

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

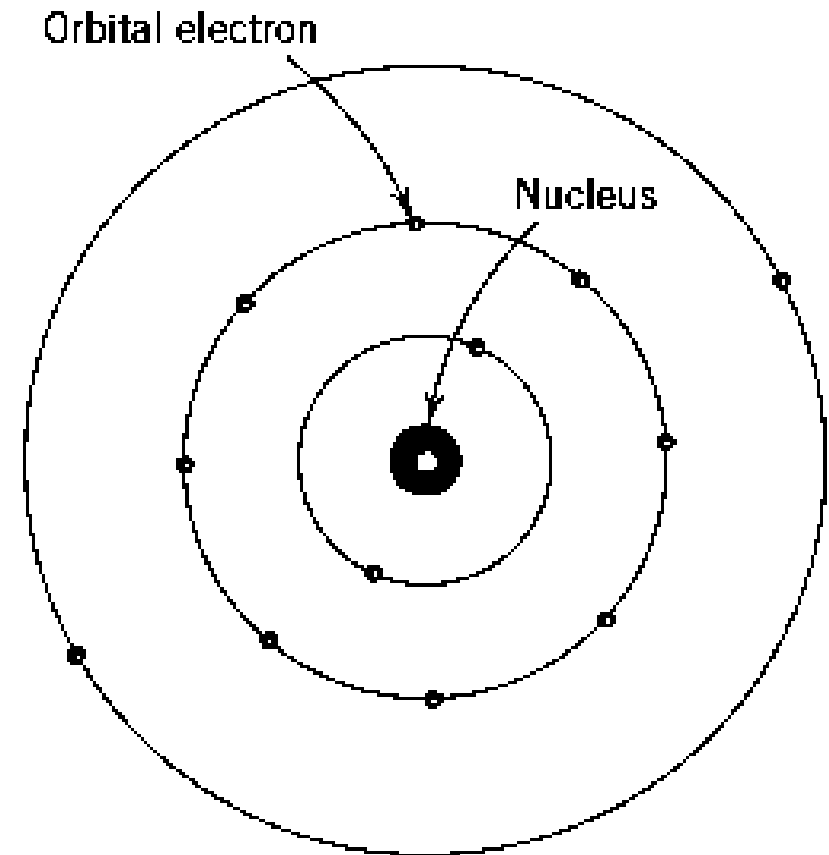
- The model of the atom that we must use to understand the atom's general behavior involves quantum mechanics - a topic we will not cover.
- We will mainly adopt a simplified atomic model called the shell model, based on the Bohr model (1913).

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

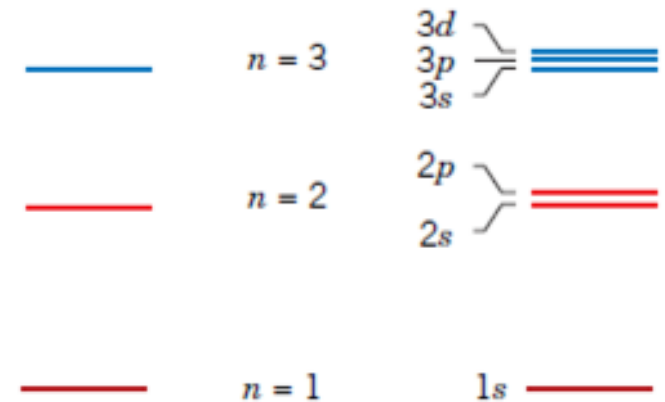
- **Electrons** do not randomly occupy the whole region around the nucleus. Instead, they occupy well defined spherical regions.
- They are distributed in various **shells** and **subshells** within the shells, obeying certain occupation (or seating) rules.
- The shells and subshells that define the 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

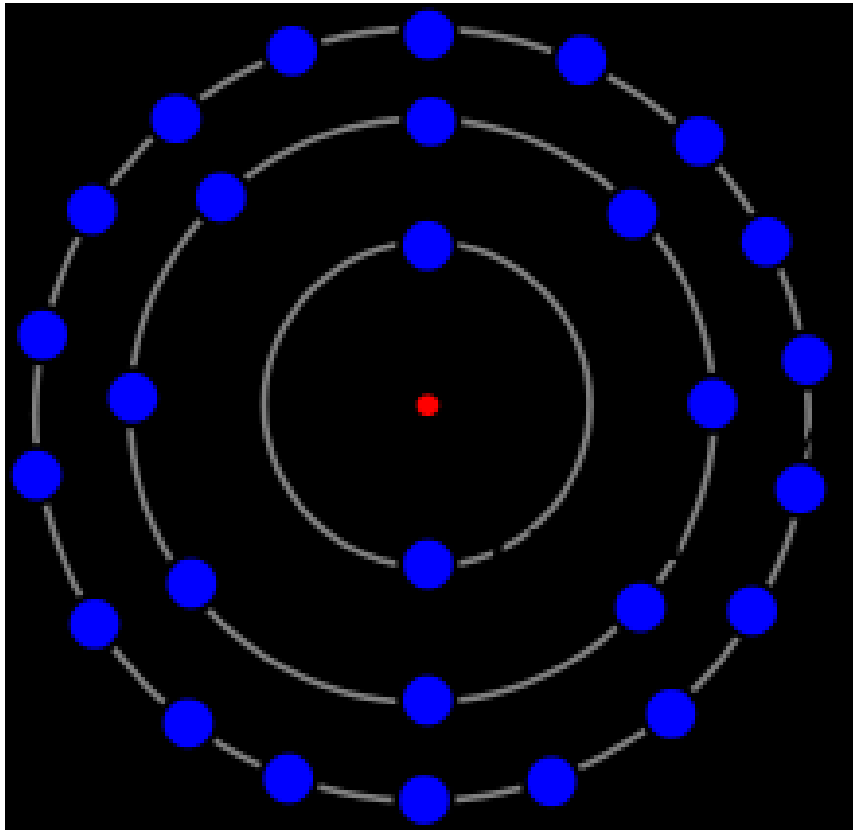
• There is a definite rule to filling up the subshells with electrons - we cannot simply put all the electrons in one subshell.

- The number of electrons a given subshell is: $2(2l + 1)$
- Max no. of electrons in each shell is $2n^2$

<i>n</i>	Shell	Subshell			
		$\ell = 0$ <i>s</i>	1 <i>p</i>	2 <i>d</i>	3 <i>f</i>
1	<i>K</i>	2			
2	<i>L</i>	2	6		
3	<i>M</i>	2	6	10	
4	<i>N</i>	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 $[\text{He}]2s^22p^2$.

• 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 $1s^22s^1$ or $[\text{He}]2s^1$.

Z	Name	# of Electrons						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

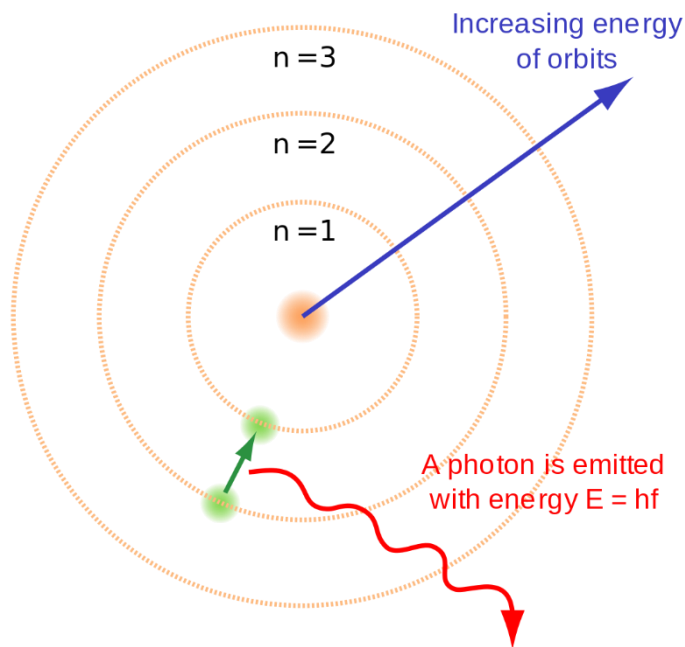
- **Electrons** occupying the outer subshells are the farthest away from the nucleus and have the most important role in atomic interactions, since these electrons are the first to interact with outer electrons on neighboring atoms.
- The outermost electrons are called valence electrons and they determine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

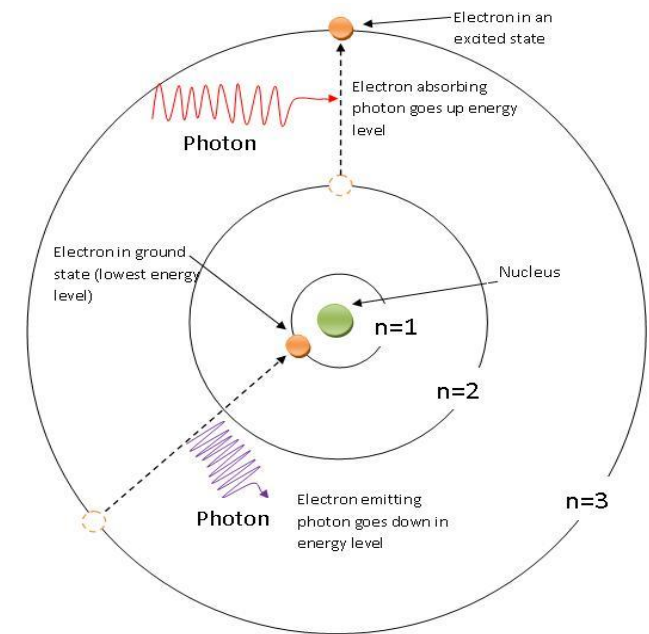
- When a subshell is full of electrons, it cannot accept any more electrons and it is said to have acquired a stable configuration.
- This is the case with the inert elements at the right-hand side of the Periodic Table, all of which have completely filled subshells and are rarely involved in chemical 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: $\Delta E = E_2 - E_1 = hf$



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



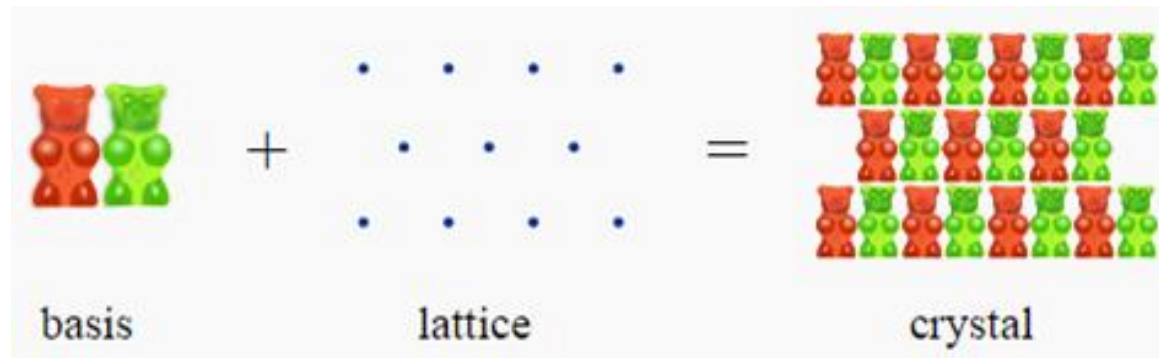
CRYSTAL STRUCTURE

- 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.

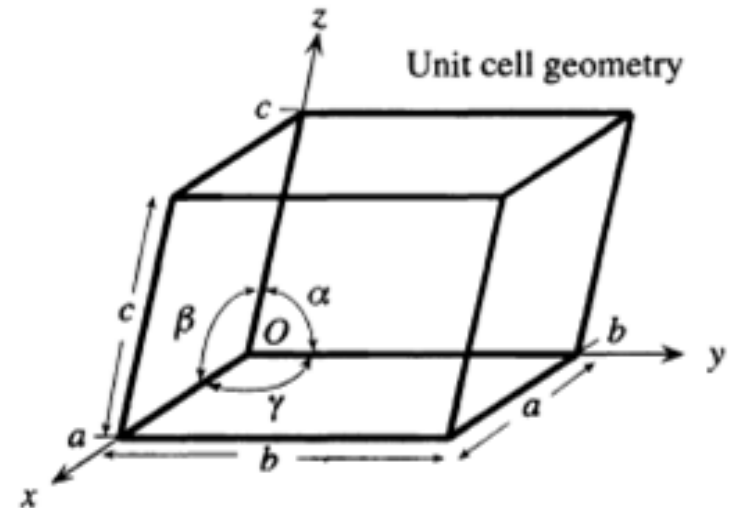
CRYSTAL STRUCTURE

- 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.

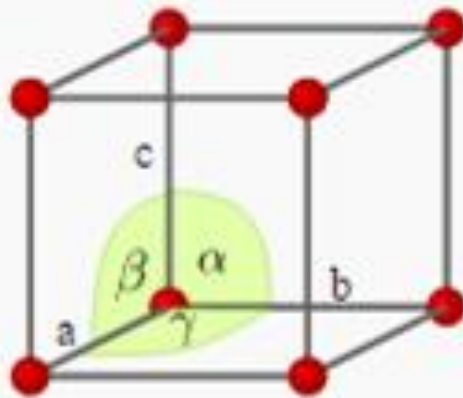


CRYSTAL STRUCTURE

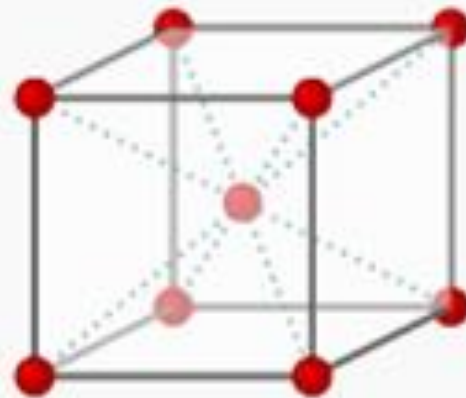
Crystal System	Lengths	Angles
cubic	$a = b = c$	$\alpha = \beta = \gamma = 90^\circ$
trigonal	$a = b = c$	$\alpha = \beta = \gamma < 120^\circ, \neq 90^\circ$
hexagonal	$a = b \neq c$	$\alpha = \beta = 90^\circ, \gamma = 120^\circ$
tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90^\circ$
orthorhombic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

CRYSTAL STRUCTURE

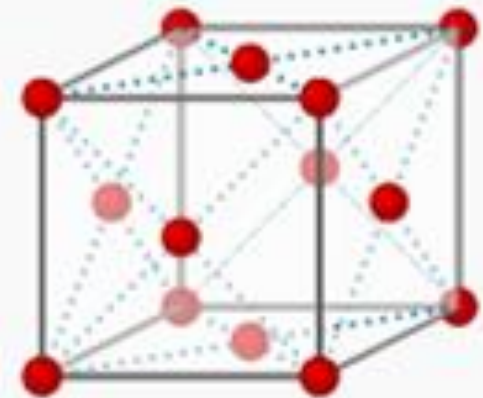
Cubic Lattice System:



primitive



body centered



face centered

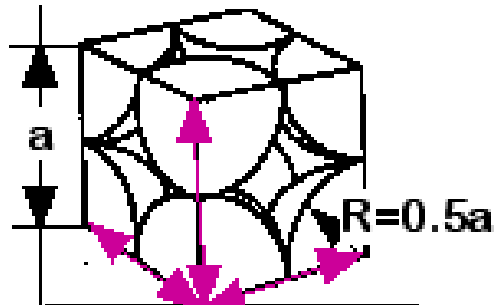
CRYSTAL STRUCTURE

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

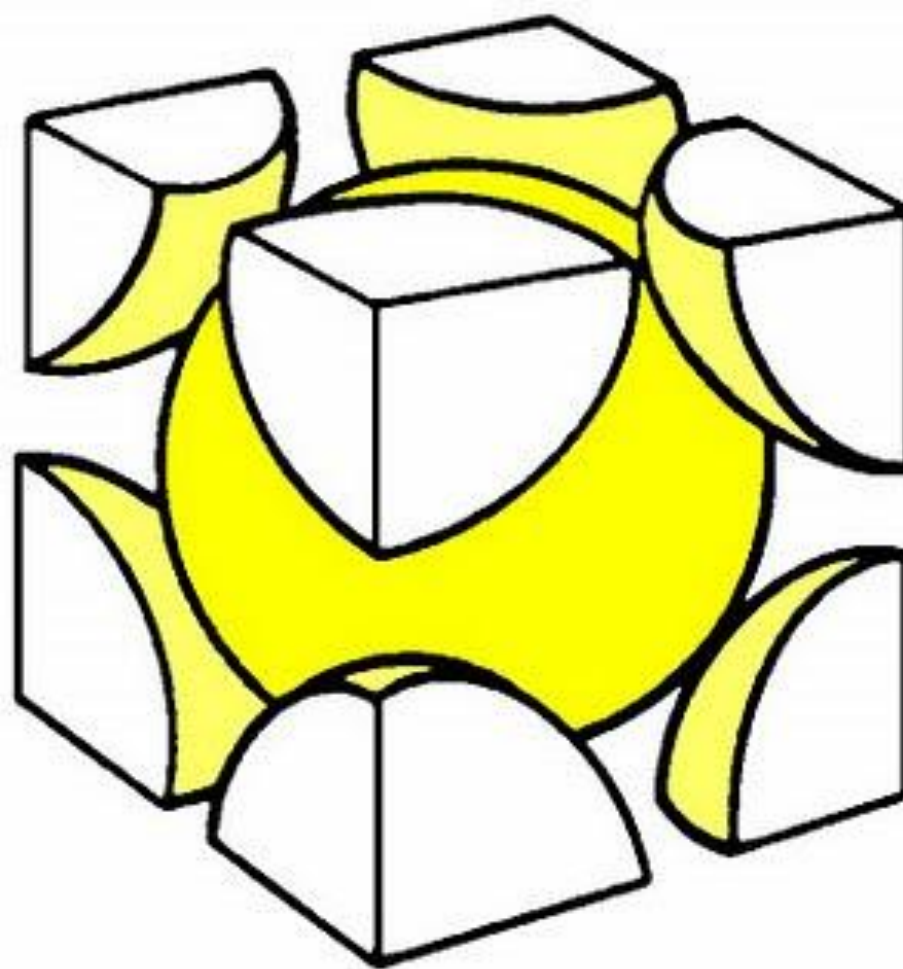
contains $8 \times 1/8 =$
1 atom/unit cell

APF = 0.52 for simple cubic

$$APF = \frac{\text{atom} \quad \text{unit cell} \quad 1 \quad \frac{4}{3} \pi (0.5a)^3}{a^3} \quad \begin{matrix} \text{volume} \\ \text{atom} \end{matrix} \quad \begin{matrix} \text{volume} \\ \text{unit cell} \end{matrix}$$

CRYSTAL STRUCTURE - BCC

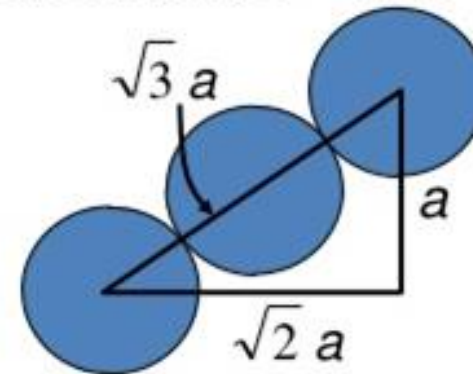
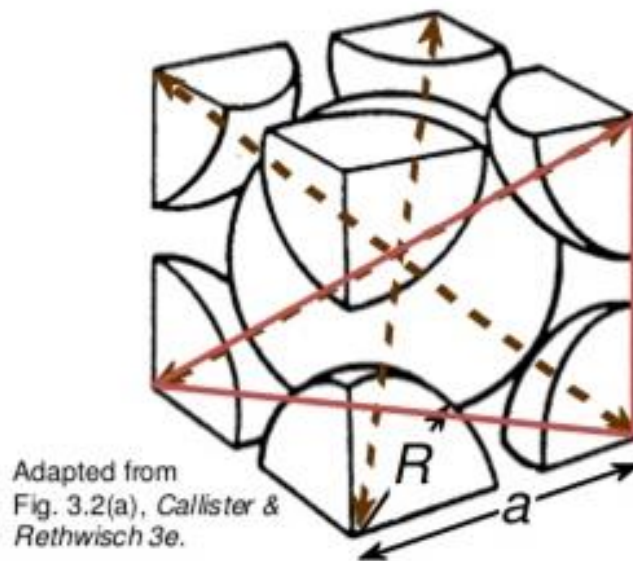
Body Centred Cubic (BCC)



CRYSTAL STRUCTURE - BCC

Atomic Packing Factor: BCC

- APF for a body-centered cubic structure = 0.68



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

$$\text{APF} = \frac{\text{atoms unit cell} \times \text{volume atom}}{\text{volume unit cell}}$$

$$\text{APF} = \frac{2 \times \frac{4}{3} \pi (\sqrt{3}a/4)^3}{a^3}$$

CRYSTAL STRUCTURE - FCC

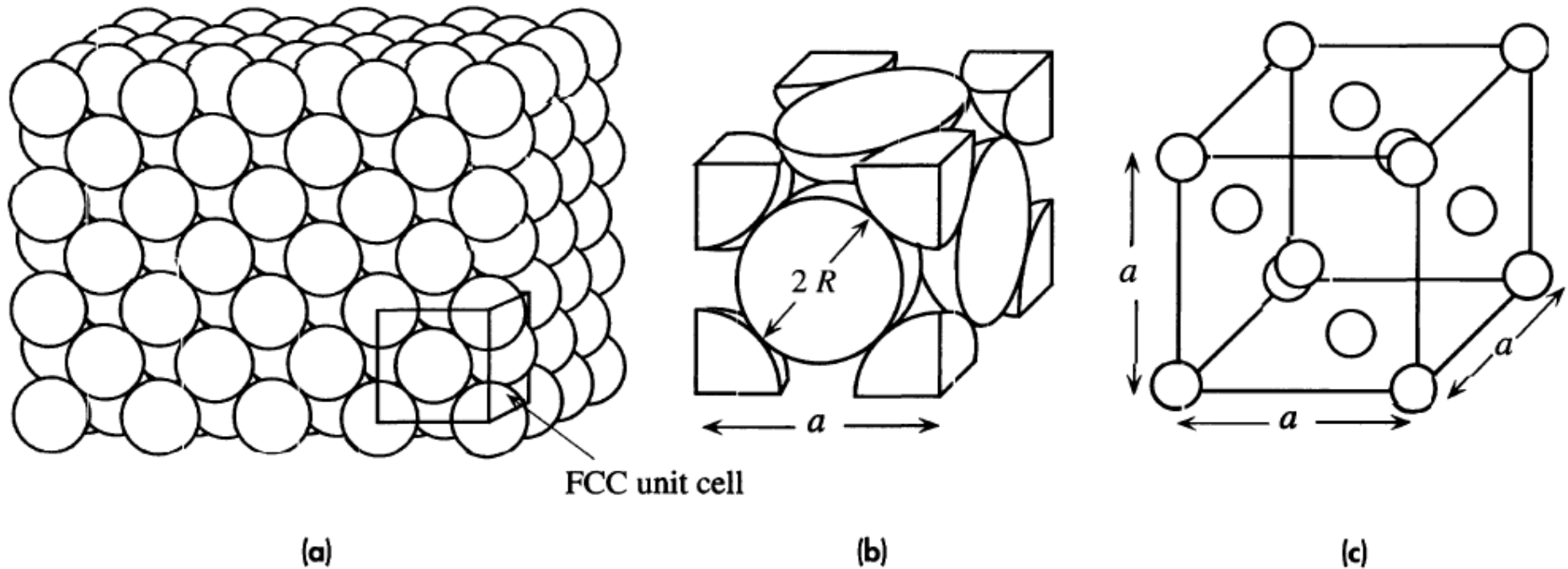


Figure 1.31

(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.

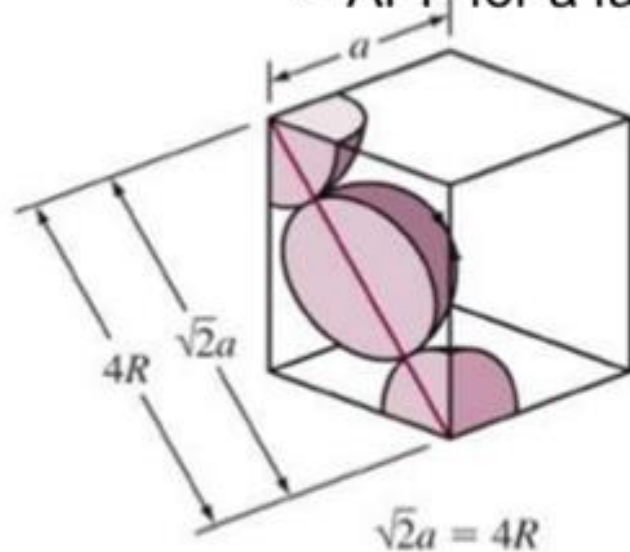
(c) Reduced-sphere representation of the FCC unit cell.

Examples: Ag, Al, Au, Ca, Cu, γ -Fe ($>912^\circ\text{C}$), 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:

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

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

Unit cell contains:

$$6 \times 1/2 + 8 \times 1/8$$

$$= 4 \text{ atoms/unit cell}$$

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

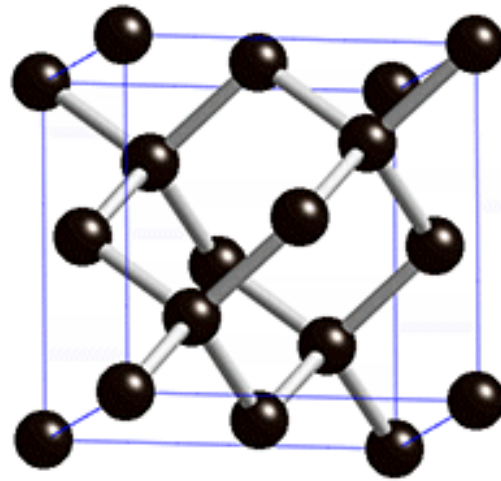
$$\text{APF} = \frac{\begin{array}{c} \text{atoms} \\ \text{unit cell} \end{array} \quad 4 \quad \frac{4}{3} \pi \left(\frac{\sqrt{2}a}{4} \right)^3 \quad \begin{array}{c} \text{volume} \\ \text{atom} \end{array}}{\begin{array}{c} \text{volume} \\ \text{unit cell} \end{array} \quad a^3}$$

CRYSTAL STRUCTURE - FCC

- The unit cell of the copper crystal is cubic with Cu atoms at its corners 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 corner 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

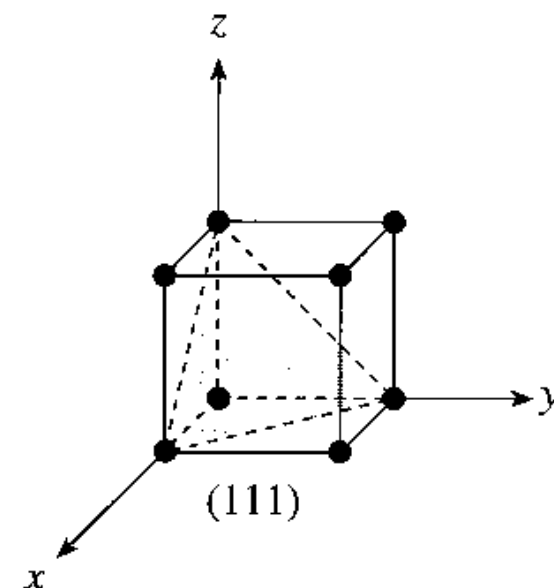
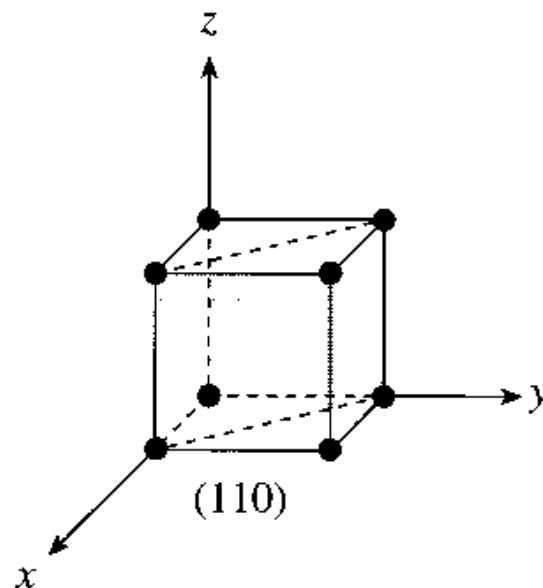
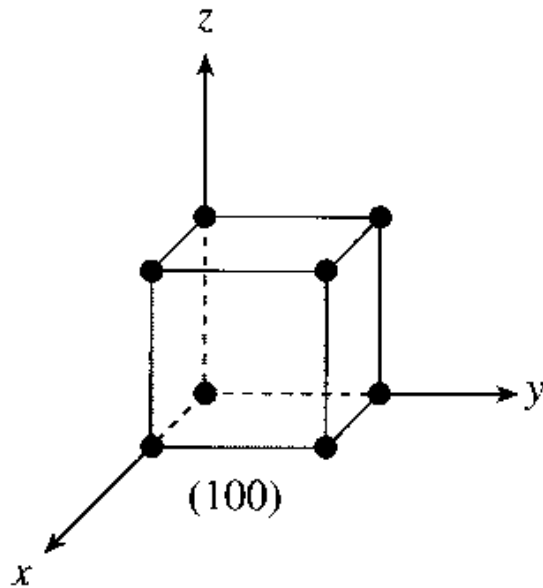
CRYSTAL STRUCTURE

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: Sefa Kasap, "Principles of Electronic Materials and Devices".

Crystallographic Planes



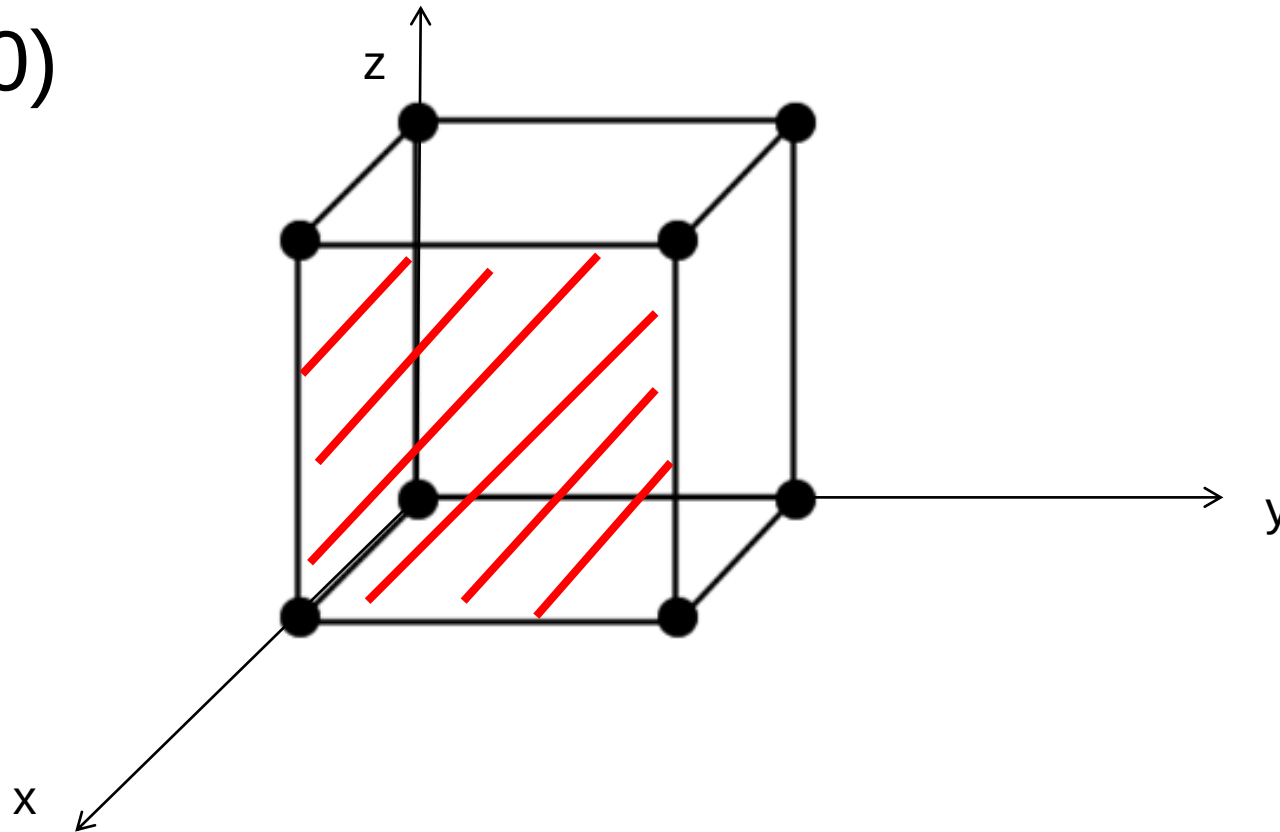
Silicon wafers are usually cut along a $\{100\}$ plane with a flat or notch to orient the wafer during IC fabrication:

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

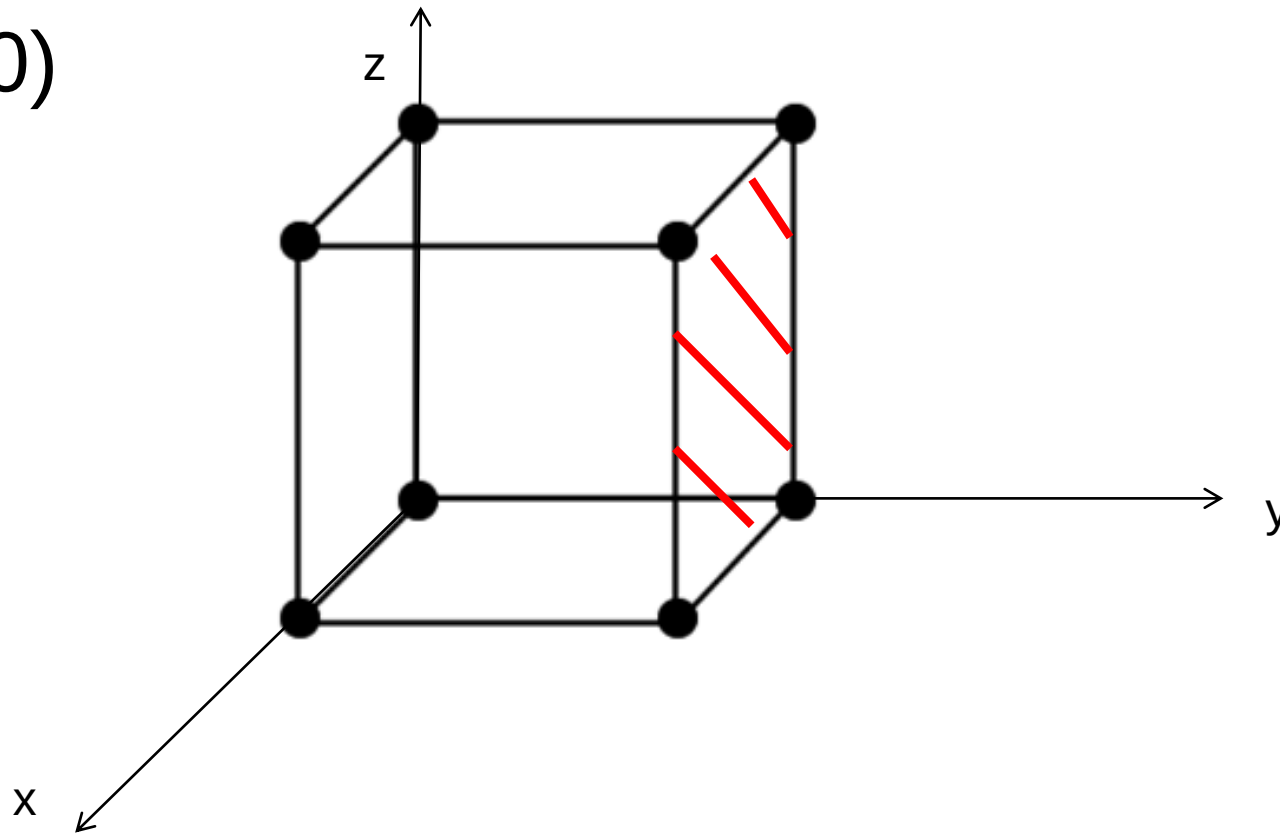
CRYSTAL STRUCTURE

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



CRYSTAL STRUCTURE

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



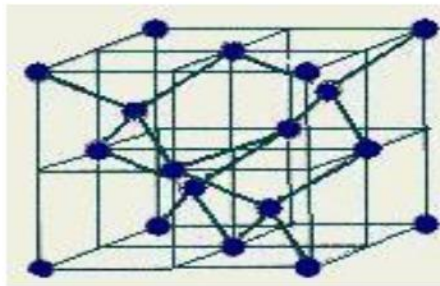
Crystallographic Notation

Notation	Interpretation
$(h\ k\ l)$	crystal plane
$\{h\ k\ l\}$	equivalent planes
$[h\ k\ l]$	crystal direction
$\langle h\ k\ l \rangle$	equivalent directions

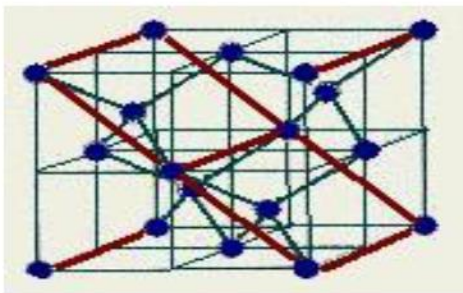
h : inverse x-intercept of plane
 k : inverse y-intercept of plane
 l : inverse z-intercept of plane

CRYSTAL DIRECTIONS

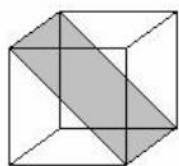
Unit cells (crystal planes)



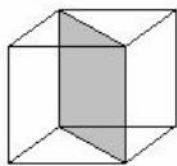
Diamond Unit cell



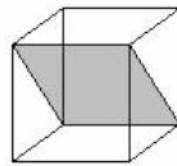
$\{110\}$ planes



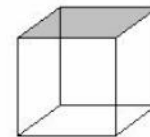
(101)



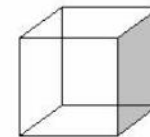
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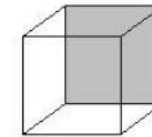
(011)



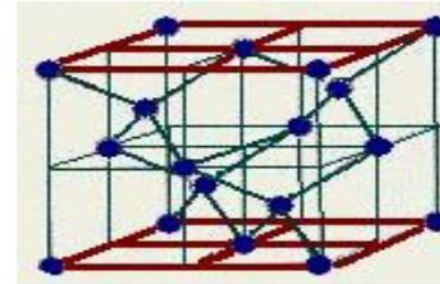
(001)



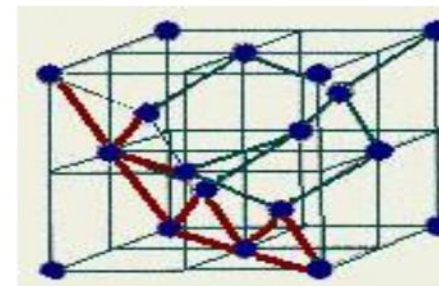
(100)



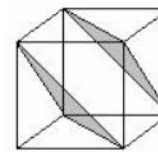
(010)



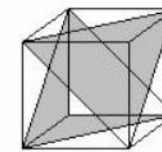
$\{100\}$ planes



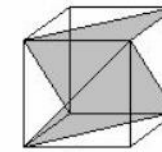
$\{111\}$ planes



(111)



(1 $\bar{1}$ 1)



($\bar{1}$ 11)

Periodic Table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1	1 H Hydrogen 1.00794	1 Atomic # Symbol Name Atomic Mass																2 He Helium 4.002602		
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182																	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050																	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798		
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293		
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71		72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (209)	85 At Astatine (209)	86 Rn Radon (222)	
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)	

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90768	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

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?