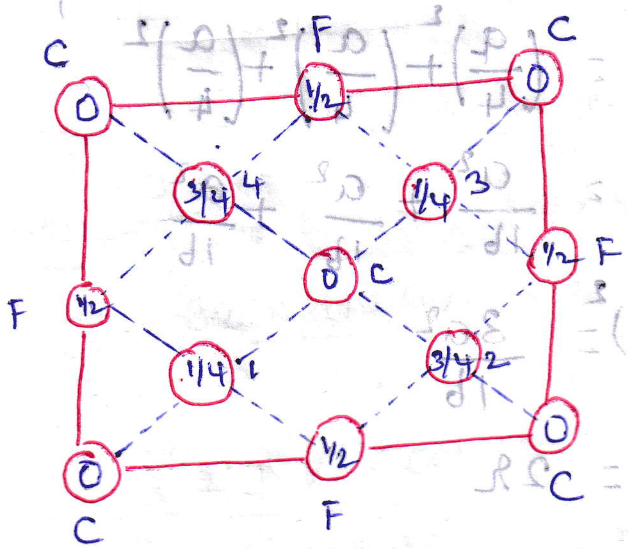
Diamond has Face centred cubic structure with the basis of two carbon atoms. One atom is located with an origin of (0,0,0) & the other atom is located with an origin of $\left(\frac{a}{4},\frac{a}{4},\frac{a}{4}\right)$.

No. of atoms per unit cell :

(i) corner atoms, represented by C

(ii) Face centred atoms, represented by F.

(iii) Four atoms present inside the unit cell represented as 1, 2, 3 & 4.



Each corner atom is shared by 8 unit cells.

$$= \frac{1}{8} \times 8 = 1 \text{ atom}$$

Each face centred atom is shared by 2 unit cells, we have 6 FC atoms

$$= \frac{1}{2} \times 6 = 3 \text{ atoms}.$$

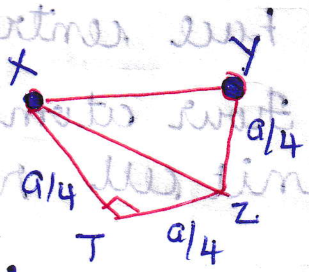
Inaddition, It has 4 atoms packed inside the unit cell.

∴ Total no. of atoms per unit cell = 1+3+4 = 8 atoms.

2. Atomic radius:

It defined as half the distance between any two nearest neighbouring atoms, which have direct contact with each other.

$$XY^2 = XZ^2 + ZY^2$$



$$= [(XT)^2 + (TZ)^2] + (ZY)^2$$

$$= \left(\frac{a}{4}\right)^2 + \left(\frac{a}{4}\right)^2 + \left(\frac{a}{4}\right)^2$$

$$= \frac{a^2}{16} + \frac{a^2}{16} + \frac{a^2}{16}$$

$$(XY)^2 = \frac{3a^2}{16}$$

$$XY = 2r$$

$$(2r)^2 = \frac{3a^2}{16}$$

$$4r^2 = \frac{3a^2}{16}$$

$$r^2 = \frac{3a^2}{64}$$

$$\boxed{r = \frac{\sqrt{3}a}{8}}$$

∴ The lattice constant $\boxed{a = \frac{8r}{\sqrt{3}}}$

3. Coordination number:

We know that number of nearest neighbouring atoms to a particular atom.

The no. of nearest atoms for Y atom is 4. Therefore, the coordination number of diamond is 4.

4. Packing factor:

No. of atoms per unit cell = 8 atoms

$$v = 8 \times \frac{4}{3}\pi r^3$$

$$V = a^3$$

$$P.f = \frac{8 \times \frac{4}{3}\pi r^3}{a^3}$$

$$r = \frac{\sqrt{3}\,a}{8}$$

$$P.f = \frac{32\pi(\sqrt{3}\,a)^3}{8^3 a^3 \times 3}$$

$$= \frac{\overset{4}{\cancel{32}}\pi\,\cancel{3}\sqrt{3}\,\cancel{a^3}}{\cancel{8} \times \cancel{8} \times \underset{16}{\cancel{64}}\,\cancel{a^3}}$$

$$\boxed{P.f = \frac{\pi\sqrt{3}}{16}}$$

$$P.f = 0.34 \times 100 \Rightarrow 34\%$$

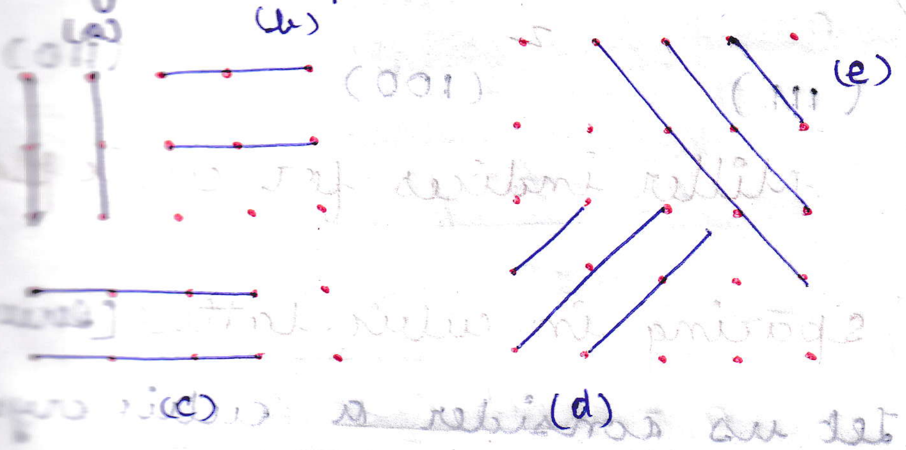
34% of the volume of unit cell is occupied by atoms & 64% is vaccant. Hence, the given crystal structure ⇒ loosely packed structure.

5. Diamond, Silicon.

.NO	SYSTEM	SC	BCC	FCC	HCP	DIAMOND
1	Atoms per unit cell	1	2	4	6	8
2	Atomic radius	$\frac{a}{2}$	$\frac{a\sqrt{3}}{4}$	$\frac{a\sqrt{2}}{4}$	$\frac{a}{2}$	$\frac{a\sqrt{3}}{8}$
3	Coordination number	6	8	12	12	4
4	Atomic packing factor	$\frac{\pi}{6} = 0.52$	$\frac{\pi\sqrt{3}}{8} = 0.68$	$\frac{\pi\sqrt{2}}{6} = 0.74$	$\frac{\pi}{3\sqrt{2}} = 0.74$	$\frac{\pi\sqrt{3}}{16} = 0.34$
5	Packing density	52 %	68 %	74 %	74 %	34 %
	Examples	Polonium	Cr, Fe	Ni, Pb	Mg, Co	Ge, Si

Miller indices :

Miller indices are used to designate the set of parallel planes (or) family planes in a crystal.



The general expression for miller indices of a plane is (hkl)

The symbol for a family of parallel planes is <hkl>.

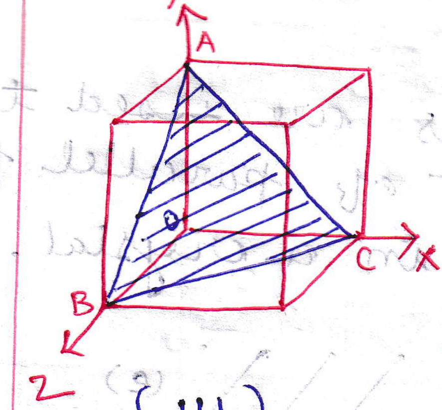
Procedure for finding Miller indices.

Step 1 : Find the intercepts of a plane along x, y and z axes (2 2 1).

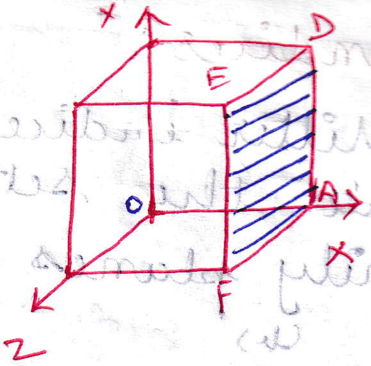
Step 2 : Take the reciprocal of these intercepts ($\frac{1}{2}:\frac{1}{2}:1$)

Step 3 : Reduce reciprocal into whole numbers by multiplying each reciprocal by LCM of the denominators.

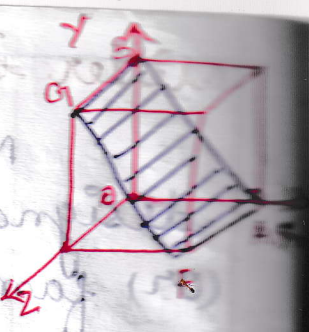
Step 4 : Write these integers within the paranthesès (112).



(111)



(100)



(110)

Miller indices for cubic planes

'd' spacing in cubic lattice [Derivation]

1. Let us consider a cubic crystal with edge a.

2. Miller indices of the plane is (h k l).

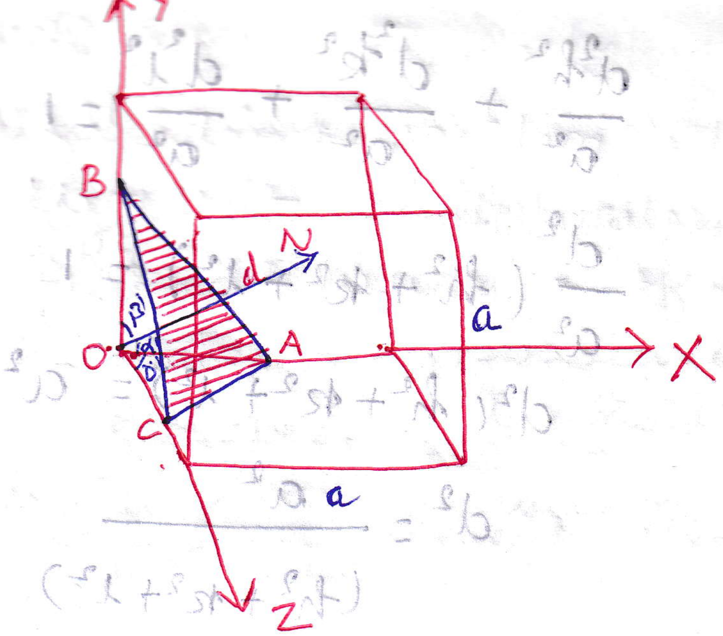
3. A normal ON is drawn to the plane ABC from the origin of the cube. Let ON be interplanar spacing (d) of this plane.

4. A plane ABC makes the intercepts OA, OB & OC on the reference axes OX, OY, & OZ.

5. α', β' & γ' are the angles between reference axes OX, OY, OZ & normal ON respectively.

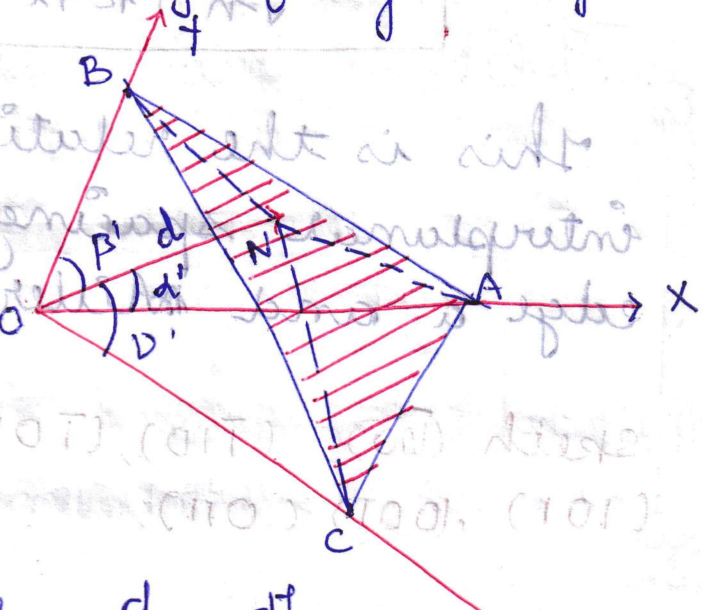
$$OA : OB : OC = \frac{1}{h} : \frac{1}{k} : \frac{1}{l}$$

$$= \frac{a}{h} : \frac{a}{k} : \frac{a}{l}$$



$$\therefore OA = \frac{a}{h}, \quad OB = \frac{a}{k} \quad \& \quad OC = \frac{a}{l}$$

From the geometry of right angles OAN, OBN & OCN



$$\cos\alpha' = \frac{ON}{OA} = \frac{d}{a/h} = \frac{dh}{a} \rightarrow ①$$

$$\cos\beta' = \frac{ON}{OB} = \frac{d}{a/k} = \frac{dk}{a} \rightarrow ②$$

$$\cos\gamma' = \frac{ON}{OC} = \frac{d}{a/l} = \frac{dl}{a} \rightarrow ③$$

The law of direction cosines is

$$\cos^2\alpha' + \cos^2\beta' + \cos^2\gamma' = 1 \rightarrow ④$$

Subst. eqns ①, ②, ③ in ④

$$\left(\frac{dh}{a}\right)^2 + \left(\frac{dk}{a}\right)^2 + \left(\frac{dl}{a}\right)^2 = 1$$

$$\frac{d^2h^2}{a^2} + \frac{d^2k^2}{a^2} + \frac{d^2l^2}{a^2} = 1$$

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

$$d^2(h^2+k^2+l^2) = a^2$$

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

$$\boxed{d = \frac{a}{\sqrt{h^2+k^2+l^2}}} \rightarrow ⑤$$

This is the relation between interplanar spacing d, cubic edge a and Miller indices (hkl).

sketh $(\bar{1}00)$, $(\bar{1}10)$, $(\bar{1}01)$, $(0\bar{1}1)$ (101), (001) (011)

Czochralski technique

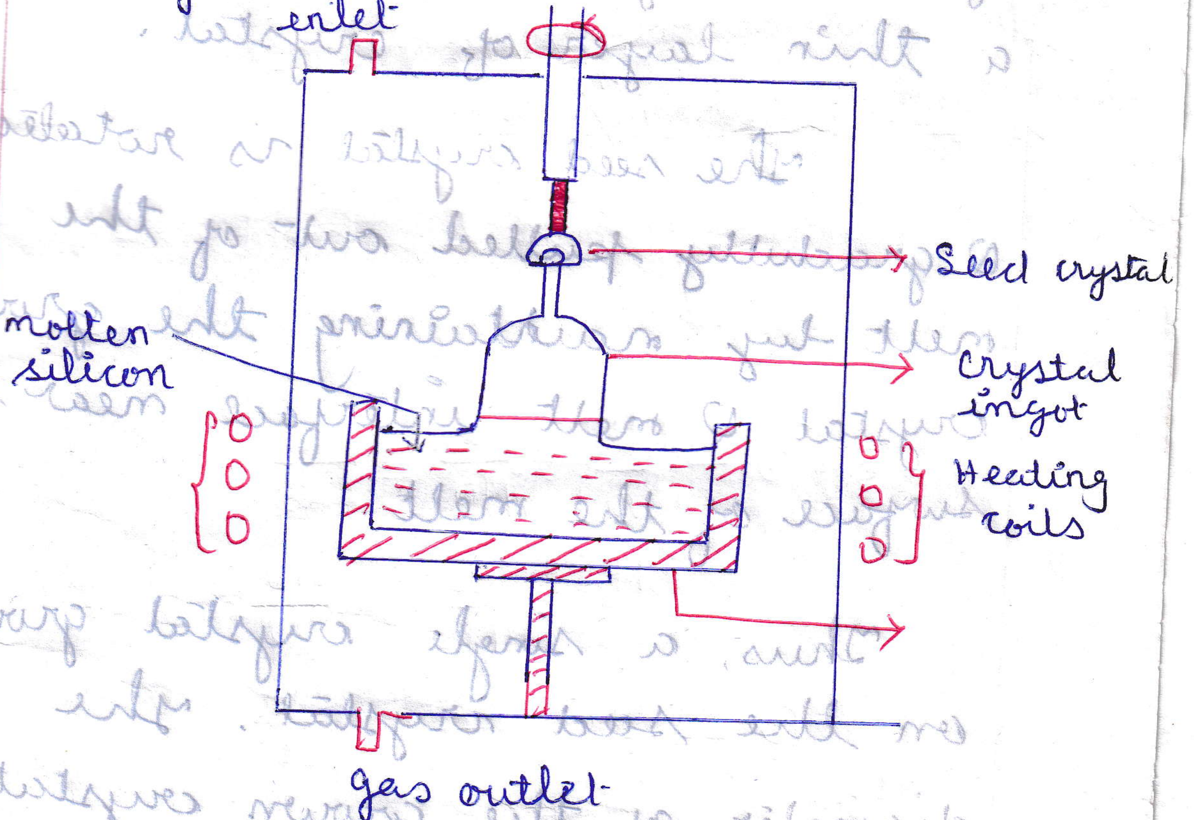
Basic principle

The czochralski method is a crystal pulling technique from the melt. The process is based on a liquid - solid phase transition driven by a seed crystal in contact with the melt.

Construction :

It consist of the following important components, they are

1. Crucible , 2. Heater , 3. Seed crystal
4. crystal holder.



The crucible is made up of graphite material, In which the given pure material has to be kept to grow single crystal.

The material is heated above the melting point by using heater. Thus, the melt is obtained in the crucible. A small defect free single crystal, called seed crystal is introduced into the melt by means of a crystal holder.

A small portion of seed crystal is melted. The temperature is suitably adjusted for the growth of seed crystal by the melt into a thin layer of crystal.

The seed crystal is rotated & gradually pulled out of the melt by maintaining the grown crystal & melt interface near the surface of the melt.

Thus, a single crystal grows on the seed crystal. The diameter of the grown crystal is controlled by the temperature of the melt & rate of pulling.

The large size cylindrical shaped grown crystal is called as

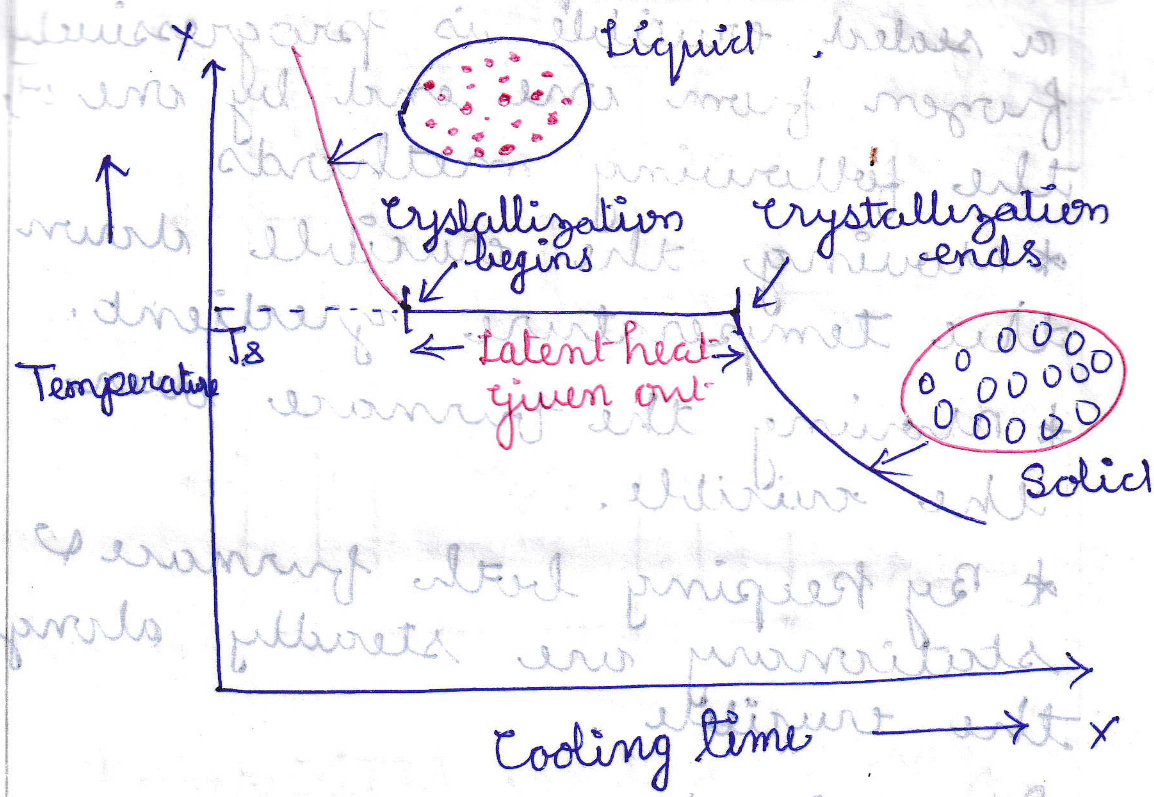
Advantages

1. Crystal growth from defeat free surface
2. It provides convenient chemical composition.
3. Easy control of atmosphere.
4. Large oriented single crystals can be grown

Limitations :

1. Liquid phase encapsulation.
2. No reproductivity of the crystal shape.
3. High vapor pressure affect the quality of crystal material.

Crystal Growth



Crystal growth techniques

1. Melt growth
2. Gel growth
3. Vapour phase growth
4. Low temp. solution growth
5. High

Melt growth

Czochralski
Bridgman technique
Zone melting "
Verneuil method.

Bridgman Technique

Principle:

The selective cooling of the molten material to form single crystal by solidification along a particular direction

Types:

Vertical Bridgman technique
Horizontal Bridgman technique

In both techniques, the melt in a sealed crucible is progressively frozen from one end by one of the following methods

* Moving the crucible down the temperature gredient.

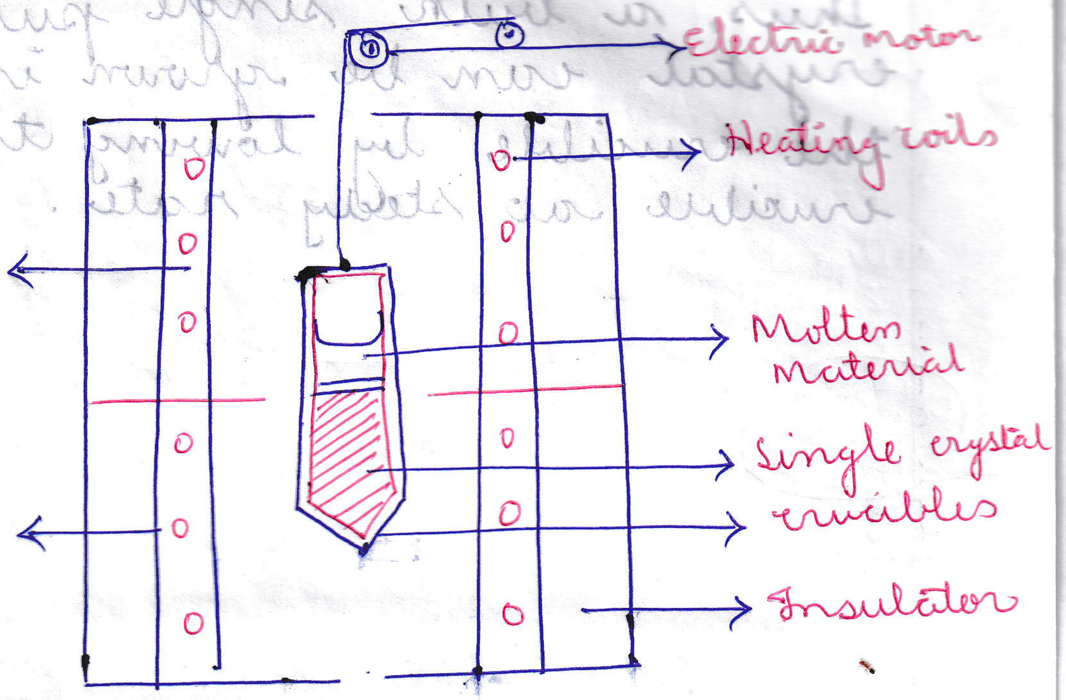
* Moving the furnace over the crucible.

* By keeping both furnace & stationary are steadly along the crucible

Dispridion:

In this method, the material to be grown in the from of a single crystal is taken in a cylinderical crucible. The crucible is made of platinum and tapered conically with pointed tip at the bottom as shown in figure.

The crucible is suspended in the upper furnace until the material in the crucible is completely melted into molten liquid.

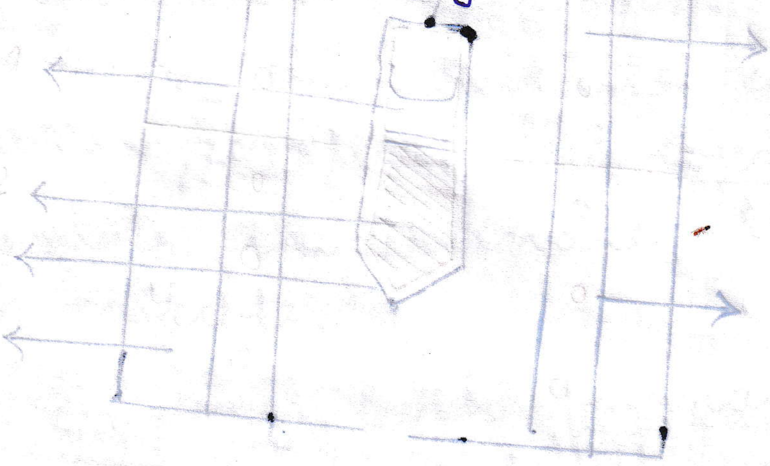


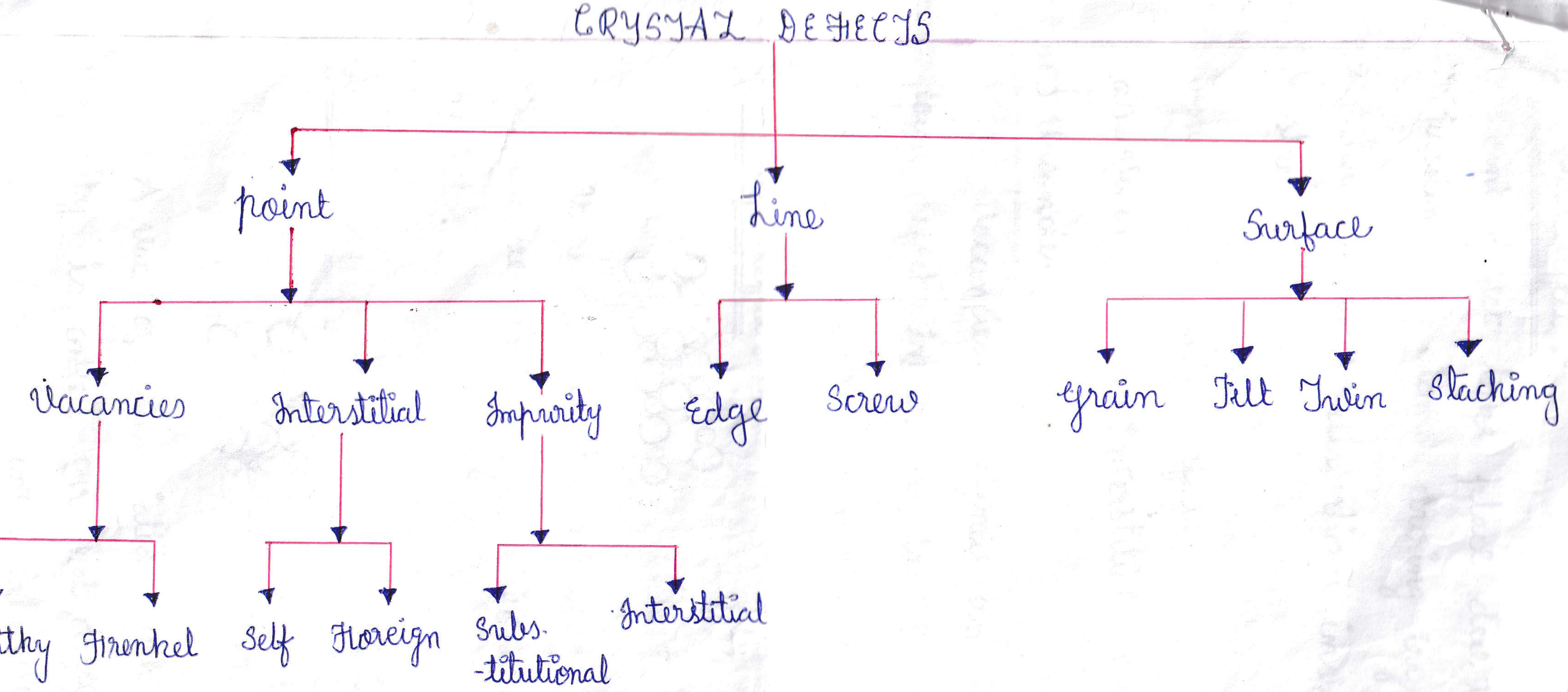
The crucible is then slowly lowered from upper furnace into the lower furnace with the help of an electric motor. The temperature of the lower furnace is maintained below the melting temperature of the melt inside the crucible.

Since, the pointed tip enters the lower first, the melt at this point starts to solidy to form crystal.

As the crucible is continuously lowered, the solidification of melt continues to form crystal ~~an~~ until all the melts becomes solid crystal.

Thus, a bulk single pure crystal can be grown in the crucible by lowing the crucible at steady rate.




CRYSTAL DEFECTS
point
Line
Surface
Vacancies
Interstitial
Impurity
Edge
Screw
Grain
Tilt
Twin
Stacking
thy
Frenkel
Self
Foreign
Subs-titutional
Interstitial

I. Point defect :-

1. Point defect take place due to imperfect packing of atoms during crystallization.
2. They produce distortion inside the crystal structure.

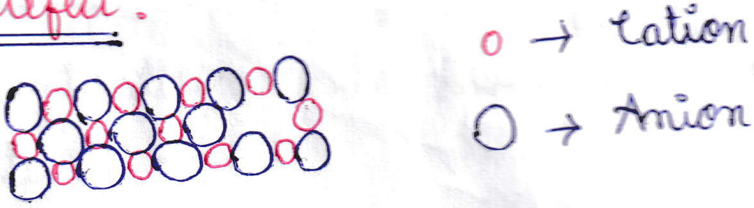
Types of points defects.

a). Vacancies b) Interstitial c) Impurity

a) Vacancies :-

Vacancies is defined as the simplest point defect in a crystal. It refers to a missing atom or vacant atomic site.

Schottky defect:



It refers to the missing of a pair of positive and negative ions in an ionic crystal.

Frenkel defect:

A vacancy associated with interstitial impurity is called Frenkel defect. If a positive ion moves into an intertitial site in an ionic crystal, a cation vacancy is created in the

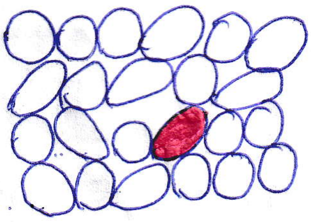
Interstitial defect :-

When an extra atom occupies interstitial space within the crystal structure without removing the parent atom, this defect is called as interstitial defect.

Types of interstitial :

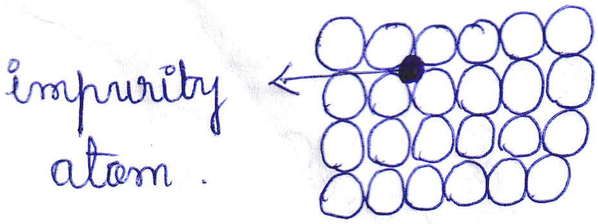
a) Self interstitial b) Foreign intertitial

a) Self interstitial :-



~~If~~ An atom from the same crystal occupies interstitial site, ~~then~~ This ~~its~~ is called self intertitial.

Foreign interstitial :-



~~If~~ An impurity atom (foreign atom) occupies intertitial site, ~~then it~~ This is called foreign interstitial.

Impurity :-

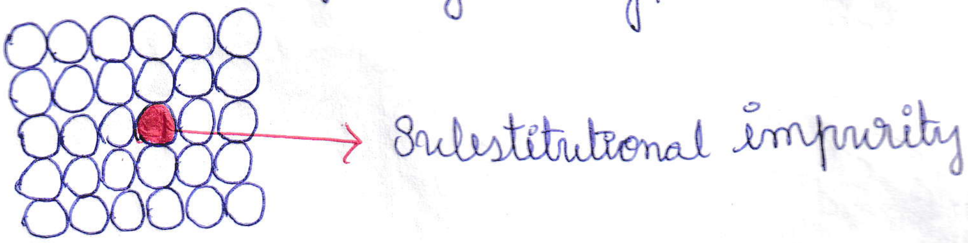
When the foreign atom (impurities) ~~are~~ is added to crystal lattices, they are known as impurities. The defect is called impurity defect.

Types of impurity defect:

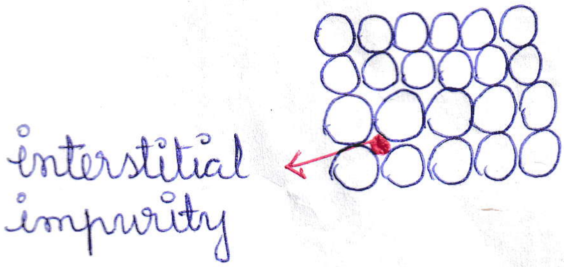
a) Substitutional b) Interstitial

a) Substitutional :-

A substitutional impurity refers to a foreign atom that replaces a parent atom in the lattices. It changes the electrical properties enormously. Eg - n-type semiconductor.



b) Interstitial :-



An interstitial impurity is a small size atom occupying the empty space (interstitial) in the parent crystal, without dislodging any of the parent atom from their sites.

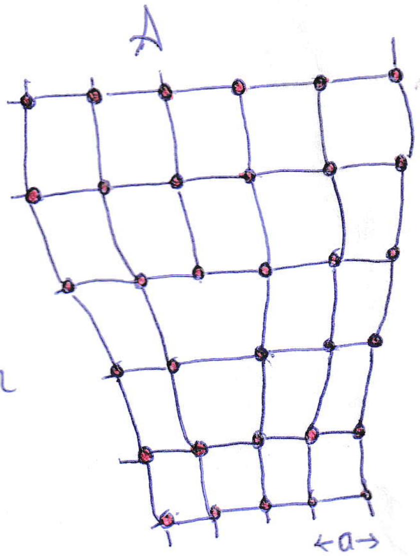
II. Line Defects (or) Dislocation :-

The defects due to dislocation of atoms along a line are known as line defects.

Types of line defect :

a) Edge dislocation b) Screw dislocation.

Edge dislocation :-



An edge distocation arises when one of the atomic planes forms only partially and does not extend through the entire crystal.

(i) positive edge distocation :

The edge dislocation is called positive, if the extra ptane of atoms is above the slip plane of the crystal. It is denoted by the symbol $\perp$.

(ii) Negative edge dislocation :

The edge dislocation is called negative, if the extra plane of atoms is below the slip plane of the crystal. It is denoted by the symbol T.