Lecture 1

Electronic Devices

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Delivery & Assessment Method

Text books		Detail
1	Title	Principles of Electronic Materials and Devices
	Author	Safa Kasap
2	Title	Solid State Electronic Devices
	Author	Ben Streetman

Lesson Plan

General Material Concepts: Structural and electrical properties of semiconductors.

Basic Semiconductors: Schottky Junction, Ohmic Contacts, PN junction diodes.

Semiconductor Devices: Bipolar Junction Transistors, MOS Transistor

Advanced Semiconductor Devices: Solar Cells, LEDs, Lasers.

Introduction

- Understanding the basic building blocks of matter is necessary for the development of technologies.
- Design, manufacturing, performance and commercialisation of any engineering product depends on materials being used for that product.
- All electronic devices rely on semiconducting materials as their basic building block.

ATOMIC STRUCTURE

- The model of the atom that we must use to understand the atom's general behavior involves quantum mechanics - a topic we will not cover.

- We will mainly adopt a simplified atomic model called the shell model, based on the Bohr model (1913).

ATOMIC STRUCTURE

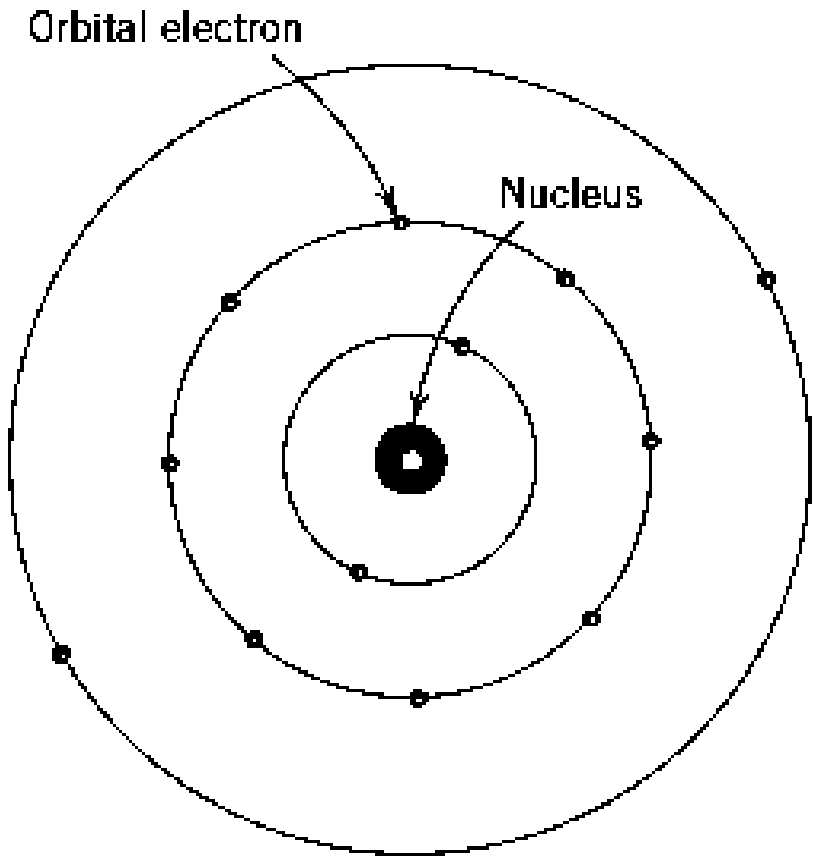
- The mass of the atom is concentrated at the **nucleus**, which contains **protons** and **neutrons**. Protons are positively charged particles, whereas neutrons are neutral particles - both have about the same mass.

- The number of protons in the nucleus is the **atomic number Z** of the element.

- The **electrons** are assumed to be orbiting the nucleus at very large distances compared to the size of the nucleus. There are as many orbiting **electrons** as there are **protons** in the nucleus.

ATOMIC STRUCTURE

- **Bohr model:** electrons orbit nucleus in discrete quantized orbits with fixed radii
- We can therefore view the electron as a charge contained within a spherical shell of a given radius.
- An electron can jump from one orbital to another by losing (emission) or gaining (absorbing) energy



ATOMIC STRUCTURE

- **Electrons** do not randomly occupy the whole region around the nucleus. Instead, they occupy well defined spherical regions.

- They are distributed in various **shells** and **subshells** within the shells, obeying certain occupation (or seating) rules.

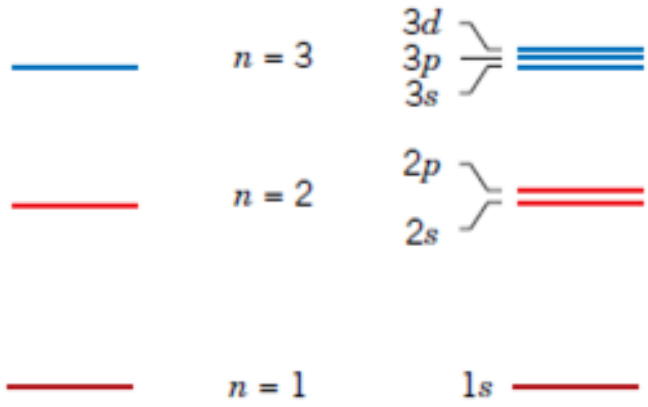
- The shells and subshells that define the whereabouts of the electrons are labeled using two sets of integers, ***n*** and ***l***

- These integers are called the **principal (*n*)** and **orbital angular momentum quantum numbers (*l*)**

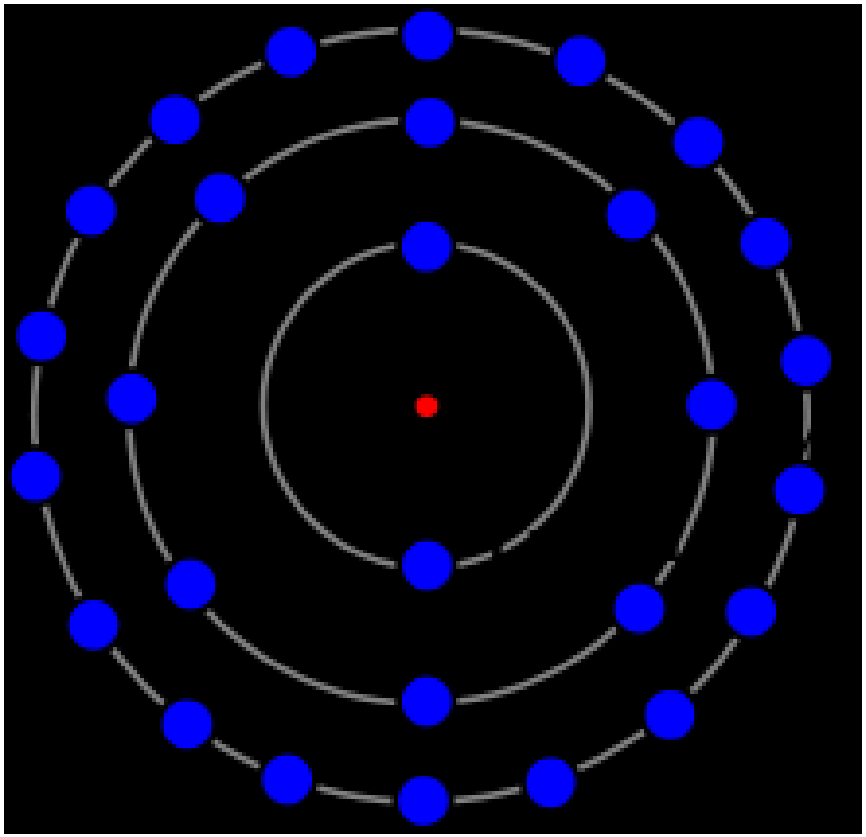
ATOMIC STRUCTURE

- There is a definite rule to filling up the subshells with electrons - we cannot simply put all the electrons in one subshell.
  - The number of electrons a given subshell is: $2(2l + 1)$
- Max no. of electrons in each shell is $2n^2$

		Subshell			
		$\ell = 0$	1	2	3
n	Shell	s	p	d	f
1	K	2			
2	L	2	6		
3	M	2	6	10	
4	N	2	6	10	14



ATOMIC STRUCTURE



Shell name	Subshell name	Subshell max electrons	Shell max electrons
K	1s	2	**2**
L	2s	2	2 + 6 = **8**
	2p	6	
M	3s	2	2 + 6 + 10 = **18**
	3p	6	
	3d	10	
N	4s	2	2 + 6 + 10 + 14 = **32**
	4p	6	
	4d	10	
	4f	14	
O	5s	2	2 + 6 + 10 + 14 + 18 = **50**
	5p	6	
	5d	10	
	5f	14	
	5g	18	

ATOMIC STRUCTURE

- For the **s subshell (*l* = *0*)**, there are **two** electrons, whereas for the ***p* subshell**, there are **six** electrons, and so on.
- The number of electrons in a subshell is indicated by a superscript on the subshell symbol
- The electronic structure, or configuration, of the **carbon** atom (atomic number 6) becomes $1s^2 2s^2 2p^2$.

ATOMIC STRUCTURE

- We can also write electronic configuration simply as [He]$2s^2 2p^2$.
  - General rule is put nearest previous inert element, in this case He, in square brackets and write the subshells thereafter.
- In an atom such as the Li, there are 2 electrons in *1s* subshell and 1 electron in *2s* subshell.
  - The atomic structure of Li is *$1s^2 2s^1$* or [He]$2s^1$.

Z	Name	# of Electrons 1	2		3			Notation
		1s	2s	2p	3s	3p	3d	
1	H	1						$1s^1$
2	He	2						$1s^2$
3	Li	2	1					$1s^2 2s^1$
4	Be	2	2					$1s^2 2s^2$
5	B	2	2	1				$1s^2 2s^2 2p^1$
6	C	2	2	2				$1s^2 2s^2 2p^2$
7	N	2	2	3				$1s^2 2s^2 2p^3$
8	O	2	2	4				$1s^2 2s^2 2p^4$
9	F	2	2	5				$1s^2 2s^2 2p^5$
10	Ne	2	2	6				$1s^2 2s^2 2p^6$
11	Na	2	2	6	1			$1s^2 2s^2 2p^6 3s^1$
12	Mg	2	2	6	2			$1s^2 2s^2 2p^6 3s^2$
13	Al	2	2	6	2	1		$1s^2 2s^2 2p^6 3s^2 3p^1$
14	Si	2	2	6	2	2		$1s^2 2s^2 2p^6 3s^2 3p^2$
15	P	2	2	6	2	3		$1s^2 2s^2 2p^6 3s^2 3p^3$
16	S	2	2	6	2	4		$1s^2 2s^2 2p^6 3s^2 3p^4$
17	Cl	2	2	6	2	5		$1s^2 2s^2 2p^6 3s^2 3p^5$
18	Ar	2	2	6	2	6		$1s^2 2s^2 2p^6 3s^2 3p^6$

ATOMIC STRUCTURE

- **Electrons** occupying the outer subshells are the farthest away from the nucleus and have the most important role in atomic interactions, since these electrons are the first to interact with outer electrons on neighboring atoms.

- The **outermost** electrons are called **valence** electrons and they determine the "valency" of the atom.
  - The combining power of an element, especially as measured by the number of hydrogen atoms it can displace or combine with.
  - *'Carbon always has a valency of 4'*

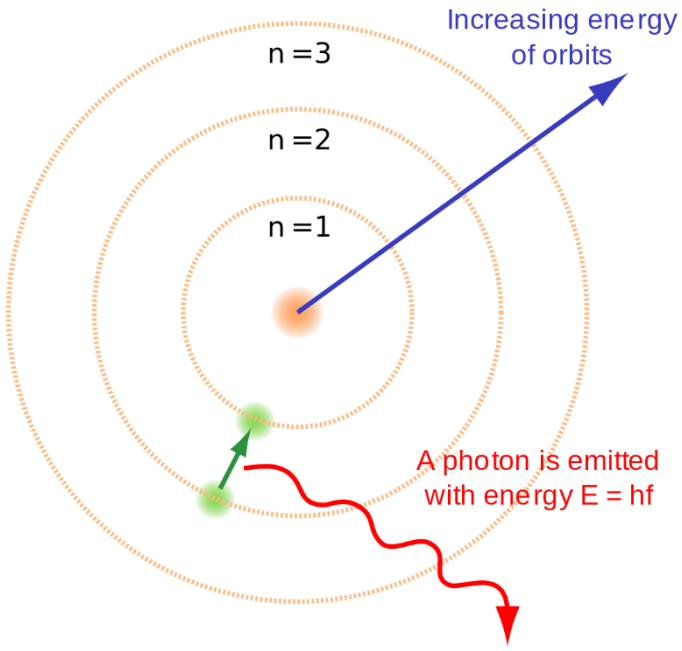
ATOMIC STRUCTURE

- When a subshell is full of electrons, it cannot accept any more electrons and it is said to have acquired a stable configuration.

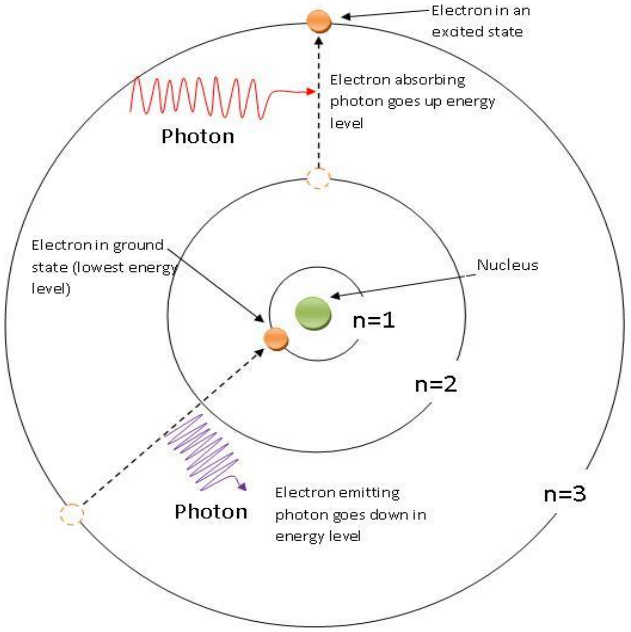
- This is the case with the inert elements at the right-hand side of the Periodic Table, all of which have completely filled subshells and are rarely involved in chemical reactions.

ATOMIC STRUCTURE

- Electrons can **gain** and **lose** energy by jumping from one allowed orbit to another, **absorbing** or **emitting** electromagnetic radiation with a frequency ν determined by the **energy difference** of the levels according to the Planck relation: $\Delta E = E2 - E1 = hf$



An electron that is closer to the nucleus has a lower energy.



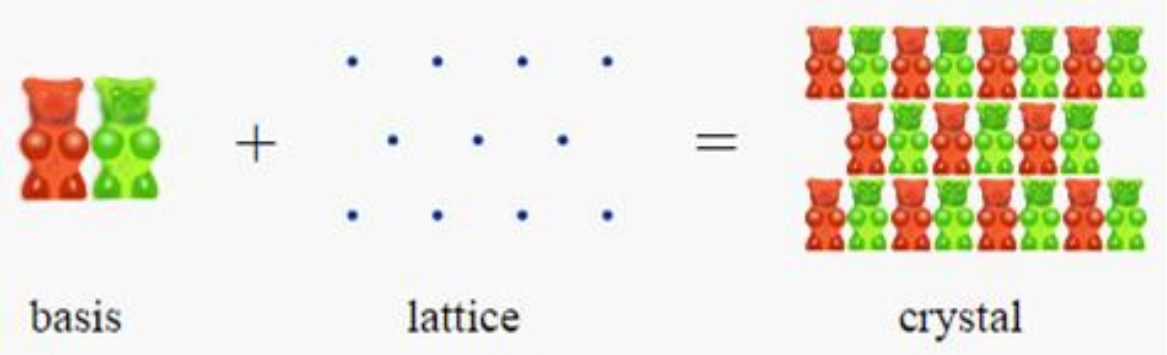
CRYSTAL STRUCTURE

- A **crystalline solid** has a **regular atomic pattern** to form a periodic collection (or array) of atoms.
- The most important property of a crystal is periodicity
  → **long-range order.**
- In a crystal, the local bonding geometry is repeated many times at regular intervals, to produce a **periodic** array of atoms that constitutes the crystal structure. The location of each atom is **well known**.

CRYSTAL STRUCTURE

- There is therefore **long-range order**, since we can always predict the atomic arrangement anywhere in the crystal.
- Nearly all semiconductors are crystalline solids in the sense that the atoms or molecules are positioned in a periodic array of points in space.
- All crystals can be defined in terms of two parameters:

CRYSTAL STRUCTURE



Crystal defined as a lattice with a basis added to each lattice site.
Usually the basis consists of an atom, a group of atoms or a molecule.

Basis: Lattice points can be replaced by complex objects such as a group of atoms, a molecule...etc.

Lattice: In infinite, discrete regular arrangement of points.

Bravais Lattice: Material/crystal that exhibits translational symmetry in their lattice, such that an observer sitting in one lattice point could observe the same environment when sitting on any other.

CRYSTAL STRUCTURE

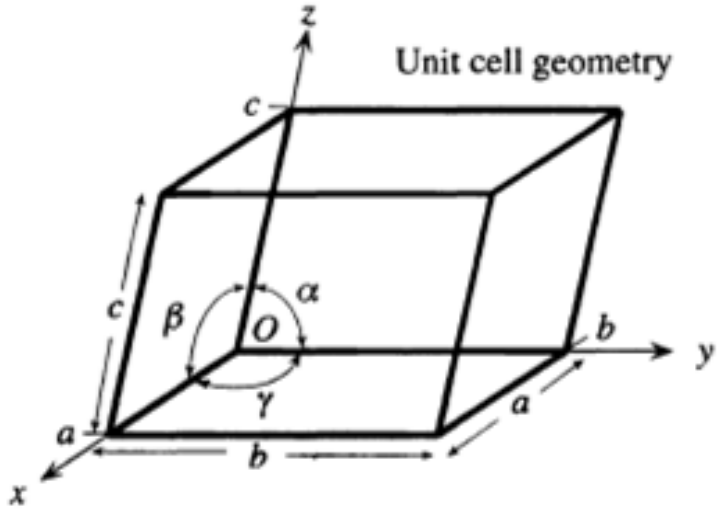
- A lattice is an infinite periodic array of geometric points in space, without any atoms. When we place an identical group of atoms (or molecules), called a basis, at each lattice point, we obtain the actual crystal structure.

- The crystal is thus a lattice plus a basis at each lattice point.

CRYSTAL STRUCTURE

- Geometry of unit cell defined as a parallel piped structure with sides **a, b** and **c** and angles **alpha, beta** and **gamma**.

- The sides **a, b, and c** and angles **alpha, beta and gamma** are referred to as the lattice parameters.

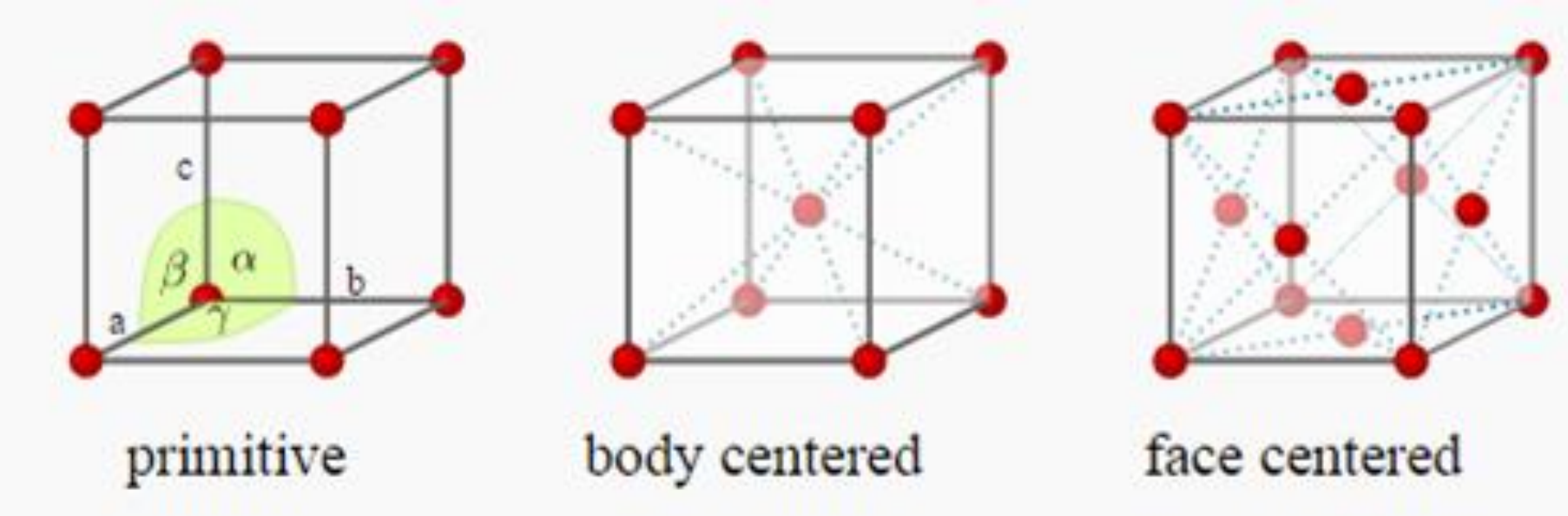


CRYSTAL STRUCTURE

Crystal System	Lengths	Angles
cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$
trigonal	$a = b = c$	$\alpha = \beta = \gamma < 120°, \neq 90°$
hexagonal	$a = b \neq c$	$\alpha = \beta = 90°, \gamma = 120°$
tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$
orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90°$
monoclinic	$a \neq b \neq c$	$\alpha = \beta = 90° \neq \gamma$
triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma$

CRYSTAL STRUCTURE

Cubic Lattice System:



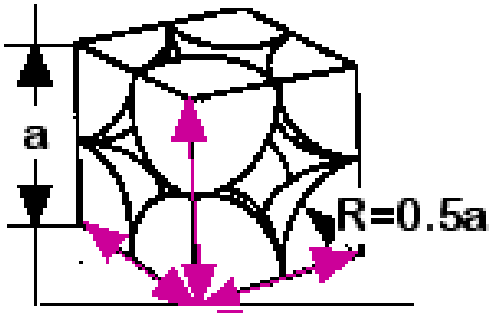
CRYSTAL STRUCTURE

Atomic Packing Factor (APF)

$$APF = \frac{\text{Volume of atoms in unit cell}^*}{\text{Volume of unit cell}}$$

*assume hard spheres

For simple cubic structure. . .



close-packed directions

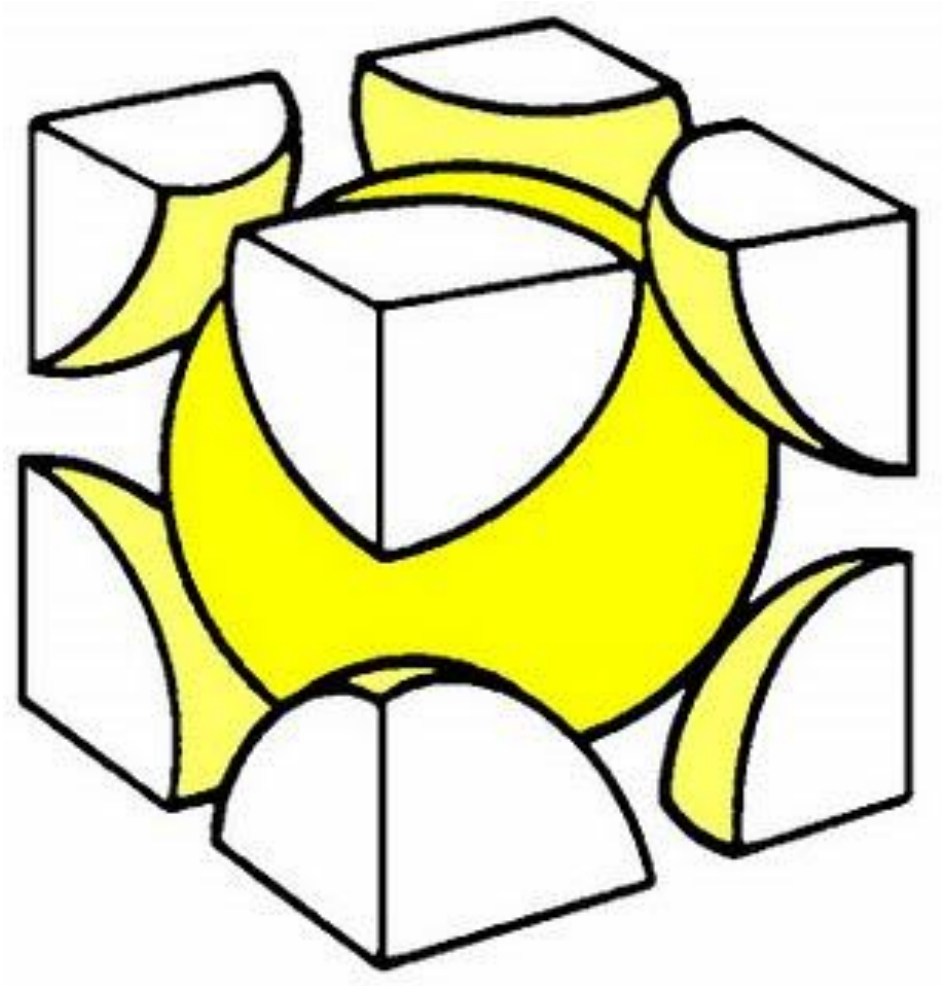
contains 8 x 1/8 = 1atom/unit cell

APF = 0.52 for simple cubic

$$APF = \frac{\text{atom}}{\text{unit cell}} \cdot \frac{\text{volume}}{\text{atom}} \Big/ \frac{\text{volume}}{\text{unit cell}} = \frac{1 \cdot \frac{4}{3}\pi (0.5a)^3}{a^3}$$

CRYSTAL STRUCTURE - BCC

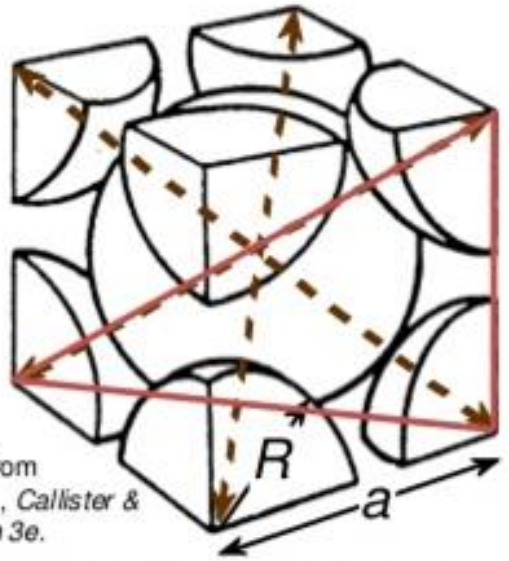
Body Centred Cubic (BCC)



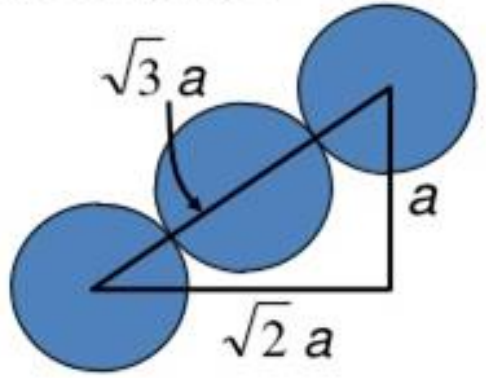
CRYSTAL STRUCTURE - BCC

Atomic Packing Factor: BCC

- APF for a body-centered cubic structure = 0.68



Adapted from Fig. 3.2(a), *Callister & Rethwisch 3e.*



Close-packed directions:
length = $4R = \sqrt{3}\,a$

$$APF = \frac{\text{atoms}}{\text{unit cell}} \cdot \frac{\text{volume}}{\text{atom}} \Big/ \frac{\text{volume}}{\text{unit cell}} = \frac{2\left(\frac{4}{3}\pi(\sqrt{3}a/4)^3\right)}{a^3}$$

CRYSTAL STRUCTURE - FCC

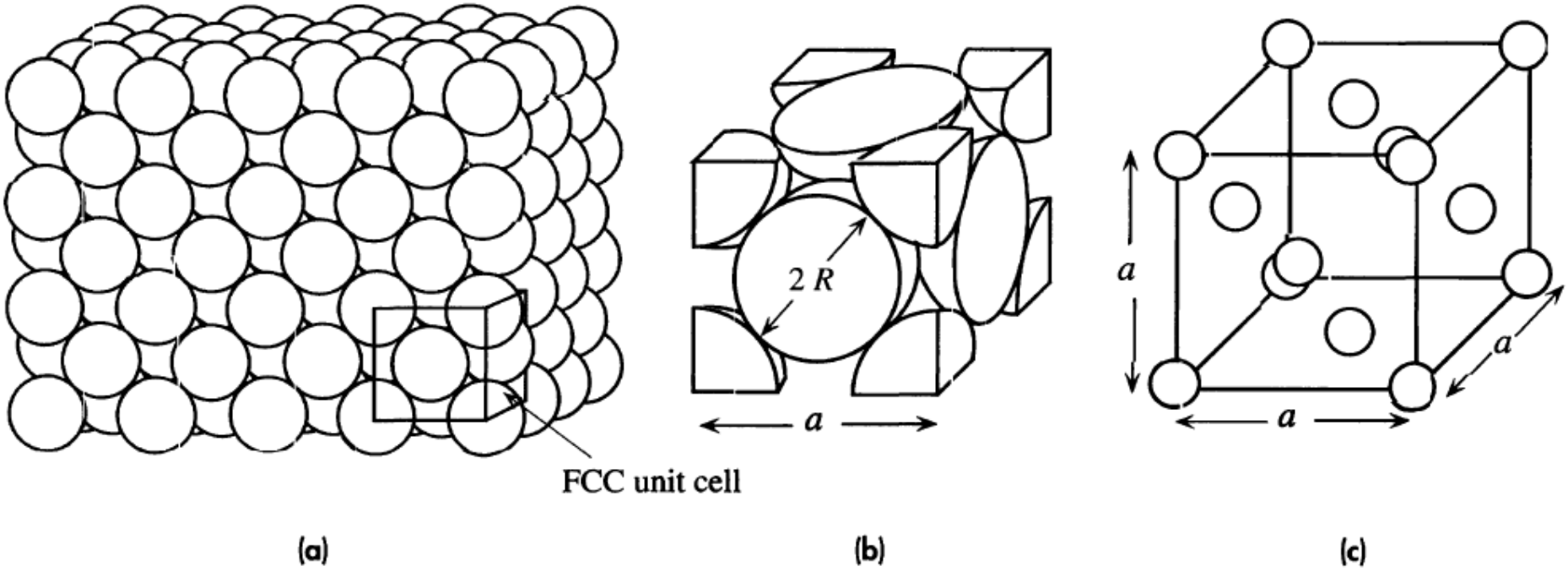


Figure 1.31

(a) The crystal structure of copper which is face-centered cubic (FCC). The atoms are positioned at well-defined sites arranged periodically, and there is a long-range order in the crystal.

(b) An FCC unit cell with close-packed spheres.

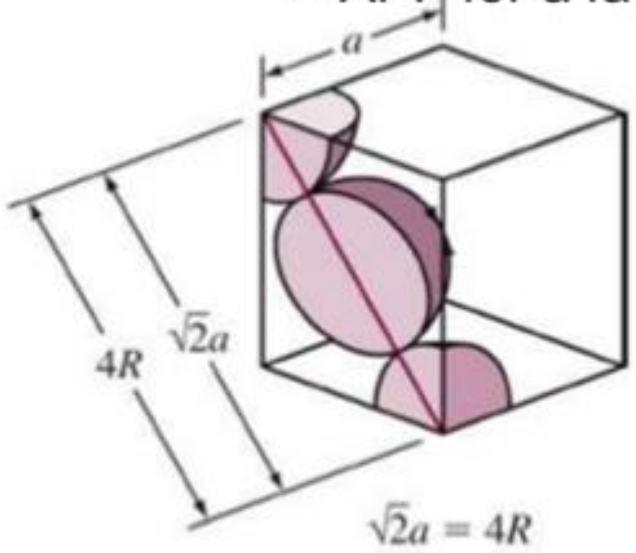
(c) Reduced-sphere representation of the FCC unit cell.

Examples: Ag, Al, Au, Ca, Cu, γ-Fe (>912 °C), Ni, Pd, Pt, Rh.

CRYSTAL STRUCTURE - FCC

Atomic Packing Factor: FCC

- APF for a face-centered cubic structure = 0.74



The maximum achievable APF!

Close-packed directions:

length = $4R = \sqrt{2}\,a$

($a = 2\sqrt{2}R$)

Unit cell contains:

6 x 1/2 + 8 x 1/8

= 4 atoms/unit cell

Adapted from Fig. 3.1(a), *Callister 7e.*

$$APF = \frac{\text{atoms}}{\text{unit cell}} \cdot \frac{\text{volume}}{\text{atom}} \Big/ \frac{\text{volume}}{\text{unit cell}} = \frac{4 \cdot \frac{4}{3}\pi(\sqrt{2}a/4)^3}{a^3}$$

CRYSTAL STRUCTURE - FCC

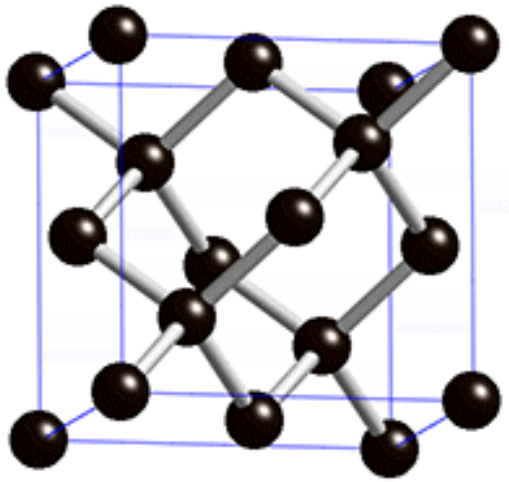
- The unit cell of the copper crystal is cubic with Cu atoms at its comers and one Cu atom at the center of each face. The unit cell of Cu is thus said to have a face-centered cubic (FCC) structure.

- The Cu atoms are shared with neighboring unit cells. Only one-eighth of a comer atom is in the unit cell and one-half of the face-centered atom belongs to the unit cell.

- There are four atoms in the unit cell. The length of the cubic unit cell is termed **the lattice parameter *a*** of the crystal structure.

CRYSTAL STRUCTURE

- Silicon crystallizes in the same pattern as diamond, in a structure which Ashcroft and Mermin call "**two interpenetrating face-centered cubic" primitive lattices**.



Known as the Zinc-blende

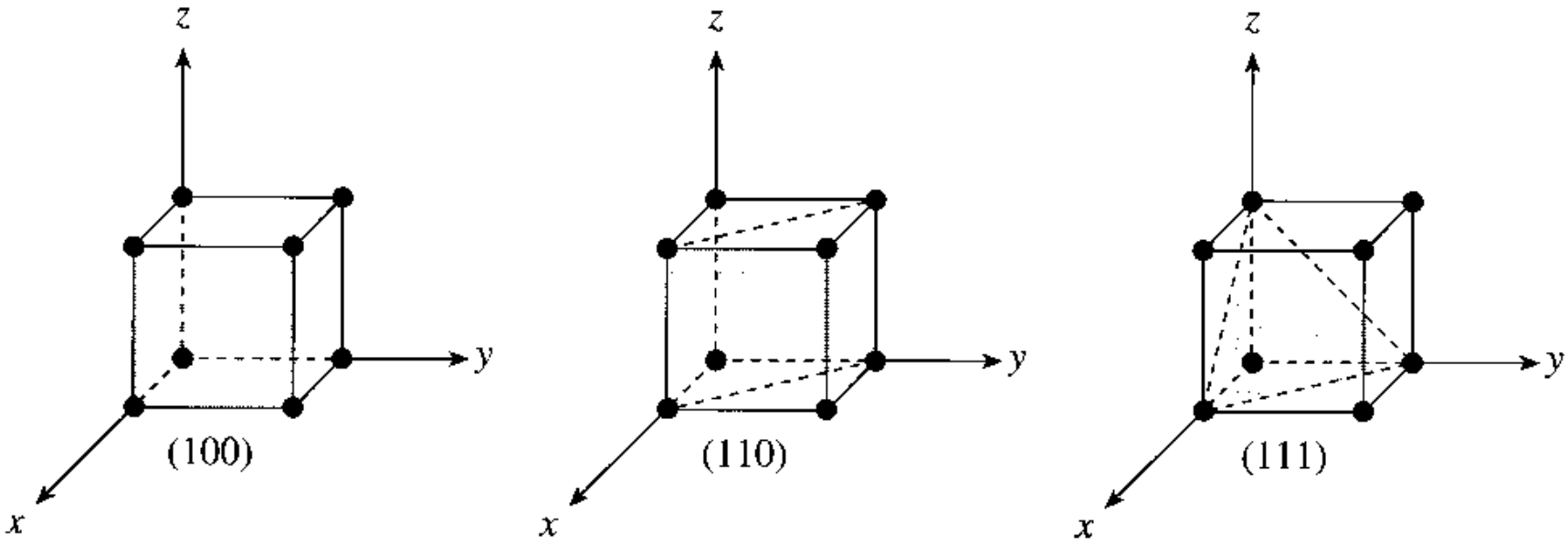
CRYSTAL STRUCTURE

Atomic Packing Factor of Different Crystal Structures

Crystal Structure	a and R (R is the Radius of the Atom)	Coordination Number (CN)	Number of Atoms per Unit Cell	Atomic Packing Factor	Examples
Simple cubic	$a = 2R$	6	1	0.52	No metals (Except Po)
BCC	$a = \frac{4R}{\sqrt{3}}$	8	2	0.68	Many metals: α–Fe, Cr, Mo, W
FCC	$a = \frac{4R}{\sqrt{2}}$	12	4	0.74	Many metals: Ag, Au, Cu, Pt
HCP	$a = 2R$ $c = 1.633a$	12	2	0.74	Many metals: Co, Mg, Ti, Zn
Diamond	$a = \frac{8R}{\sqrt{3}}$	4	8	0.34	Covalent solids: Diamond, Ge, Si, α-Sn
Zinc blende		4	8	0.34	Many covalent and ionic solids. Many compound semiconductors. ZnS, GaAs, GaSb, InAs, InSb

** Source: Safa Kasap, "Principles of Electronic Materials and Devices".*

Crystallographic Planes



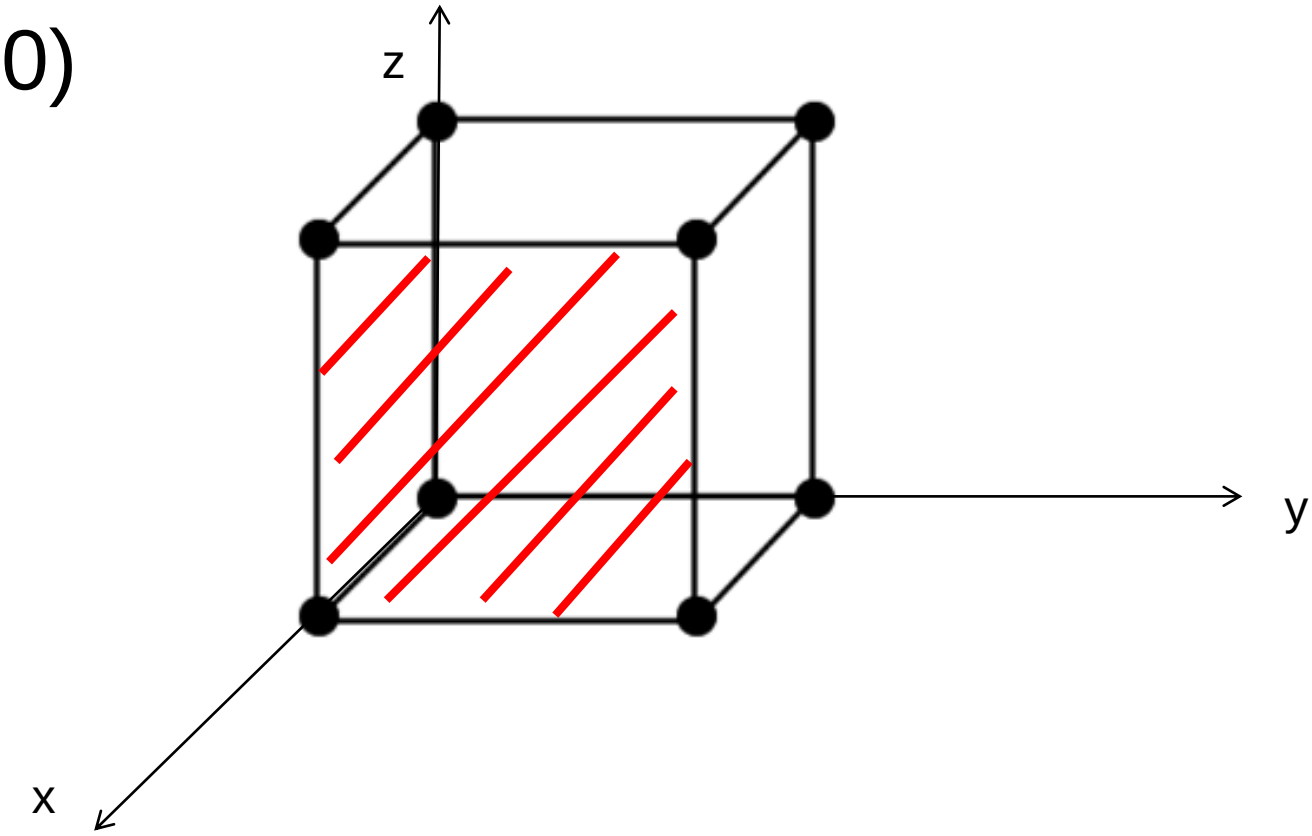
Silicon wafers are usually cut along a {100} plane with a flat or notch to orient the wafer during IC fabrication:

CRYSTAL STRUCTURE

- Crystallographic or Miller indices of a plane:
  - Translate plane so origin is not on plane
  - (1) Determine distance to intercept plane, by traveling from along each axis from origin
  - (2) Determine reciprocal
  - (3) Enclose in parentheses

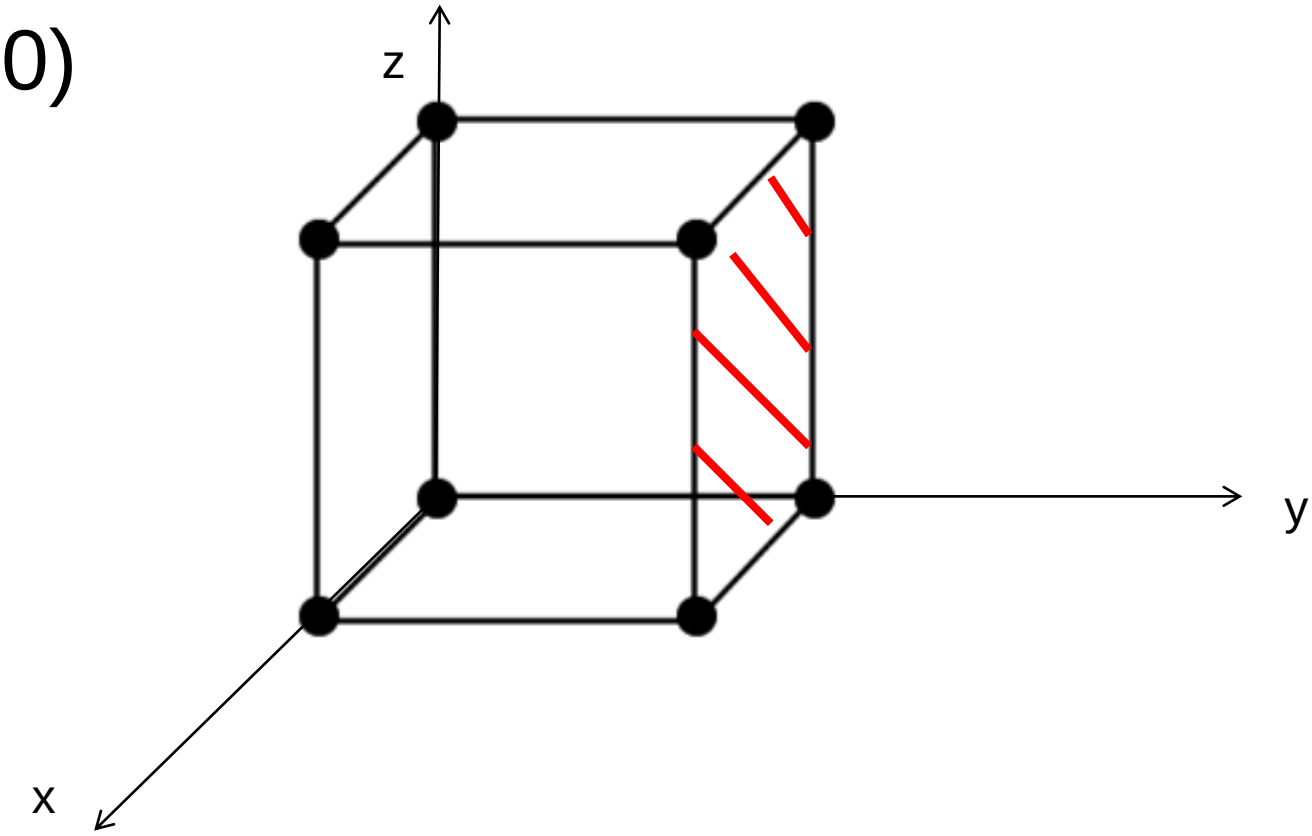
CRYSTAL STRUCTURE

- Crystallographic or Miller indices of a plane:
  - (1,0,0)



CRYSTAL STRUCTURE

- Crystallographic or Miller indices of a plane:
  - (0,1,0)



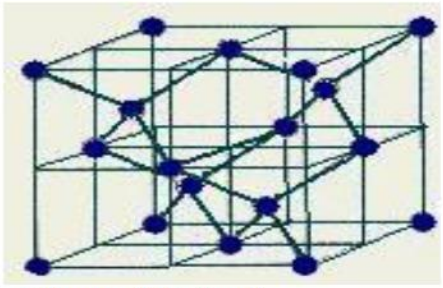
Crystallographic Notation

Notation	Interpretation
(*h k l*)	crystal plane
{ *h k l* }	equivalent planes
[*h k l*]	crystal direction
< *h k l* >	equivalent directions

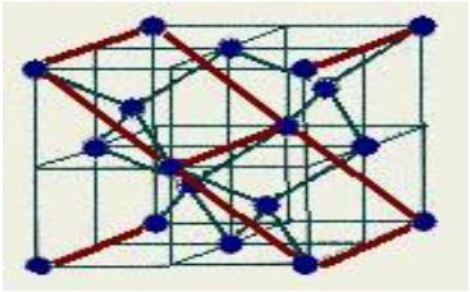
***h*: inverse *x*-intercept of plane**
***k*: inverse *y*-intercept of plane**
***l*: inverse *z*-intercept of plane**

CRYSTAL DIRECTIONS

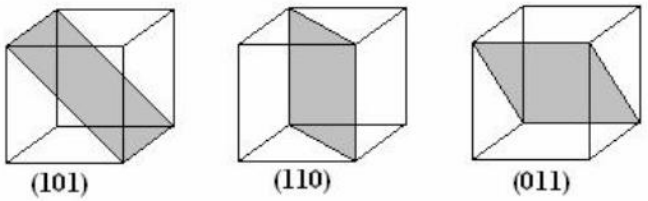
Unit cells (crystal planes)

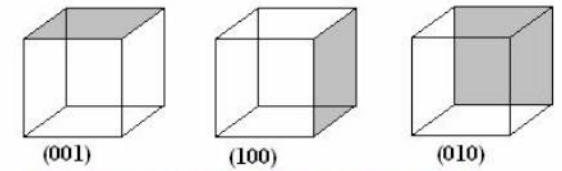


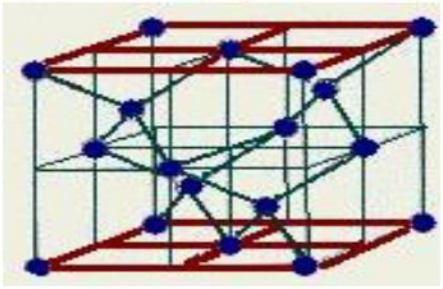
Diamond Unit cell



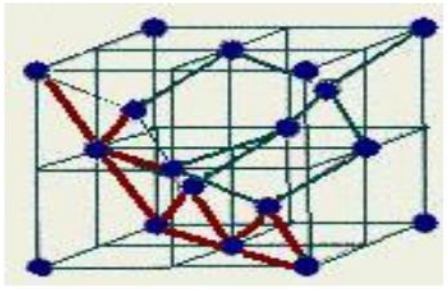
{110} planes



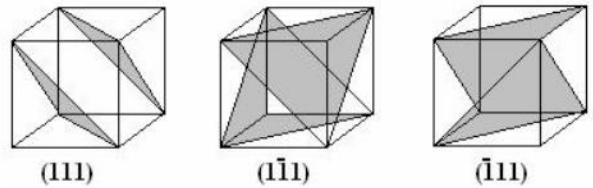




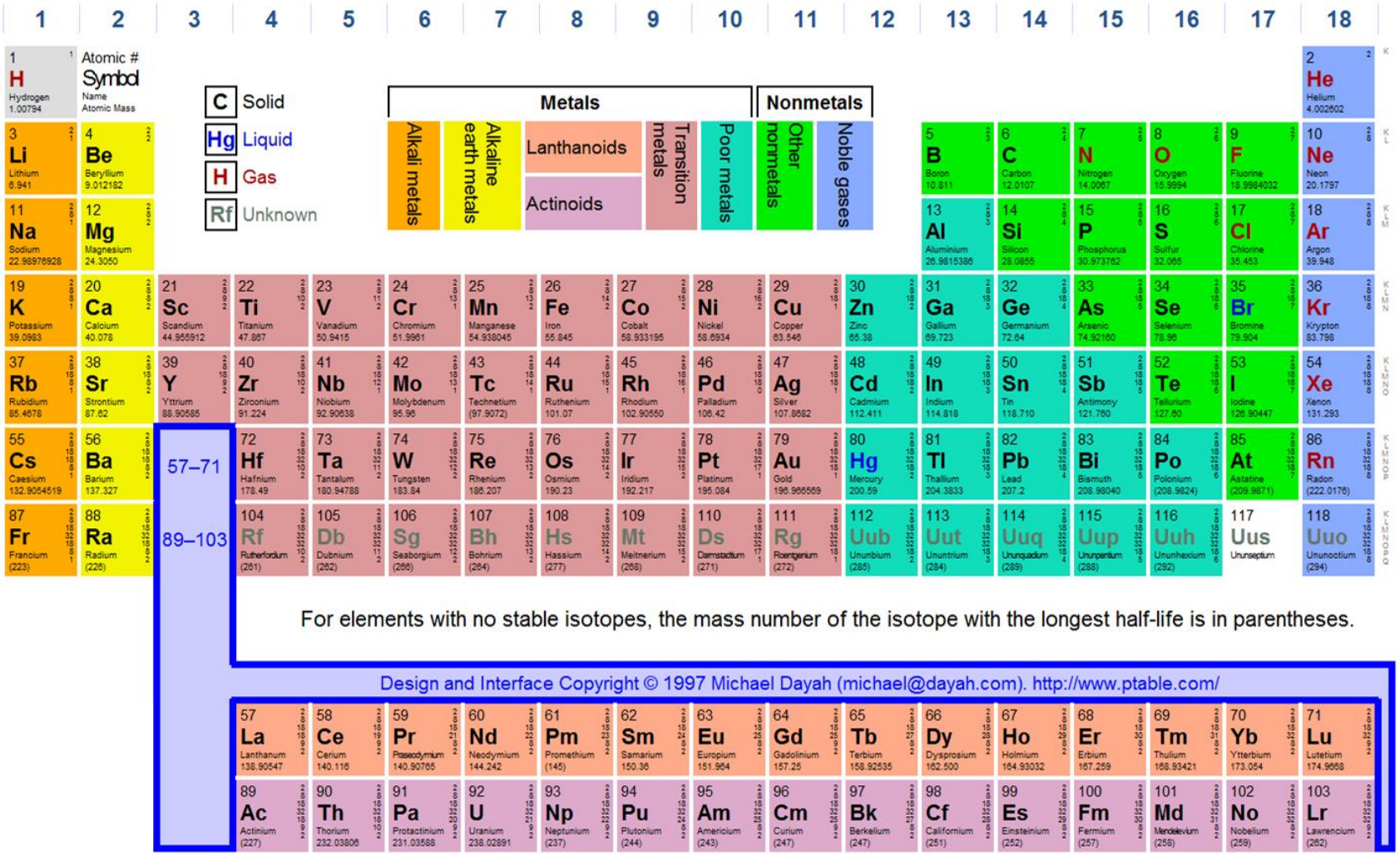
{100} planes



{111} planes



Periodic Table



Atomic Bonding

- For review purposes, there are three main types of atomic bonding:
  - Covalent
  - Ionic
  - Metallic

- What type of bonding is found in Silicon?

Revision

- Crystalline Si:
  - 4 valence electrons per atom
  - Diamond lattice

- Crystallographic notation
  - Miller indices are used to designate planes and directions within a crystalline lattice

Example Question

Silver has an FCC crystal structure. The lattice parameter **a** of Ag is 0.4084nm.

Calculate the planar concentration (number of atoms per m^2) in the planes (100), (110) and (111). Which plane has highest concentration?