Tutorial – 1

EC2000 Solid State Electronic Devices

1. Consider a hypothetical crystal with a simple cubic (SC) crystal structure. The lattice constant of the crystal is 5 angstroms (Å). Calculate the following parameters:
   a) Number of atoms per unit cell.
   b) Nearest neighbour distance.
   c) Atomic radius (r).
   d) Surface density.
   e) Volume density of atoms in the crystal.
   f) Packing factor of the crystal.

2. Repeat Question 1 for FCC and BCC crystal structure with the same lattice constant.

3. n-type silicon is obtained by doping silicon with ……………………..a) Germanium b)Aluminum c)Boron d)Phosphorous

4. The concentration of minority carriers in an extrinsic semiconductor under equilibrium is directly proportional to the …………… a)doping concentration b) Inversely proportional to the doping concentration c) Directly proportional to the intrinsic concentration d) Inversely proportional to the intrinsic concentration

5. A bar of Gallium Arsenide (GaAs) is doped with Silicon such that the Silicon atoms occupy Gallium and Arsenic sites in the GaAs crystal. Which one of the following statement is true? a) Silicon atoms act as p-type dopants in Arsenic sites and n- type dopants in Gallium sites b) Silicon atoms act as n-type dopants in Arsenic sites and p-type dopants in Gallium sites c) Silicon atoms act as p-type dopants in Arsenic as well as Gallium sites

6. If the lattice constant of silicon is 5.43 Å, calculate (a) the distance from the center of one silicon atom to the center of its nearest neighbour, (b) the number density of silicon atoms (#/cm^3)
7. The lattice constant of a single crystal is 4.73 Å. Calculate the surface density (#/cm^2) of atoms on the (i) (100), (ii) (110)

8. If the lattice constant of silicon is 5.43 Å, (a) Determine the surface density of atoms for silicon on the (111) plane. (b) Calculate the density of valence electrons in silicon.

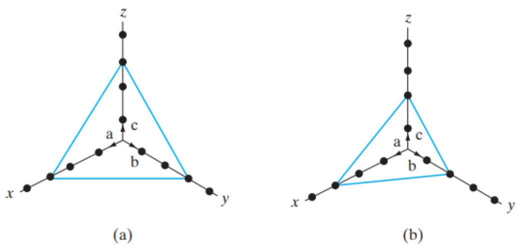
9. In many semiconductors, atoms are arranged in a basic diamond structure but are different on alternating sites called ……………………. structure which is typical of ……………………… compounds.
10. List the semiconductor used in the development of Light Emitting Diodes.

11. Calculate the volume density of Si atoms (number of atoms/cm3), given that the lattice constant of Si is 5.43 Å. Calculate the areal density of atoms (number/cm2) on the (100) plane

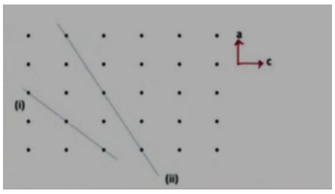
12. A body-centered cubic lattice has a lattice constant of 4.83 Å. A plane cutting the lattice has intercepts of 9.66 Å, 19.32 Å, and 14.49 Å along the three cartesian coordinates. What are the Miller indices of the pane?

13. Consider a face-centered cubic lattice. Assume the atoms are hard spheres with the surfaces of the nearest neighbours touching. Assume the effective radius of the atom is 2.37 Å. (a) Determine the volume density of atoms in the crystal. (b) Calculate the surface density of atoms in the (110) plane. (c) Determine the distance between nearest (110) planes. (d) Repeat parts (b) and (c) for the (111) plane

14. Label the planes illustrated in Fig



15. The Miller indices of the planes parallel to the b axis and intersecting the a and c axis, as shown in the figure,



16. Silver crystallizes in face-centered cubic structure. The 2nd order diffraction angle of a beam of X-ray (lambda = 1A) of (111) plane of the crystal is 30°. Therefore, the unit cell length of the crystal would be __.
17. A compound A B, has a cubic structure with A atoms occupying all corners of the cube as well as all the face xy centre positions. The B atoms occupy four tetrahedral voids. The values of x and y respectively, are __.
18. Metallic silver crystallizes in face-centred-cubic lattice structure with a unit cell of length 40 nm. The first order diffraction angle of X-ray beam from (2, 1, 0) plane of silver is 30 deg The wavelength of X-ray used is close to __
19. Diamond lattice can be considered as a combination of two fcc lattice displaced along the body diagonal by one quarter of its length. There are eight atoms per unit cell. The packing fraction of the diamond structure is __.
20. The number of second-nearest neighbor ions to a N a^ + ion in NaCl crystal is __ .

Solution 1:

Number of Atoms per Unit Cell = 8 *1/8 = 1

Nearest Neighbour Distance, d_{nn} = 5 Å

Atomic Radius, r = a/2 = 5/2 Å = 2.5 Å

Surface Density = Number of atoms on the plane/Area of the plane = 1/a^2 = 1/5^2 = 1/25

= 0.04 atoms/Å^2

Volume Density = Number of atoms in the unit cell/Volume of the unit cell= 1/a^3 = 1/5^3

= 1/125 = 0.008 atoms/Å^3

Packing Factor = Volume occupied by atoms in the unit cell/Volume of the unit cell $= \frac{\frac{4}{3}\pi r^3}{a^3} = \frac{\frac{4}{3}\pi(2.5)^3}{5^3}$ = 0.524.

Solution 2:

For FCC

Number of Atoms per Unit Cell = $8 * \frac{1}{8} + 6 * \frac{1}{2} = 1 + 3 = 4$

In an FCC structure, the nearest neighbours are located along the face diagonals. The face diagonal can be calculated as: $a\sqrt{2}$

The nearest neighbour distance d_{nn} is half of the face diagonal:

Nearest Neighbour Distance, d_{nn} = $a\frac{\sqrt{2}}{2} = 5 * \frac{\sqrt{2}}{2} = 3.54$ Å

Atomic Radius, r = d_{nn} /2 = 3.54/2 Å = 1.77 Å

Surface Density

Number of atoms per surface = $1 + 4 * \frac{1}{4} = 1 + 1 = 2$

Area = $a^2 = 5^2 = 25$

Surface Density = Number of atoms on the plane/Area of the plane = 2/25 = 0.08 atoms/$Å^2$

Volume Density

Volume Density = Number of atoms in the unit cell/Volume of the unit cell= $4/a^3 = 4/5^3$

= 4/125 = 0.032 atoms/$Å^3$

Packing Factor

Packing Factor = Volume occupied by atoms in the unit cell/Volume of the unit cell $= \frac{\frac{4}{3}\pi r^3}{a^3}$

$= \frac{\frac{4}{3}\pi(1.77)^3}{5^3}$ = 0.74

For BCC

Number of Atoms per Unit Cell = $8 * \frac{1}{8} + 1 = 1 + 1 = 2$

In a BCC structure, the nearest neighbours are along the body diagonal. The body diagonal can be calculated as: $a\sqrt{3}$

The nearest neighbour distance d_{nn} is half of the body diagonal:

Nearest Neighbour Distance, d_{nn} = $a\frac{\sqrt{3}}{2} = 5 * \frac{\sqrt{3}}{2} = 4.33$ Å

Atomic Radius, r = d_{nn} /2 = 4.33 /2 Å = 2.165 Å

Surface Density

Number of atoms per surface = $4 * \frac{1}{4} = 1$

Area = $a^2 = 5^2 = 25$

Surface Density = Number of atoms on the plane/Area of the plane = 1/25 = 0.04 atoms/Å^2

Volume Density

Volume Density = Number of atoms in the unit cell/Volume of the unit cell= $2/a^3 = 2/5^3$

= 2/125 = 0.0165 atoms/Å^3

Packing Factor

Packing Factor = Volume occupied by atoms in the unit cell/Volume of the unit cell $= 2 * \frac{\frac{4}{3}\pi r^3}{a^3}$

$= 2 * \frac{\frac{4}{3}\pi(2.165)^3}{5^3}$ = 0.68

Solution 3: Phosphorus

n-type silicon is obtained by doping silicon with elements that can donate extra electrons, increasing the electron concentration. For this, usually elements from group V of the periodic table, such as phosphorus, arsenic, or antimony are used.

Solution 4: Directly proportional to the intrinsic concentration

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Solution 5: Silicon atoms act as p-type dopants in Arsenic sites and n- type dopants in Gallium sites

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Solution 6:

Silicon crystallizes in a diamond cubic structure, where the nearest neighbour distance is half of the face diagonal of the unit cell.

The lattice constant of silicon (a) is given as 5.43 Å

The face diagonal (d_f) of a cube with side length a is given by: $d_f = a\sqrt{2} = 5.43 * \sqrt{2}$

Nearest Neighbour Distance, d_{nn} = $\mathbf{5.43 * \frac{\sqrt{2}}{2} = 3.84}$ Å

Volume of the unit cell = $a^3 = (5.43 * 10^{-8}\ cm)^3 = 1.6 * 10^{-22}\ cm^3$

In a diamond cubic structure, there are 8 atoms per unit cell.

The number density of atoms, N = $\frac{\boldsymbol{Number\ of\ atoms\ per\ unit\ cell}}{\boldsymbol{Volume\ of\ the\ unit\ cell}} = \frac{\mathbf{8}}{\mathbf{1.6*10^{-22}}} = \mathbf{5 * 10^{22}}$ atoms/cm^3

Solution 7:

To find the surface density of atoms on different planes of a crystal, we need to calculate the number of atoms per unit area on the specified planes.

Area of the (100) plane, $A_{100} = a^2 = (4.73 * 10^{-8}\ cm)^2 = 2.24 * 10^{-15} cm^2$

Number of atoms per (100) plane = $4 * \frac{1}{4} = 1$

Surface density on the (100) plane,

$$\boldsymbol{\sigma_{100}} = \frac{\boldsymbol{Number\ of\ atoms}}{\boldsymbol{Area}} = \frac{\mathbf{1}}{\mathbf{2.24*10^{-15}}\boldsymbol{cm^2}} = \mathbf{4.46 * 10^{14}}\boldsymbol{atoms/cm^2}$$

Area of the (110) plane, $A_{110} = a * a\sqrt{2} = 4.73 * 4.73\sqrt{2} = (4.73 * 10^{-8} * 4.73 * 10^{-8} * \sqrt{2}\ cm)^2 = 3.35 * 10^{-15} cm^2$

Number of atoms per (110) plane = 2

Surface density on the (110) plane,

$$\boldsymbol{\sigma_{110}} = \frac{\boldsymbol{Number\ of\ atoms}}{\boldsymbol{Area}} = \frac{\mathbf{2}}{\mathbf{3.35*10^{-15}}\boldsymbol{cm^2}} = \mathbf{5.98 * 10^{14}}\boldsymbol{atoms/cm^2}$$

Solution 8:

Area of the (111) Plane:

The face diagonal (d_f) of a cube with side length a is given by: $d_f = a\sqrt{2} = 5.43 * \sqrt{2} = 7.68$Å

The equilateral triangle area (A_{111}) formed on the (111) plane, $A_{111} = \frac{\sqrt{3}}{4} * {d_f}^2 = \frac{\sqrt{3}}{4} * 7.68^2 =$

$$\frac{\sqrt{3}}{4} * (7.68 * 10^{-8} cm)^2 = 2.55 * 10^{-15} cm^2$$

Number of Atoms per (111) Plane : $3 + 3 * \frac{1}{6} = 3.5\ atoms$

Surface density on the (111) plane,

$$\boldsymbol{\sigma_{111}} = \frac{\boldsymbol{Number\ of\ atoms}}{\boldsymbol{Area}} = \frac{\mathbf{3.5}}{\mathbf{2.55 * 10^{-15} cm^2}} = \mathbf{1.37 * 10^{15} atoms/cm^2}$$

Number of valence electrons per silicon atom: 4

Atomic density of silicon, $N = 5 * 10^{22}\ atoms/cm^3$

Density of valence electrons, $\boldsymbol{n_e = 4 * N = 4 * \ 5 * 10^{22} \frac{electrons}{cm^3} = \ 2 * 10^{23}\ electrons/cm^3}$

Solution 9: Zinc Blende structure, which is typical of III-V compounds.

Solution 10:

1. Gallium Arsenide (GaAs)
2. Gallium Phosphide (GaP)
3. Gallium Nitride (GaN)
4. Indium Gallium Nitride (InGaN)
5. Aluminum Gallium Arsenide (AlGaAs)
6. Indium Phosphide (InP)

Solution 11:

Silicon has FCC structure.

Number of Atoms per Unit Cell = $8 * \frac{1}{8} + \ 6 * \frac{1}{2} = 1 + 3 = 4$

Volume of Unit Cell $= a^3 = (5.43 * \ 10^{-8}\ cm)^3 = \ 1.6 * \ 10^{-22} cm^3$

Volume Density = $\frac{\boldsymbol{Number\ of\ atoms\ per\ unit\ cell}}{\boldsymbol{Volume\ of\ the\ unit\ cell}} = \frac{\mathbf{4}}{\mathbf{1.6 * 10^{-22}}} = \ \mathbf{2.5 * 10^{22}}$ **atoms/cm³**

The area of the (100) plane corresponds to a square with sides equal to the lattice constant a.

Area, A $= a^2 = (5.43 * 10^{-8} cm)^2 = 2.95 * 10^{-15} cm^2$

In the FCC structure, the (100) plane contains 2 atoms per unit cell surface.

Areal Density in (100) plane: $\frac{\boldsymbol{Number\ of\ atoms\ in\ the\ (100)\ plane}}{\boldsymbol{Area\ of\ the\ (100)\ plane}} = \frac{\mathbf{2}}{\mathbf{2.95 * 10^{-15} cm^2}} = \mathbf{6.75 * 10^{14}}$ **atoms/cm²**

Solution 12:

Identify the intercepts of the plane with the x, y, and z axes.

The given intercepts are 9.66 Å, 19.32 Å, and 14.49 Å.

Express the intercepts in terms of the lattice constant , a = 4.83 Å

9.66/4.83 = 2

19.32/4.83 = 4

14.49/4.83 = 3

Take the reciprocals of these fractional intercepts:

1/2 1/4 1/3

Clear the fractions by finding a common multiple:

The LCM of 2, 4, and 3 is 12

Multiplying each reciprocal by 12: h= 6, k = 3, l = 4

Miller indices = (6, 3, 4)

Solution 13:

Radius of the atom, r = 2.37 A°

(a) Volume Density of Atoms in the FCC Crystal

Determine the lattice constant a

In an FCC lattice, the atoms touch along the face diagonal. The face diagonal (d_f) is related to the lattice constant a by: $d_f = a\sqrt{2}$

For FCC, this diagonal spans 4 atomic radii (since the face diagonal in FCC passes through the centre of four atoms): $d_f = 4r$

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

$$a = \frac{4r}{\sqrt{2}} = \frac{4 * 2.37}{\sqrt{2}} = 6.71 \text{ A}^\circ$$

Volume of the unit cell = a^3 = $(6.71 * 10^{-8})^3 = 3.02 * 10^{-22} cm^3$

There are 4 atoms per FCC unit cell.

Volume density of atoms = $\frac{Number\ of\ atoms}{Volume\ of\ unit\ cell} = \frac{4}{3.02*10^{-22} cm^3} = 1.33 * 10^{22}$ atoms/cm^3

(b) Surface Density of Atoms in the (110) Plane

In an FCC lattice, the (110) plane contains atoms arranged in a rectangular array. The dimensions of this rectangle are $a * a\sqrt{2}$

Calculate the area of the (110) plane, $A_{110} = a^2\sqrt{2} = (6.71 * 10^{-8}\ cm)^2\sqrt{2} = 6.37 * 10^{-15} cm^2$

The (110) plane of FCC has 4 atoms within the unit cell (two full atoms and two atoms shared on the edges).

Surface density of atoms in (110) plane, $\boldsymbol{\sigma_{110}} = \frac{\boldsymbol{Number\ of\ atoms}}{\boldsymbol{Area}} = \frac{\mathbf{4}}{\mathbf{6.37*10^{-15}}\boldsymbol{cm^2}} = \mathbf{6.28 * 10^{14}}\boldsymbol{atoms/cm^2}$

(c) Distance Between Nearest (110) Planes

The distance between (110) planes in an FCC lattice, $d_{110} = \frac{a}{\sqrt{2}} = \frac{6.71}{\sqrt{2}} = 4.75\ A^{\circ}$

(d) Surface Density and Distance for the (111) Plane

Calculate the area of the (111) plane

In an FCC lattice, the (111) plane contains atoms arranged in a hexagonal array. The area of the (111) plane, $A_{111} = \frac{\sqrt{3}}{2} * a^2 = \frac{\sqrt{3}}{2} * (6.71 * 10^{-8} cm)^2 = 3.899 * 10^{-15} cm^2$

The (111) plane contains 3 atoms within the unit cell.

Surface density of atoms in (111) plane, $\boldsymbol{\sigma_{111}} = \frac{\boldsymbol{Number\ of\ atoms}}{\boldsymbol{Area}} = \frac{\mathbf{3}}{\mathbf{3.899*10^{-15}}\boldsymbol{cm^2}} = \mathbf{7.69 * 10^{14}}\boldsymbol{atoms/cm^2}$

The distance between (111) planes in an FCC lattice, $\mathbf{d_{111}} = \frac{\boldsymbol{a}\sqrt{\mathbf{3}}}{\mathbf{3}} = \frac{\mathbf{6.71}\sqrt{\mathbf{3}}}{\mathbf{3}} = \mathbf{3.87 A^{\circ}}$

Solution 14:

(i) a = 3
b = 3
c = 3

Take the reciprocals of these fractional intercepts:

1/3 1/3 1/3

Clear the fractions by finding a common multiple 3:

h= 1, k = 1, l = 1

Miller indices = (1 1 1)

(ii) a = 3
b = 2
c = 2

Take the reciprocals of these fractional intercepts:

1/3 1/2 1/2

Clear the fractions by finding a common multiple:

The LCM of 3, 2, and 2 is 6

Multiplying each reciprocal by 6: h= 2, k = 3, l = 3

Miller indices = (2 3 3)

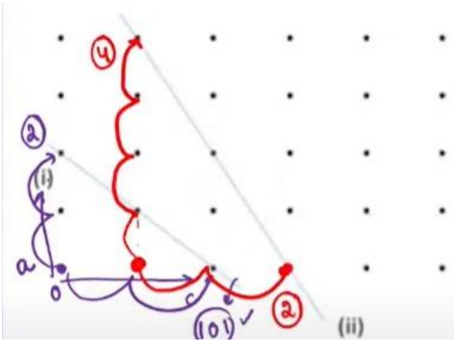
Solution 15:

Miller Indices: represents the nature of the plane

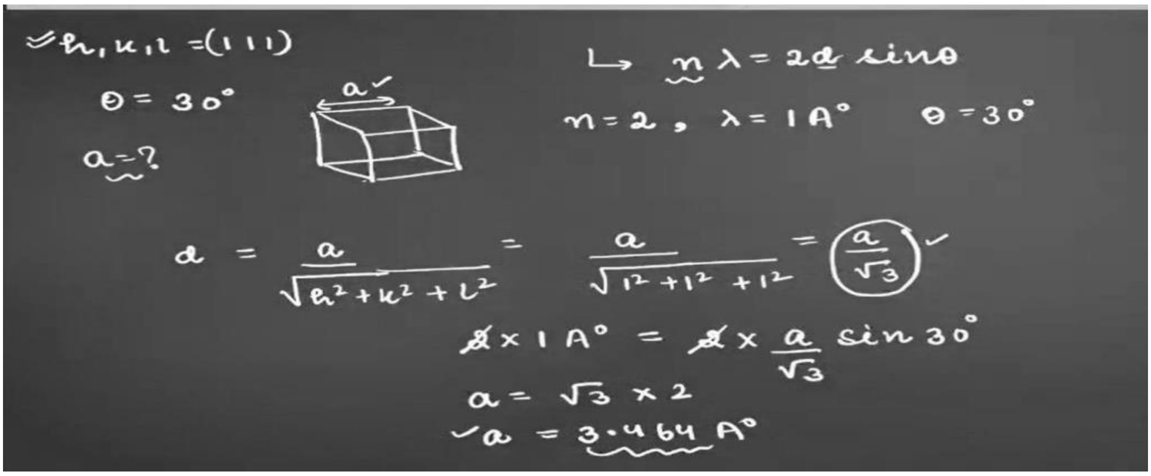
From figure, PLANE – 1: a = 2, b = ∞, c = 2; then $\frac{1}{a}\ \frac{1}{b}\ \frac{1}{c}$

=> $\frac{1}{2}\ \frac{1}{\infty}\ \frac{1}{2}$ => LCM => (1, 0, 1)

PLANE – 2: a = 4, b = ∞, c = 2; then similarly $\frac{1}{4}\ \frac{1}{\infty}\ \frac{1}{2}$ => LCM =>



Solution 16:



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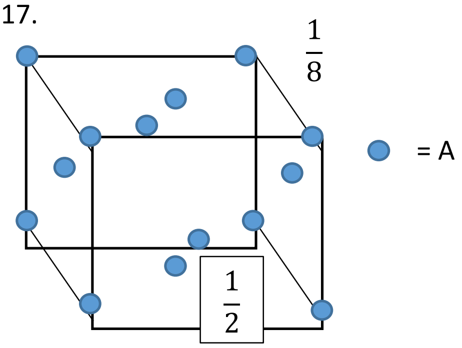

A → FCC → 1 + 3 = 4

FCC → 2n = 8 → z = 4

B → FCC → n = 4

So A_xB_y → $\boxed{x = 4, y = 4}$

Solution 18:

$$n(\lambda) = \left(2 \times \frac{a}{\sqrt{h^2+k^2+l^2}}\right) \sin\theta$$

$$\lambda = \frac{\cancel{2} \times 40\,nm}{\sqrt{5}} \times \cancel{\sin 30^\circ}$$

$$\lambda = 18\,nm$$

Solution 19:

$$\text{Solution: } P \cdot F = \frac{n_{eff} \times \frac{4\pi}{3} r^3}{V}$$

$$\text{Where, } n_{eff} = 8, V = a^3 \text{ and } \frac{\sqrt{3}a}{4} = 2r \Rightarrow a = \frac{8r}{\sqrt{3}}$$

$$\therefore P \cdot F = \frac{8 \times \frac{4\pi}{3} r^3}{\left(\frac{8r}{\sqrt{3}}\right)^3} = \frac{\sqrt{3}\pi}{16} = 0.34$$

Solution 20:

The 2nd nearest neighbour is at distance = $\frac{\sqrt{2}a}{2} = \frac{a}{\sqrt{2}}$

The number of 2nd nearest neighbour = $\frac{3 \times 8}{2}$ = 12