ELECTRONIC DEVICES NOTES

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Electronic Devices Notes, First Edition

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Semiconductors

Semiconductor
- → Conductivity varies with Temp., optical excit^n & impurity content
- → used for electronic & optoelectronic f^{ns} because of its variety of electronic & optical properties.

Silicon better than Germanium
- → Stable, ~~&~~ strong material, crystal structure like diamond.
- → less noisy (output isn't linear → variations come)
- → Higher operating temp (125–175 °C)
- → Ge breaks above 90 °C
- → Easily available

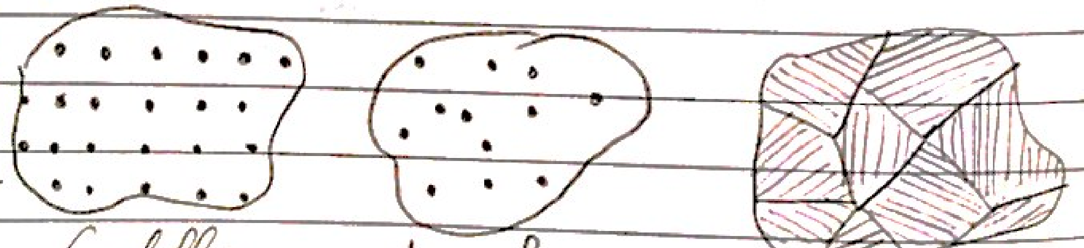
Compounds semiconductors (doped)
- → used for high-speed devices
- → devices requiring emission & absorption of light.

If ∃
- → 2 elemts : BINARY (GaN,
- → 3 elemts : TERNARY
- → 4 elemts : QUATERNARY

* ZnS semiconductor : used for fluorescent materials
* InSb, CdSe or PbTe & HgCdTe : Light detectors.
* Si & Ge : Infrared & nuclear radiation detectors
* GaAs & or InP : Microwave devices like Gunn Diode
  produce high ν oscillations.
* GaAs, AlGaAs & other ternary & quaternary compds :- Semiconductor lasers.

* Semiconductor diff^t from metal & insulator
  → Energy band gap.
    eg → GaAs = 1.43 eV (λ near infra red)
       → GaP = 2.3 eV (λ in green portion)
  → Energy band gap
    → 0 : conductor
    → small : semiconductor
    → ∞ (very large) : insulator.

* Polycrystalline solids : have many small regions of crystalline materials.



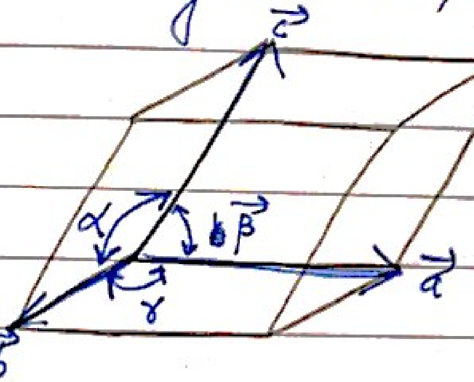
Crystalline　　Amorphous　　Polycrystalline.

* Lattice : Periodic Array of pts. in space.
* Basis : Atoms or groups of atoms in each lattice pt.
  Crystal structure = Lattice + Basis.
* Unit cell : Smallest volume that repeats itself throughout the crystal.

* A primitive cell has lattice pts. ~~at~~ only in the corners. hence ~~But~~ effective no. of lattice pts. is always UNITY ($\because$ one lattice pt. can make vector connecting other lattice pts. to make a unit cell)

* 3D lattices can be generated with 3 basis vectors.

* Unit cell of a general 3D lattice is described by 6 nos. (need not be independent):
  - ▷ 3 distances (a, b, c)
  - ▷ 3 angles (α, β, γ)



CUBIC LATTICE

Simple cubic (SC) | Face Centered (FCC) | Body Centered (BCC)

* Calcul^n of nearest neighbour distance

$= \frac{1}{2}$ of diagonal of a face

$= \frac{1}{2}(a\sqrt{2})$

$= \frac{1}{2}\left[4 \times (\text{Radius of atom})\right]$

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☆ BCC : Nearest neighbour distance

$= \frac{1}{2} \times$ (Diagonal of a cube)

$= \frac{1}{2} \times (\sqrt{3}\, a)$

$= \frac{1}{2} \times$ (4 × Radius of atom)

☆ Semiconductors are having Diamond Structure.
→ FCC structure
→ One extra atom at $\frac{a}{4} + \frac{b}{4} + \frac{c}{4}$ from each FCC atom
→ eg : GaAs (Zinc Blende)

☆ PLANES & DIR^{ns}

☆ The planes are known as <u>Miller Indices</u>, denoted by (h k l)

→ To find a plane:

1. Find intercepts of the plane along 3 axis in integral multiple of basis vectors.
2. Take reciprocal of intercepts
3. Reduce to smallest set of integers.
4. Label the plane (h k l)

for indices with ∥ to plane. Intercept = ∞. So, reciprocal gives 0.

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* Dir^n in a lattice is expressed as a set of 3 Z [p q r] being the components of a vector in that dir^n.
The 3 vector components are expressed in multiples of basis vectors, reduced to the smallest values with the same rel^{nship}.

* INTERPLANAR DISTANCE
Distance b/w adjacent planes is d or d_{hkl} is the interplanar distance.

ONLY in a cubic sys, dir^n indices of a dir^n $\perp$ to a crystal plane are the same as its Miller Indices.

Calculate interplanar distance

$$d = d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

* Angle θ b/w 2 diff^t miller indices (planes)

$$\cos\theta = \frac{h_1 h_2 + k_1 k_2 + l_1 l_2}{\sqrt{h_1^2 + k_1^2 + l_1^2}\,\sqrt{h_2^2 + k_2^2 + l_2^2}}$$

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* EGS : Electronic Grade Silicon.

* BULK ~~CYS~~ CRYSTAL GROWTH.

• Starting material (SiO_2)

$$SiO_2 + \underset{(coke)}{2C} \rightarrow \underset{(MGS)}{Si} + \underset{(impurity)}{2CO}$$

↳ Metallurgical Grade Silicon

• Impurity reduced to 1 ppb (parts per billion) to get EGS.

$$Si + \underset{(dry)}{3HCl} \rightarrow SiHCl_3 + H_2\uparrow$$

• Extract $SiHCl_3$ (trichlorosilane)

• $SiHCl_3$ is converted to EGS or semiconductor grade Si → React with H_2.

$$SiHCl_3 + 2H_2 \rightarrow \underset{(pure)}{2Si} + 6HCl\,(l)$$

* Polycrystallizⁿ method of Si
↳ ~~Czol~~ Czochralski Method.
→ Melted & held in Quartz.
→ Seed crystal put & taken out slowly by rotating.
→ Si, Ge, GaAs are grown by this method.

* LEC Growth (Liquid Encapsulated Czochralski)
For volatile elemts, layer of B_2O_3 is floated on the surface of the melt to prevent evaporⁿ.

* DOPING
Done at solidifying interface b/w melt & solid.

$$\text{Distribⁿ coeff}(k_d) = \frac{C_s}{C_l}$$

$C_s \rightarrow$ conc. of impurity in solid

$C_l \rightarrow$ conc. of impurity in liquid

eg. For a BCC lattice of identical atoms with a lattice constant of 5Å, calculate the max packing fraction and the radius of the atoms treated as hard spcies with the nearest neighbours touching.

Nearest atoms are at a distance $= \frac{\sqrt{3}}{2} \times 5 \times 10^{-10}$ m

$\simeq 4.33$ Å

Radius of atoms $= \frac{1}{2} \times$ Nearest neighbour distance

$$r = \frac{1}{2} \times (4.33 \text{ Å})$$

Volume of each atom $= \frac{4}{3}\pi r^3 = 42.5$

No. of atoms per cube $= 1 + \left(8 \times \frac{1}{8}\right) = 2$

$$\text{Packing fraction } (\phi) = \frac{\overset{\rightarrow 42.5}{\text{Volume of each atom}} \times \overset{2}{\text{No. of atoms}}}{\underset{5^3}{\text{Volume of cube}}}$$

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★ If Miller Indicies $= 0 \Rightarrow$ Its $\parallel$ to other 2 axis
($\because \frac{1}{0} = \infty \Rightarrow \perp$ to that axis)

Q. Calculate %age of free space $(100 - \phi)$ in FCC

Radius $(r) = \frac{1}{2}(a\sqrt{2}) = \frac{a}{\sqrt{2}}$

Volume of each atom $= \frac{4}{3}\pi r^3 = \frac{2\cancel{4}}{3}\pi \frac{(a^3)}{\cancel{2}\sqrt{2}}$

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

No. of atoms $= \left(8 \times \frac{1}{8}\right) + 6\left(\frac{1}{2}\right) = 4$

$\phi = \dfrac{\frac{\sqrt{2}}{3}\pi \cancel{a^3} \times 4}{\cancel{a^3}}$

$\phi = \frac{4\sqrt{2}}{3}\pi = 5.92$

Q. Calculate miller indices of plane shown.

	X	Y	Z
Intercepts	2/3	-1	1/2
Reciprocal	3/2	-1	2
Reduction	3	-2	4

Miller Indices $(3\ \bar{2}\ 4)$

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Q. Calculate of volume density of Si atoms (no. of atoms/cm^3) given that lattice constant of Si is 5.43 Å. Calculate areal density of atoms (number/cm^3) on (1 0 0) plane

DIAMOND structure of Si $\longrightarrow$ FCC
+ 4 atoms completely inside cubic cell

$$= 4 + 8\left(\frac{1}{8}\right) + 6\left(\frac{1}{2}\right) = 8 \text{ atoms.}$$

$$\text{Volume of cell} = (5.43\ \text{Å})^3 = 1.6 \times 10^{-22}\ cm^3$$

$$\text{Density} = \frac{8}{cm^3} = \frac{8}{1.6\times10^{-22}} = 5\times10^{22}\ \text{atoms}/cm^3$$

$$\text{In } (1\,0\,0) \text{ plane} = \left(4\times\frac{1}{4}\right) + \left(\cancel{\frac{1}{2}} \cancel{\times 2}\ 1\right) = 2 \text{ atoms}$$

$$= \frac{2}{(5.43\ \text{Å})^2} = 6.8\times10^{14}\ cm^{-2}$$

Q. A Si crystal is to be grown by the Czochralski method & its desired that the ingot contain 10^{16} phosphorous atoms/cm^3.

(a) What conc. of phosphorous atoms should the melt contain to give this impurity concentration in the crystal during the initial growth? For P in Si, $k_d = 0.35$

(b) If the initial load of Si in the crucible is 5 kg, how many grams of P should be added. Atomic weight of P = 31.

(a) $k_d = \frac{C_s}{C_l} \Rightarrow C_l = \frac{10^{16}}{0.35}$ Ans

(b)

✳ EPITAXIAL GROWTH or EPITAXY

Methods

Chemical vapor deposition (CVD)	Molecular beam Epitaxy ~~EMB~~	?

- ✳ Heteropitaxy : In case of Epitaxial Layer mismatch.
- ✳ Any compd (mono, binary, ternary or quartenary) compd can be grown over the other : provided their Lattice Constt. match).
- ✳ If ∃ a mismatch in Lattice constt, we can change Lattice constt during Epitaxial growth
- ✳ Pseudomorphic : If ∃ little mismatch, compression or tension would be there. Thin layers grown.
- ✳ Misfit dislocn : If layer exceeds critical thickness.
- ✳ SLS : Strained - layer . . . .

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Ch: ELEMENTARY QUANTUM MECHANICS

developed by Heisenberg & Schrödinger

- Quantum particles can act both as particles & waves
  ⇓
  WAVE - PARTICLE duality.
- Quantum mechanics uses Probability theory.

☆ Heisenberg's Uncertainty Principle.

$$(\Delta x)(\Delta p) \geq \frac{\hbar}{2} \quad ; (\Delta x)(\Delta p) \geq \frac{h}{4\pi}$$

∴ ∃ uncertainty in energy & time

$$(\Delta E)(\Delta t) \geq \frac{\hbar}{2} \quad ; h = 6.625 \times 10^{-34}\ Js$$

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

☆ In 1D : probability of finding the particle in range, x to $(x+dx)$ is $P(x)\,dx$.

☆ P(particle is somewhere in the entire space)

$$\int_{-\infty}^{\infty} P(x)\,dx = 1.$$

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* Ψ = Probability density (a wavefunction)
$|\Psi^2|$ = Probability.

Postulate (1)

* Each particle in a physical sys. is described by a wavef^n & $\Psi(x,y,z,t)$.

&

$\nabla \Psi$ should be
→ finite
→ single valued
→ cts.

* BASIC POSTULATES

Postulate (2)

Classic variable	Quantum operator
x	x
$f(x)$	$f(x)$
momentum, $p(x)$	$\frac{\hbar}{j}\frac{\partial}{\partial x}$
E	$-\frac{\hbar}{j}\frac{\partial}{\partial t}$

; $\hbar = \frac{h}{2\pi}$, j : complex constt.

Postulate (3)

* Probability of finding a particle with wavef^n Ψ in volume $dxdydz$ is $\Psi^* \Psi \, dxdydz$.

Normaliz^n cond^n of wavef^n :-

$$\int_{-\infty}^{\infty} \Psi^* \Psi \, dxdydz = 1$$

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* We can find only avg. values of these physical quantities.
These avg. values, called EXPECTATION VALUES & for an operator Q_{op} its.

$$\int_{-\infty}^{\infty} Q_{op}\, \psi^{*} \psi \, dx\,dy\,dz.$$

* SCHROEDINGER EQ^n.

KE + PE = Total energy i.e $\frac{p^2}{2m} + V(x) = E$

to Quantum

2D: $$-\frac{\hbar^2}{2m} \frac{\partial^2 \psi(x,t)}{\partial^2 x} + V_{(x)} \psi_{(x,t)} = -\frac{\hbar}{j} \frac{\partial}{\partial t} \psi_{(x,t)}$$

3D: $$-\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi = -\frac{\hbar}{j} \frac{\partial \psi}{\partial t}$$

$$\psi_{(x,t)} = \psi_{(x)} \phi_{(t)}$$

$$\hookrightarrow -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial^2 x} \psi_{(x)} \phi_{(t)} + V_{(x)} \psi_{(x)} \phi_{(t)}$$

$$= -\frac{\hbar}{j} \psi_{(x)} \frac{\partial \phi_{(t)}}{\partial t}$$

Separate in 2 eq^{ns}

Time dependent

$$\frac{d\,\phi(t)}{dt} + \frac{jE}{\hbar} \phi(t) = 0$$

Time Independent

$$\frac{d^2 \psi(x)}{dx^2} + \frac{2m}{\hbar^2} [E - V(x)] \psi(x) = 0$$

* For particle in a box sys,

$$E \text{ (or } V) = 0 \quad , \; 0 < x < L$$
$$\rightarrow \infty \quad , \; x = 0 \; \& \; x = L.$$

So, b/w 0 & L, eq^n changes to

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

$$\Rightarrow \frac{\partial^2 \psi(x)}{\partial x^2} = -\underbrace{\frac{2mE}{\hbar^2}}_{k} \psi(x)$$

Solving :-

$$\psi(x) = A \sin kx + B \cos kx.$$

$\hookrightarrow x = 0 \; \& \; x = L, \; \psi(x) = 0$

$$\Rightarrow \psi(0) = A \sin(0) + B\cos(0) = 0$$
$$\Rightarrow B = 0$$
$$\Rightarrow \psi(x) = A \sin kx$$

At $x = L$

$$\Rightarrow \psi(L) = A \sin kL = 0$$
$$\Rightarrow kL = n\pi$$
$$\Rightarrow k = \frac{n\pi}{L} \text{ or } k_n = \frac{n\pi}{L}. \; ; n \in \mathbb{Z}$$

So, $\psi(x) = A \sin\left[\left(\frac{n\pi}{L}\right)x\right] \; ; n \in 1, 2, \ldots$

$\hookrightarrow$ Find A : Using normalization.

$$\int_0^L \psi^*(x) \, \psi(x) = A^2 \frac{L}{2} = 1$$

(Total Probability = 1)

So $\psi_n(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi}{L} x\right)$

↳ Schrodeinger eq^n for particle well ~~or particle in a box~~.

*TUNNELING:

When KE of particle is smaller than the potential barrier in front of it, it still has some property to penetrate through barrier.

Note: This happens only when the barrier potential is not infinite. & $\psi \neq 0$ at barrier

⇓

ψ^2 exists. So, $\exists$ probability of existence of particle ahead of boundary.

* SEMICONDUCTOR - QUESTIONS.

Q. Sketch an SC unit cell with a lattice const, $a = 4\,\text{Å}$, whose diatomic basis of atom A is located at lattice sites, and with atom B displaced by $\left(\frac{a}{2}, 0, 0\right)$. Assume that both atom has same size and we have a closed packed structure.

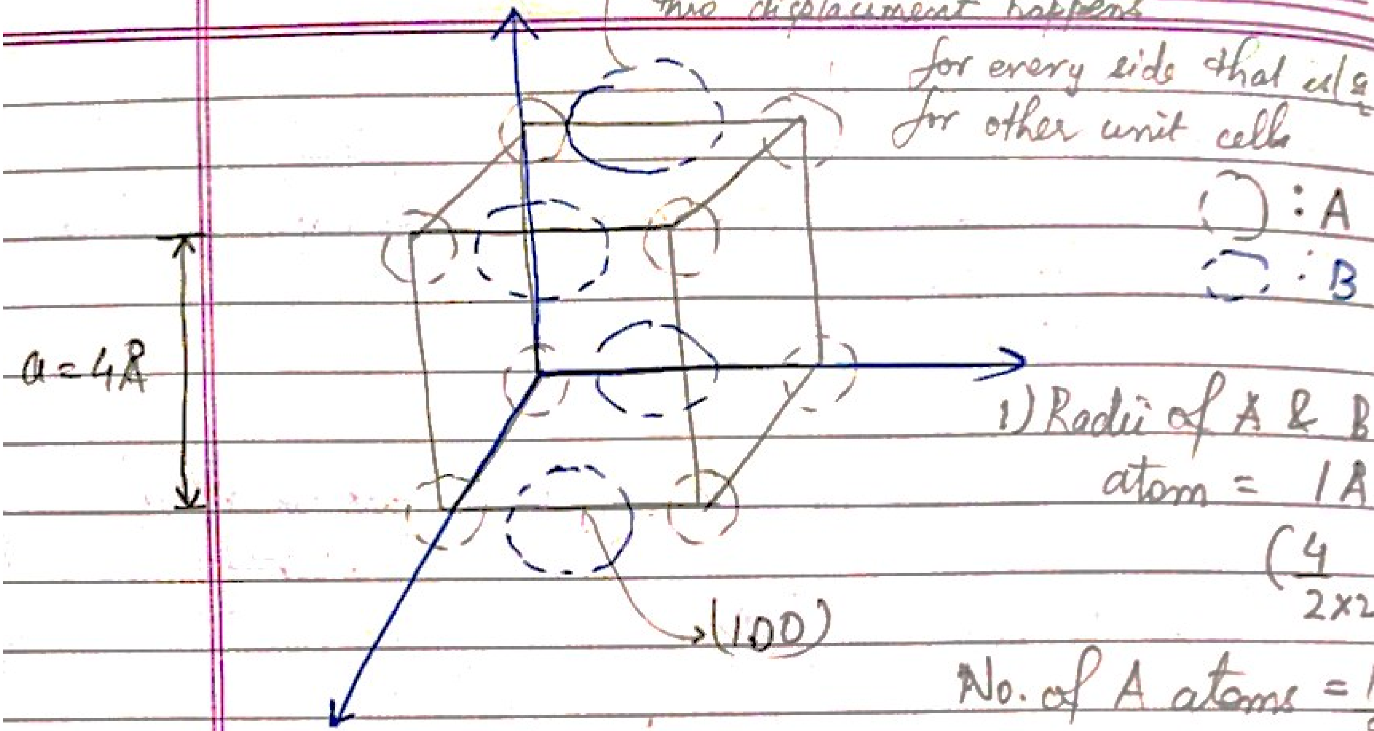
Calculate:

(i) Packing fraction.

(ii) No. of B atoms p.u volume

(iii) No. of A atoms p.u area on (100) plane.

They are displaced by $(\frac{a}{2},0,0)$ They are 4 so this displacement happens for every side that is $(\frac{a}{2},0,0)$ for other unit cells



1) Radii of A & B atom = 1Å $\left(\frac{4}{2\times2}\right)$

No. of A atoms $= \frac{1}{8}\times8 = 1$

No. of B atoms $= \frac{1}{4}\times4 = 1$

Volume of atoms $= 1\times\frac{4}{3}\pi r^3 + 1\times\frac{4}{3}\pi r^3$, $r = 1Å$

$= 8.373\times10^{-30}$ ~~unit~~ m^3

(a) Packing fraction $= \dfrac{\frac{8\pi}{3}\times(Å)^3}{a^3} = \dfrac{\frac{8\pi}{3}\times\cancel{(Å)^3}}{64\times\cancel{(Å)^3}}$

$= \dfrac{\pi}{24} = 13.083\%$

(b) Packing fraction of ~~No.~~ of B atoms ~~[illegible]~~ $= \dfrac{Vol_B}{Total\ vol}$

$= \dfrac{\frac{4}{3}\pi\times(Å)^3\times1}{a^3}$

$= \dfrac{1\,4\pi}{3\times64} = \dfrac{\pi}{48} = 0.0654$

(ii) $\frac{1}{64(\text{Å})^3} = 1.56 \times 10^{+22} /cm^3$

(iii) $\cancel{\frac{1}{2}}\ \frac{\frac{1}{8} \times 4}{16(\text{Å})^3} = \cancel{7.8125}\ 3.125 \times 10^{+14}$ per cm^3

Q A crystal with a SCC & a monoatomic basis has atomic radius of 2.5 Å & At. wt 5.42. Find ρ assuming atoms touch each other

$r = 2.5$ Å

$\cancel{\rho = \frac{5.42}{\frac{4}{3}\pi r^3} \times 1 = 8.285 \times 10^{22}\ u/cm^3}$

5.42 is g/mol. So, g/atom = ? $5.42 \times N_A$

$= 5.42 \times 6.022 \times 10^{23}$ g/atom.

$$\rho = \frac{5.42 \times 6.022 \times 10^{23}}{a^3} \times (1)$$

$$= \frac{5.42 \times 6.022 \times 10^{23}}{(2 \times 2.5)^3 \times (\text{Å})^3}$$

$$= 2.611 \times 10^{22} \times 10^{24}$$

$$\rho = 2.611 \times 10^{46}\ g/atom.$$

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Q. A Si crystal is to be grown using Czochralski method & its desired that ingot contains 10^{16} phosphorous atoms /cm^3.

(a) What conc. of P atoms should the melt contain to give this impurity conc in the crystal during initial growth? For P in Si, $k_d = 0.35$

$$10^{16} \leftarrow \frac{C_S}{C_L} = k_d \Rightarrow C_L = 2.86 \times 10^{16}$$

(b) If initial load of Si in crucible is 5 kg, how many grams of P should be added?

P → at. wt = 31

Ans :- Given $\rho_{Si} = 2.33\ g/cm^3$

P is very less in Volume (∵ 5 kg Si)
So, can be neglected.

$$(\text{Volume})_{melt} = \frac{m_{Si}}{\rho_{Si}} = \frac{5000}{2.33} = 2146\ cm^3 \text{ of Si}$$

& $\boxed{\text{No. of atoms} = \text{Conc.} \times \text{Vol}}$

$$(N) = 2.86 \times 10^{16} \times 2146 = 6.14 \times 10^{19} \text{ atoms.}$$

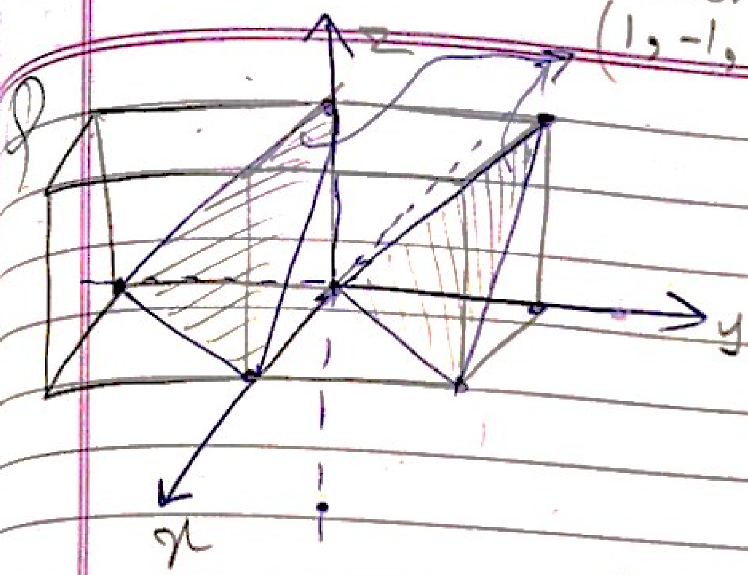
So, amt. of P req^d $(m) = \frac{N \times M}{N_A} = \frac{6.14 \times 10^{19} \times 31}{6.022 \times 10^{23}}$

$$= 3.16 \times 10^{-3}\ g$$

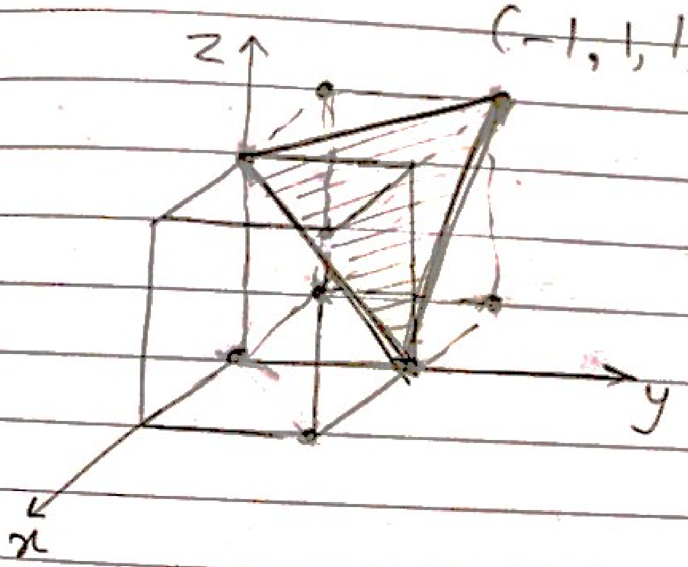
Drawing plane with Miller Indices.

$(1, -1, 1)$

Q



$(-1, 1, 1)$



Q A Si crystal is to be pulled from the melt & doped with As ($k_d = 0.3$). If Si weighs 1kg, how many grams of As should be introduced to achieve $10^{15}\ cm^{-3}$ doping during initial growth.

$$\frac{C_S}{C_L} = k_d \quad \frac{10^{15}}{0.3} = C_L$$

(Given As = 74.9 g/mol ≈ 75)

$$= 3.33 \times 10^{15}$$

$$\text{Volume} = \frac{1000}{2.33} = 429.184\ cm^3$$

No. of atoms $= 3.33 \times 10^{15} \times 429.184$ atoms

$$\text{amt. of As} = \frac{3.33 \times 10^{15} \times 429.184 \times 75}{6.022 \times 10^{23}} = 1.78 \times 10^{-4}\ g$$