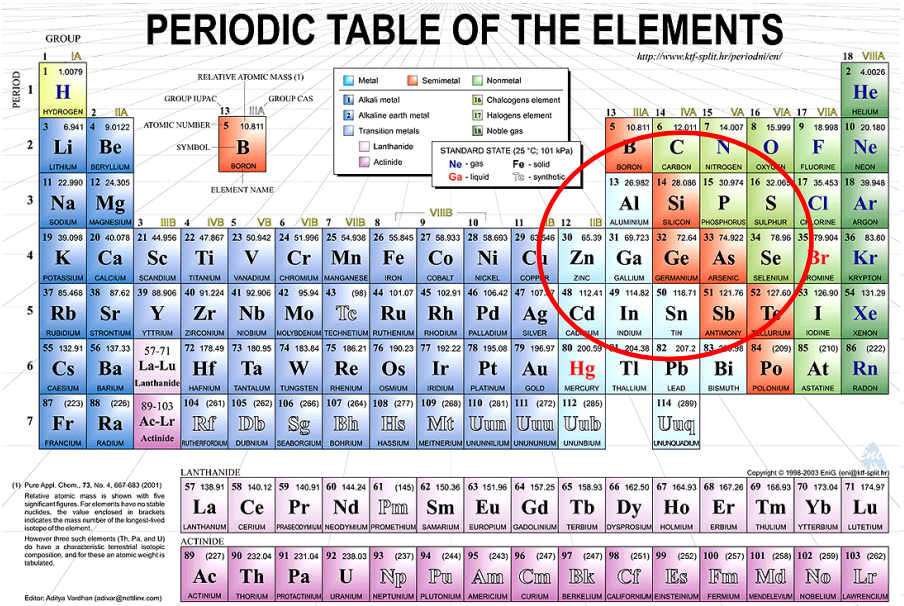
ELEC 424
Solid State Devices

Chapter 1: Crystal Properties and Growth of Semiconductors

What are Semiconductors?

- Materials with electrical conductivity between metals and insulators.
  - Can vary by orders of magnitude
    - Impurity concentration
    - Temperature
    - Light
- In or centered on Group IV of the periodic table.
  - Elemental semiconductors are in group IV
  - Compound semiconductors are from groups that average IV
    - III/V or II/VI

Semiconductor Territory



- ✓ Group IV
  - Elemental, Si and Ge
  - Compound, SiC and SiGe
- ✓ Binary III-V
  - AlP, AlAs, AlSb
  - GaN, GaP, GaAs, GaSb
  - InP, InAs, InSb
- ✓ Binary II-VI
  - ZnS, ZnSe, ZnTe
  - CdS, CdSe, CdTe

Why So Many?

- ✓ Si and Ge
  - Transistors, diodes and integrated circuits.
  - Nuclear detectors
  - Ge was the early choice.
- ✓ GaN, GaP, GaAs
  - Light Emitting Diodes
  - Along with some ternary and quaternary compounds
- ✓ InSb, CdSe, PbTe, HgCdTe
  - Light detectors
- ✓ GaAs, InP
  - Gunn diodes (microwave device)
- ✓ GaAs, AlGaAs
  - Semiconductor lasers

OK, But Why So Many?

- ✓ Varying Energy Band Gaps
  - Si – 1.11 eV
  - Ge – 0.67 eV
  - SiC – 2.86 eV
  - GaP – 2.26 eV
  - GaN – 3.4 eV
  - InSb – 0.18 eV
  - ZnS – 3.6 eV
  - PbTe – 0.29 eV

  …and on and on.

Three Types of Solids

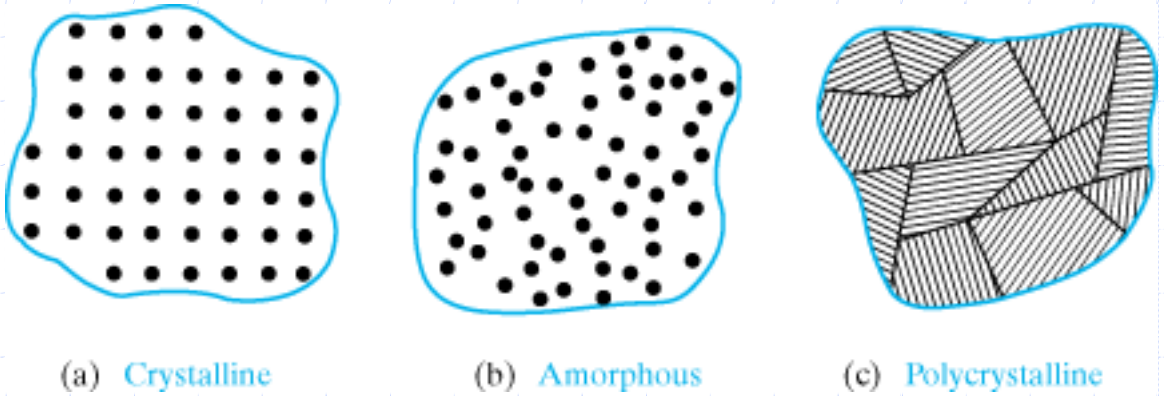


Figure 1—1
Three types of solids, classified according to atomic arrangement: (a) crystalline and (b) amorphous materials are illustrated by microscopic views of the atoms, whereas (c) polycrystalline structure is illustrated by a more macroscopic view of adjacent single-crystalline regions, such as (a).

SRO – short range order
LRO – long range order
Liquids – No SRO, no LRO
Crystalline – SRO and LRO
Amorphous – SRO, no LRO
Polycrystalline – small crystals pasted together

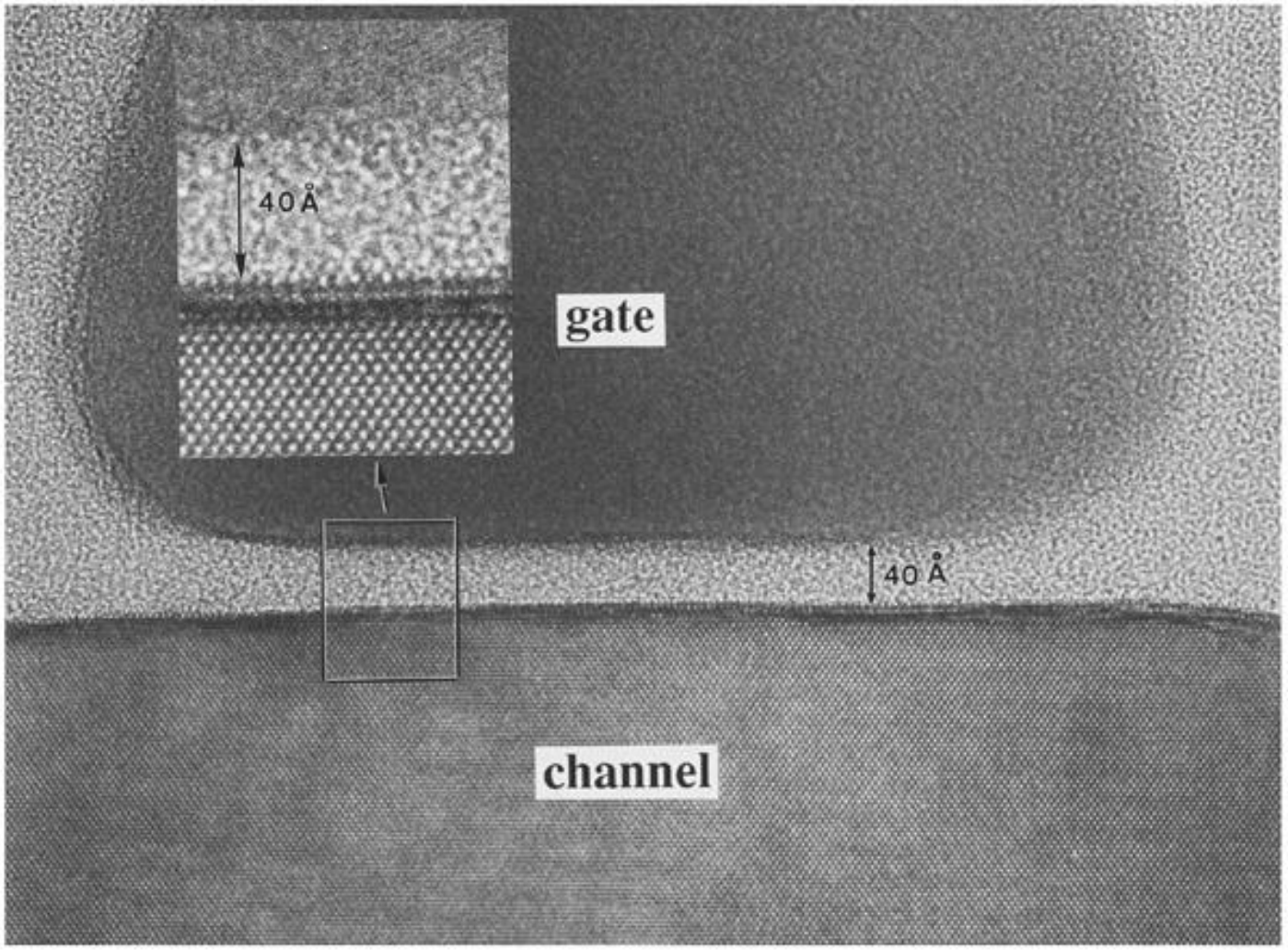


Figure 6—33
Cross section of a MOSFET. This high resolution transmission electron micrograph of a silicon Metal–Oxide Semiconductor Field Effect Transistor shows the silicon channel and metal gate separated by a thin (40Å, 4nm) silicon–dioxide insulator. The inset shows a magnified view of the three regions, in which individual rows of atoms in the crystalline silicon can be distinguished. (Photograph courtesy of AT&T Bell Laboratories.)

The Crystal Unit Cell

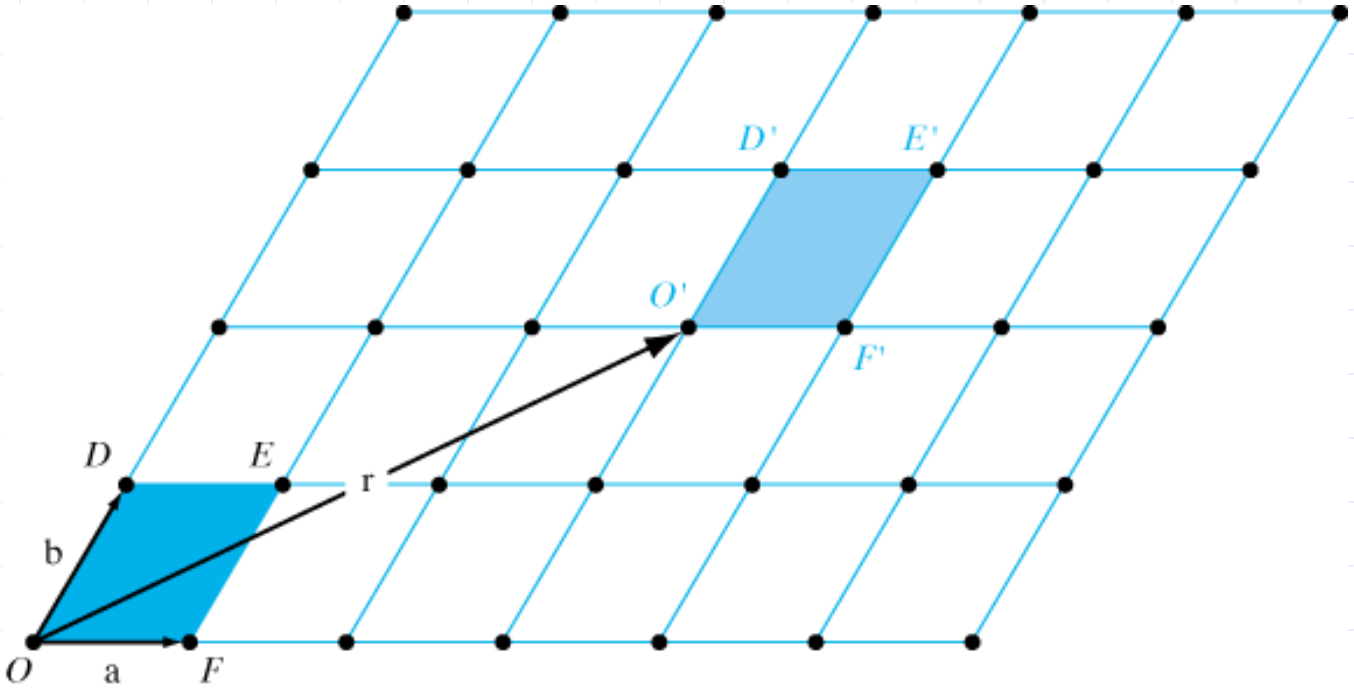


Figure 1—2
A two-dimensional lattice showing translation of a unit cell by r = 3a + 2b.

Three Cubic Lattices

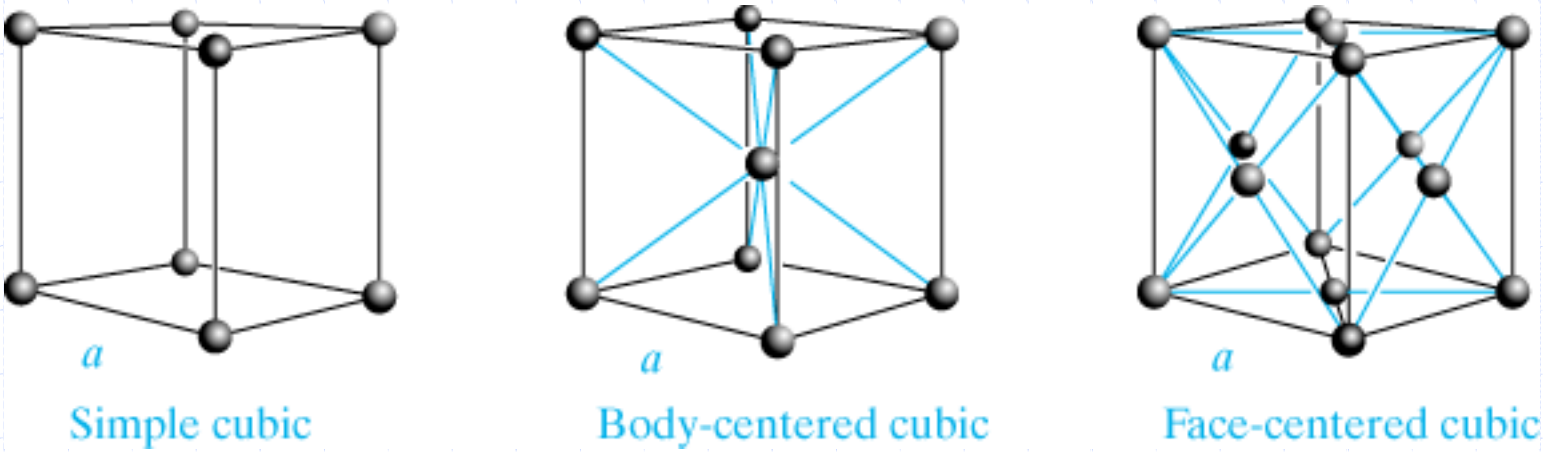
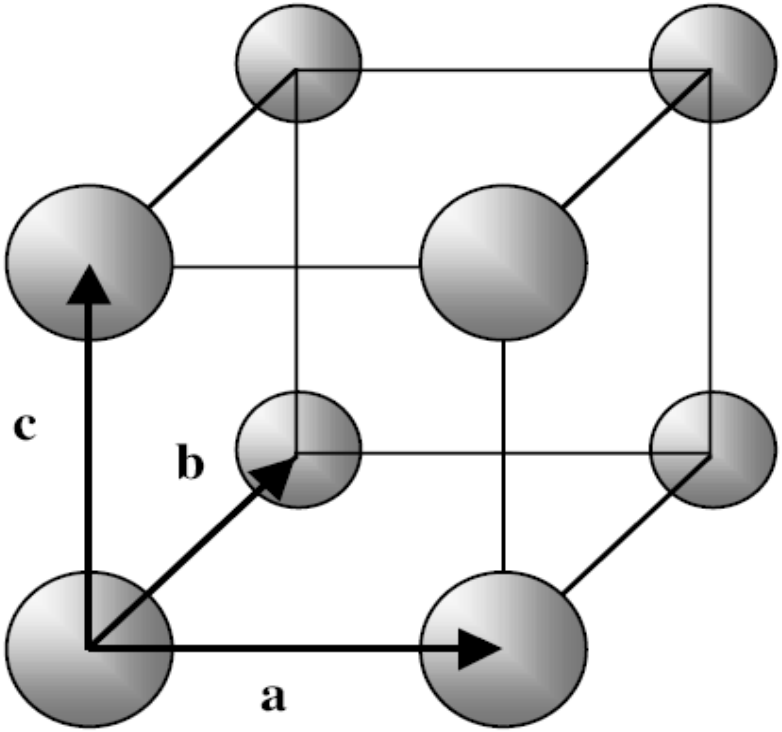
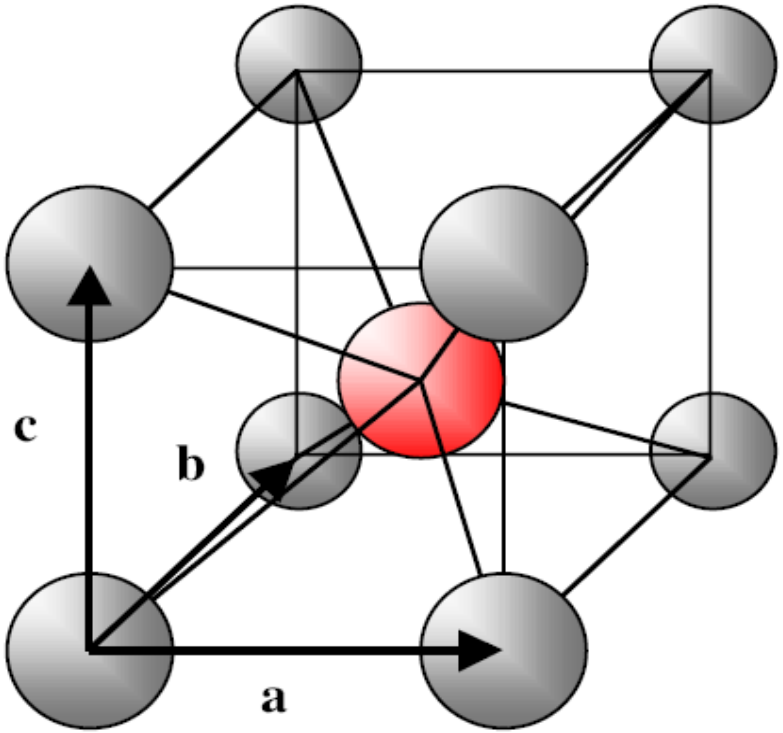


Figure 1—3
Unit cells for three types of cubic lattice structures.

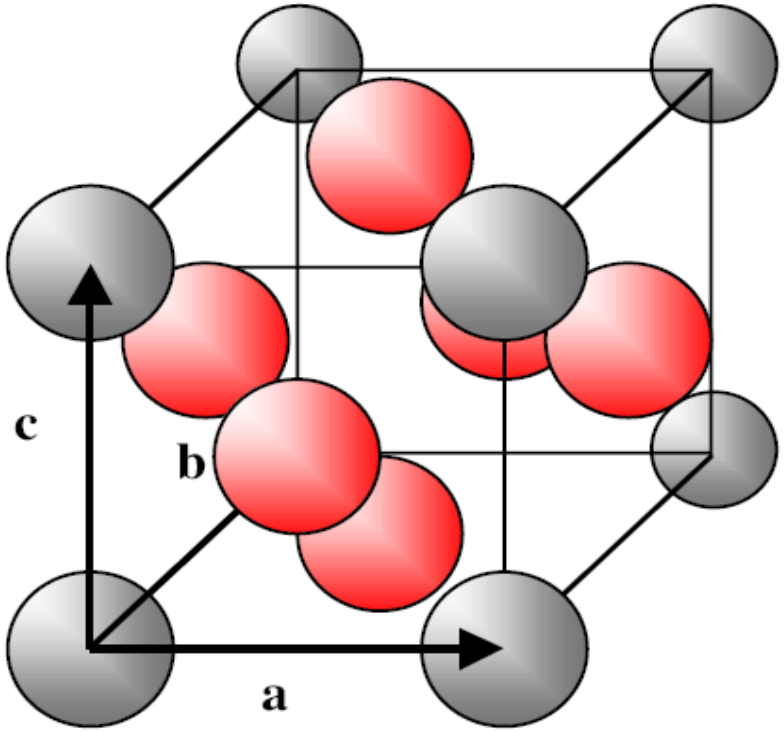
Simple Cubic Unit Cell



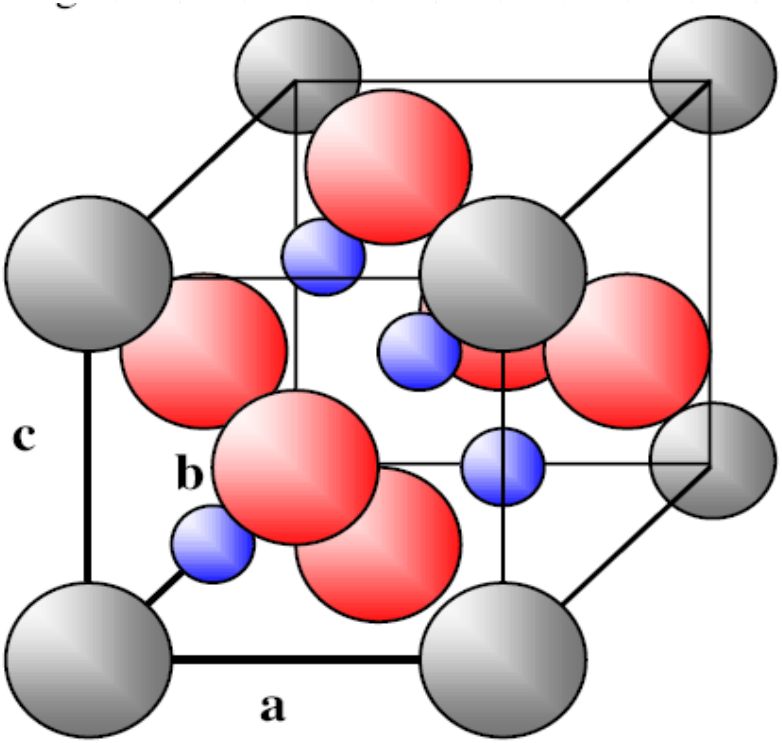
Body Centered Unit Cell



Face Centered Unit Cell



Diamond Unit Cell



Hard Sphere Approximation

Presumes atoms are hard spheres and tightly packed (touching) in their unit cells.

- ✓ Cubic unit cells have a lattice constant of ***a*** (the distance between adjacent cell corners)
- ✓ Calculate lattice constants, Inter-atomic distances and Packing Factor

Packing Factor

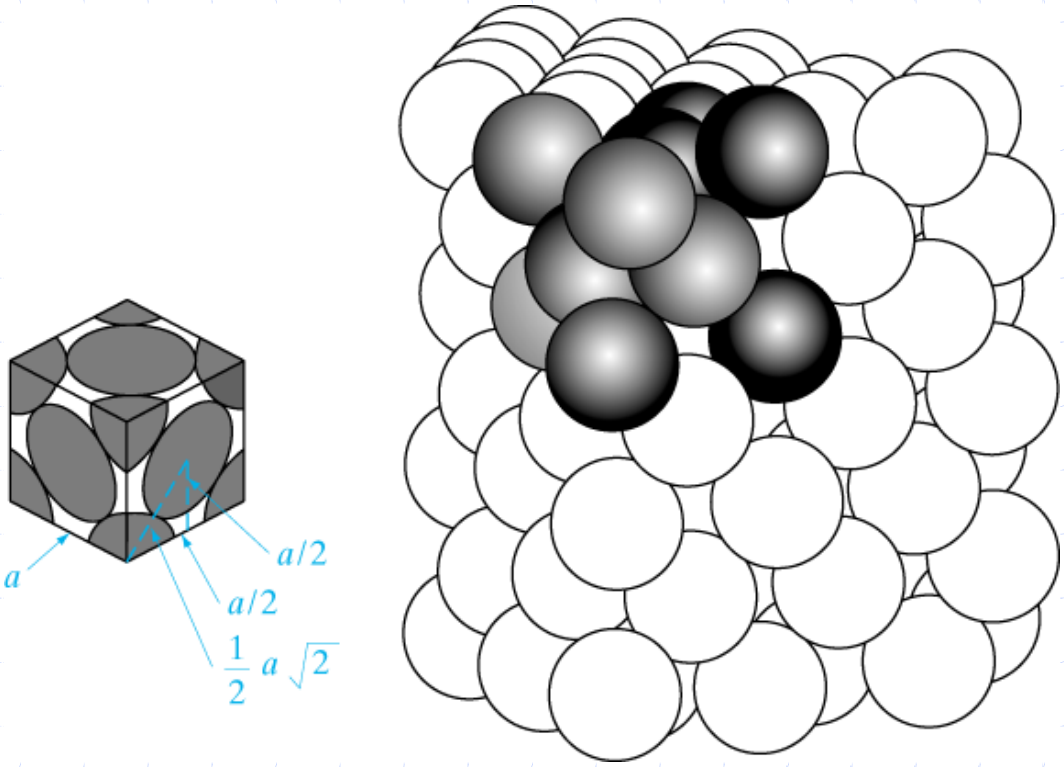


Figure 1—4
Packing of hard spheres in an fcc lattice.

Example 1-1, p. 6

Body centered cube – lattice constant is 5Å.

What is the atomic radius?

What is the packing factor?

What do we know?

✓3 atoms touching tangentially form the cube diagonal, so 2 radii of corner atoms plus 1 diameter of the body centered atom equals the cube diagonal.

✓From Pythagoras

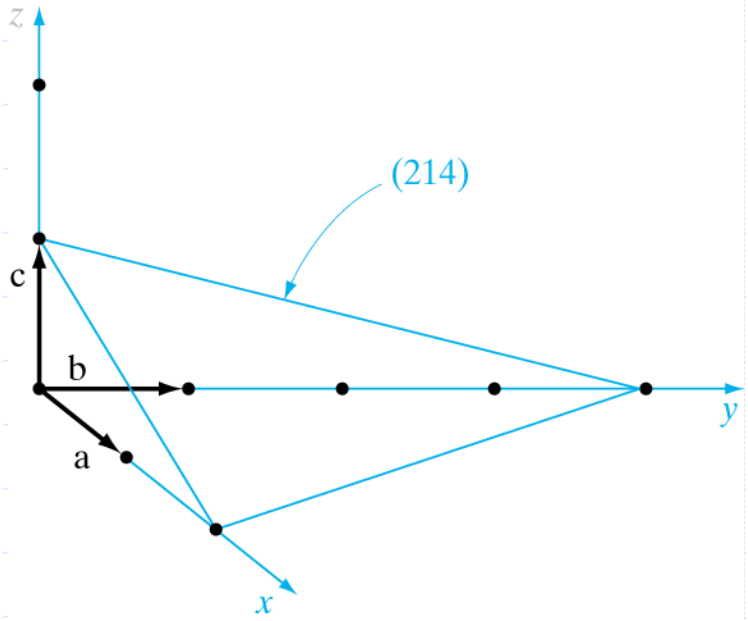
(cube diagonal)^2 = a^2 + ((a^2 + a^2)$^{1/2}$)^2 = 3a^2

The cube diagonal, 4 atomic radii = a$\sqrt{3}$

Thus the atomic radius is 1/4 a$\sqrt{3}$ = 2.165 Å

Packing fraction will be 2*4/3лr^3/ a^3 = 2*4/3л(1/4 a$\sqrt{3}$)^3/a^3 = 68%

Miller Indices



The Miller Index designating the crystal plane is the normalized reciprocal of the intercepts.

Intercepts
a = 2
b = 4
c = 1

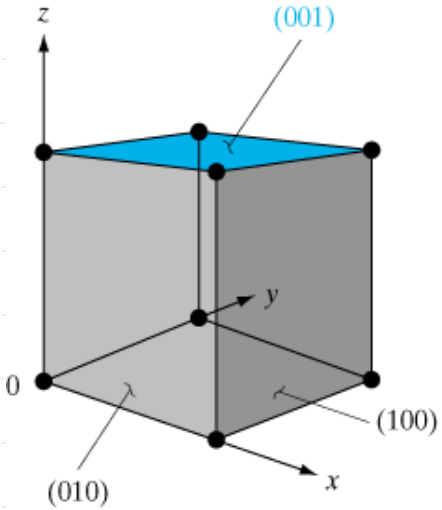
Reciprocals = ½, 1/4, 1/1

Normalized = 2,1,4 = (214)

Notation is important. The index shown without commas and within parentheses implies a crystal plane designation.

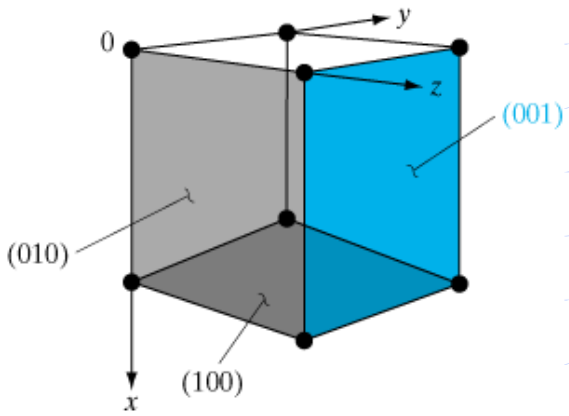
(*hkl*) = (214)

Equivalent Planes



More on notation:

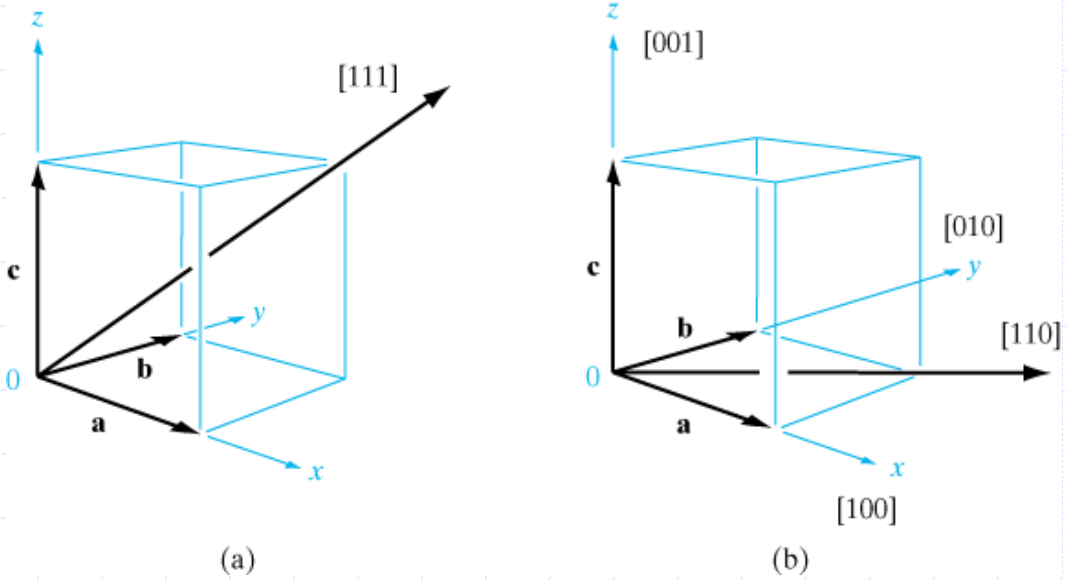
Families of equivalent planes are denoted within braces {}.



The set of planes indicated above can be specified simply as the cube faces {100}.

The planes are equivalent upon rotation of the unit cell within the cubic lattice. Remember, all the atoms look alike, so the only reference is the distance and angle (vector) to the neighboring atoms.

Crystal Direction



Direction is simply the Cartesian coordinate of the unit cell intercept in brackets [].

Families of equivalent directions are enclosed in “arrows” , <>.

No commas, so as not to mistake as a Cartesian coordinates.

Diamond Lattice

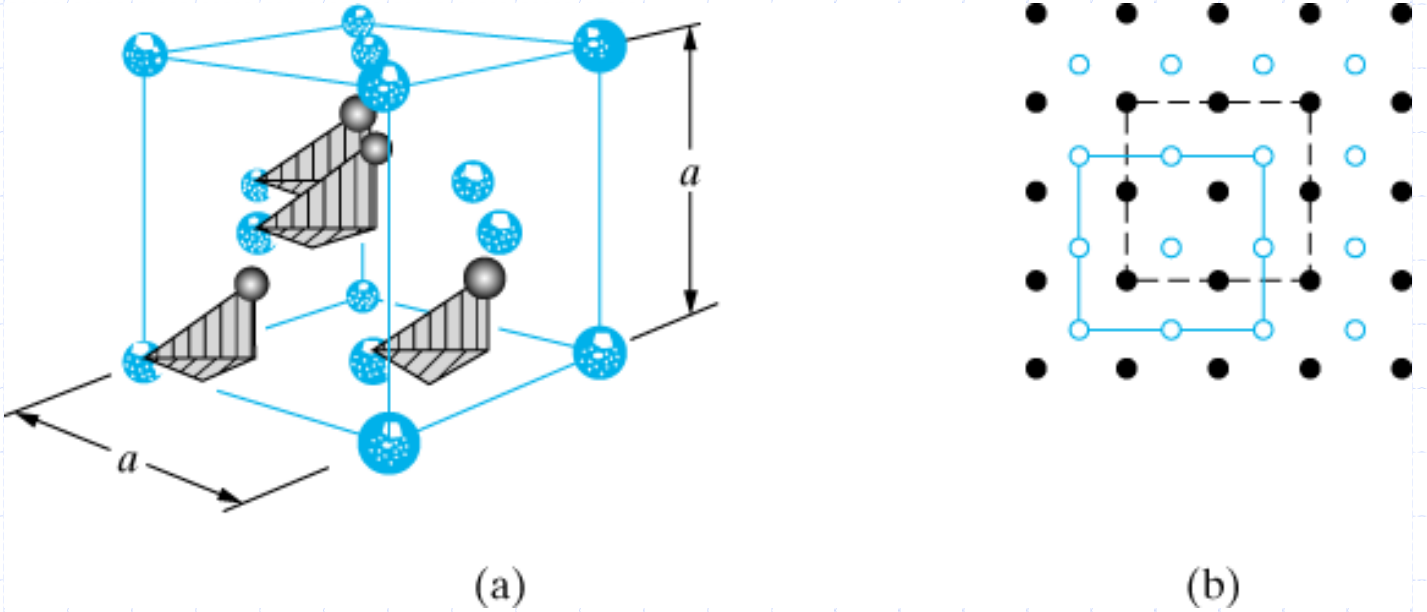


Figure 1—8
Diamond lattice structure: (a) a unit cell of the diamond lattice constructed by placing atoms from each atom in an fcc; (b) top view (along any 100 direction) of an extended diamond lattice. The colored circles indicate one fcc sublattice and the black circles indicate the interpenetrating fcc.

Diamond

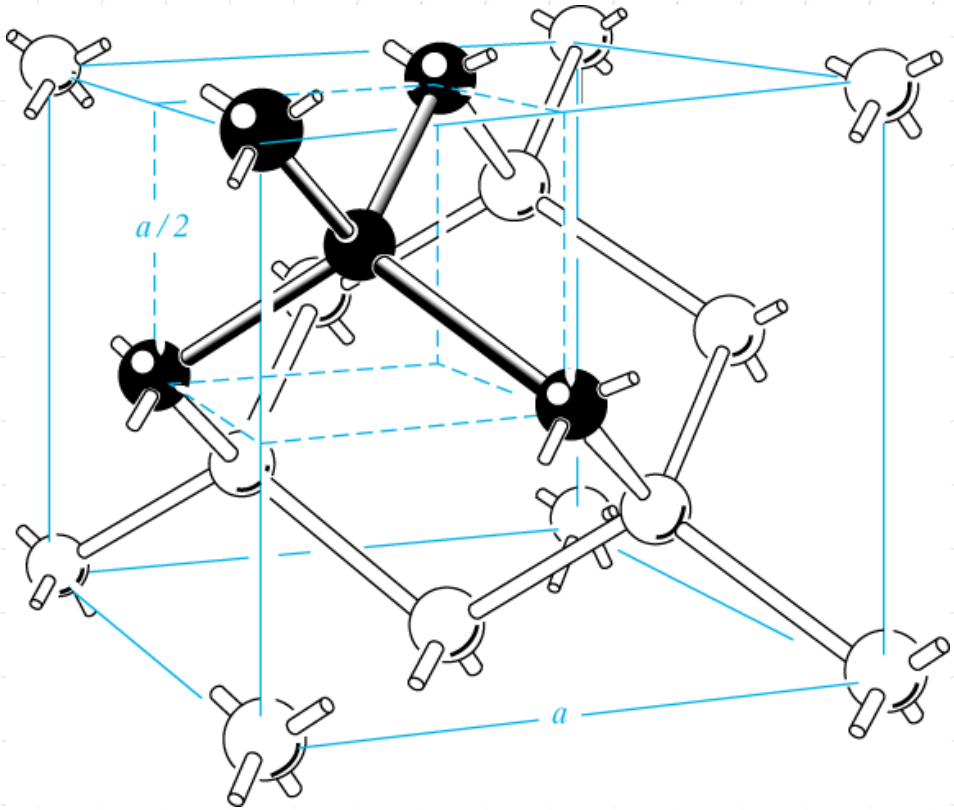
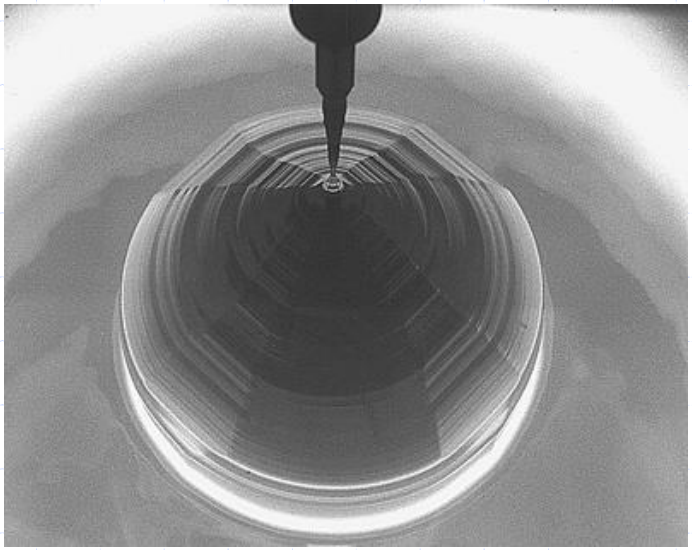
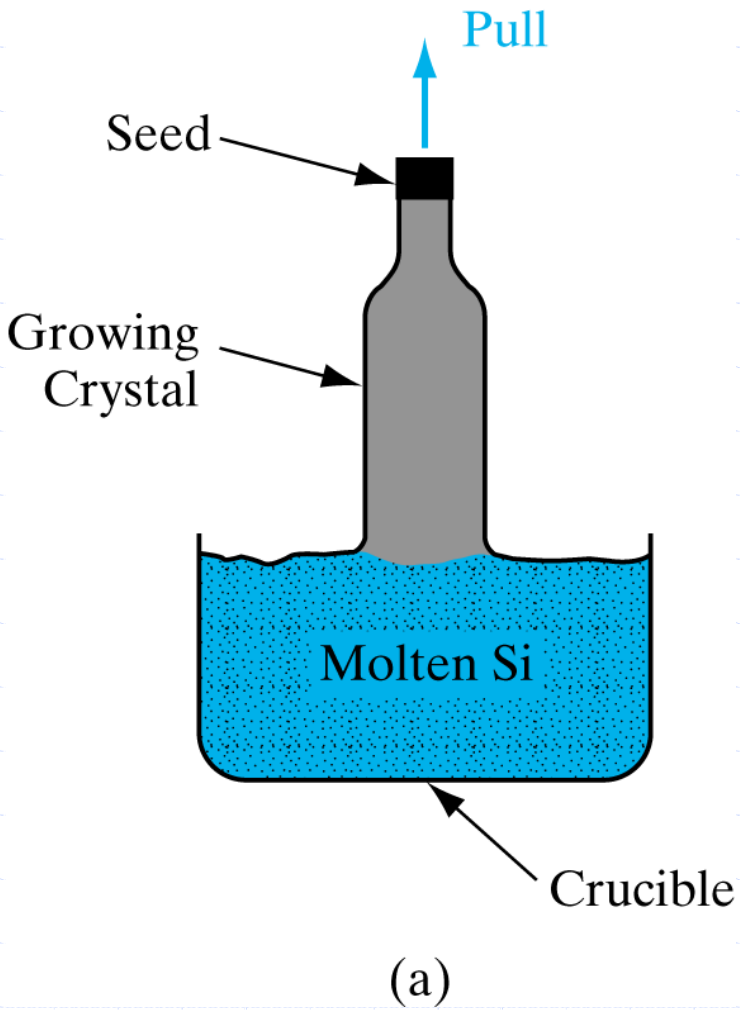


Figure 1—9
Diamond lattice unit cell, showing the four nearest neighbor structure. (From Electrons and Holes in Semiconductors by W. Shockley, © 1950 by Litton Educational Publishing Co., Inc.; by permission of Van Nostrand Reinhold Co., Inc.)

Crystal Growth



(b)



(a)

Figure 1—10
Pulling of a Si crystal from the melt (Czochralski method): (a) schematic diagram of the crystal growth process; (b) an 8-in. diameter, (100) oriented Si crystal being pulled from the melt. (Photograph courtesy of MEMC Electronics Intl.)

Boule of Silicon

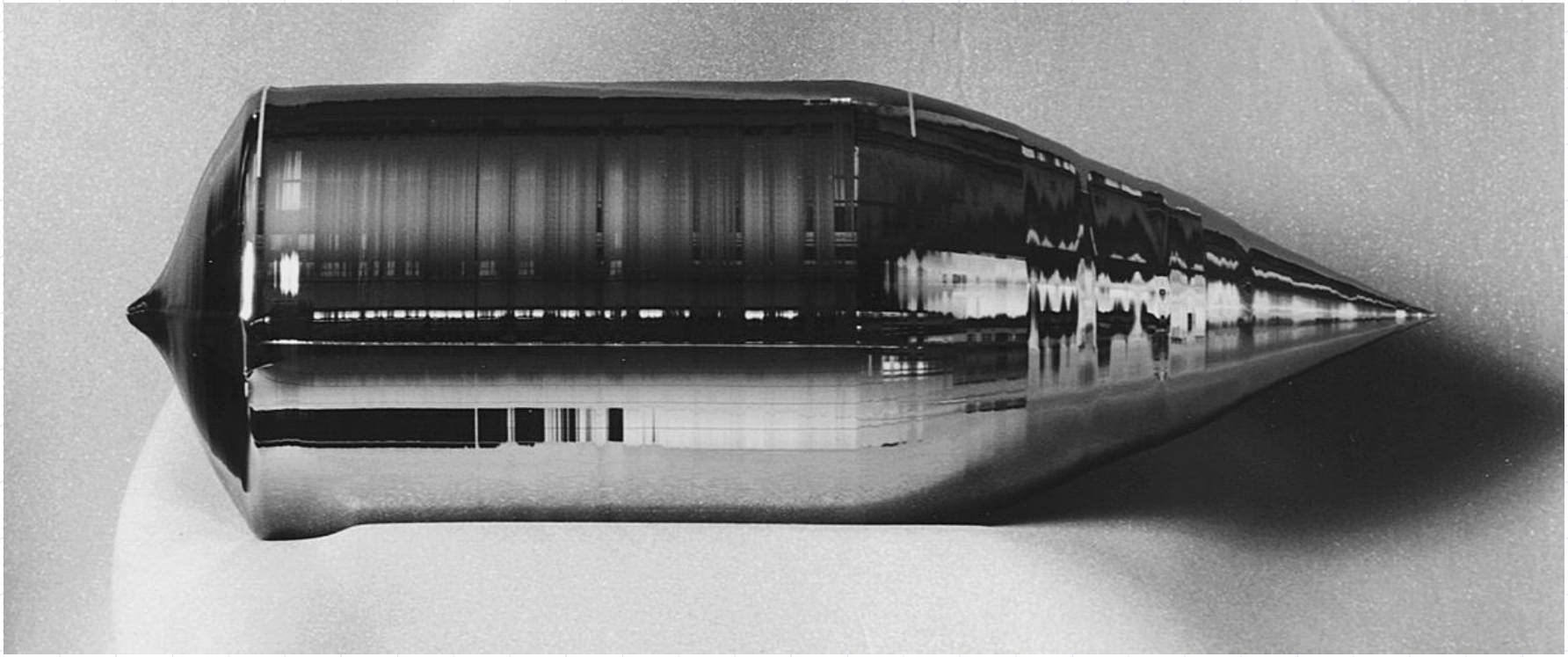


Figure 1—11
Silicon crystal grown by the Czochralski method. This large single-crystal ingot provides 300 mm (12-in.) diameter wafers when sliced using a saw. The ingot is about 1.5 m long (excluding the tapered regions), and weighs about 275 kg. (Photograph courtesy of MEMC Electronics Intl.)

Wafer Resistivity
Example 1-4, p. 17

Determined by the density and species of impurity atoms
Controlled during silicon growth
- Sort of like mixing paint
- Presumes knowledge of k_d the distribution coefficient

What concentration of phosphorus atoms should we 'drop' into the silicon melt to grow and ingot with 10^{16} phosphorous atoms/cm^3, given $k_d = 0.35$?

$k_d = C_S / C_L$ *The distribution coefficient is the ratio of the impurity concentration in the solid to that in the liquid at equilibrium.*

For this example only 35% of the melt phosphorous concentration are redistributed in the solid state silicon. Therefore we need nearly three times the target concentration in the melt, or more precisely the melt must contain $0^{16}/0.35 = 2.86*10^{16}$ P atoms/cm^3.

So how much do we need to to dope 5 kg of silicon to 10^{16} atoms/cm^3?

Si density (from Appendix III) is 2.33 grams/ cm^3. Therefore 5 kg of silicon is 2146 cm^3.

So we need $2.86*10^{16}$ P atoms/cm^3 times 2146 cm^3 or $6.14*10^{19}$ phosphorous atoms, or ($6.14*10^{19}$atoms * 31 g/mole)/$6.02 * 10^{23}$ atoms/mole = $3.16 * 10^{-3}$ grams of phosphorous.

A whopping 3+ milligrams of phosphorous will do the job for 5 kg (11 pounds) of silicon.

Silicon Wafers

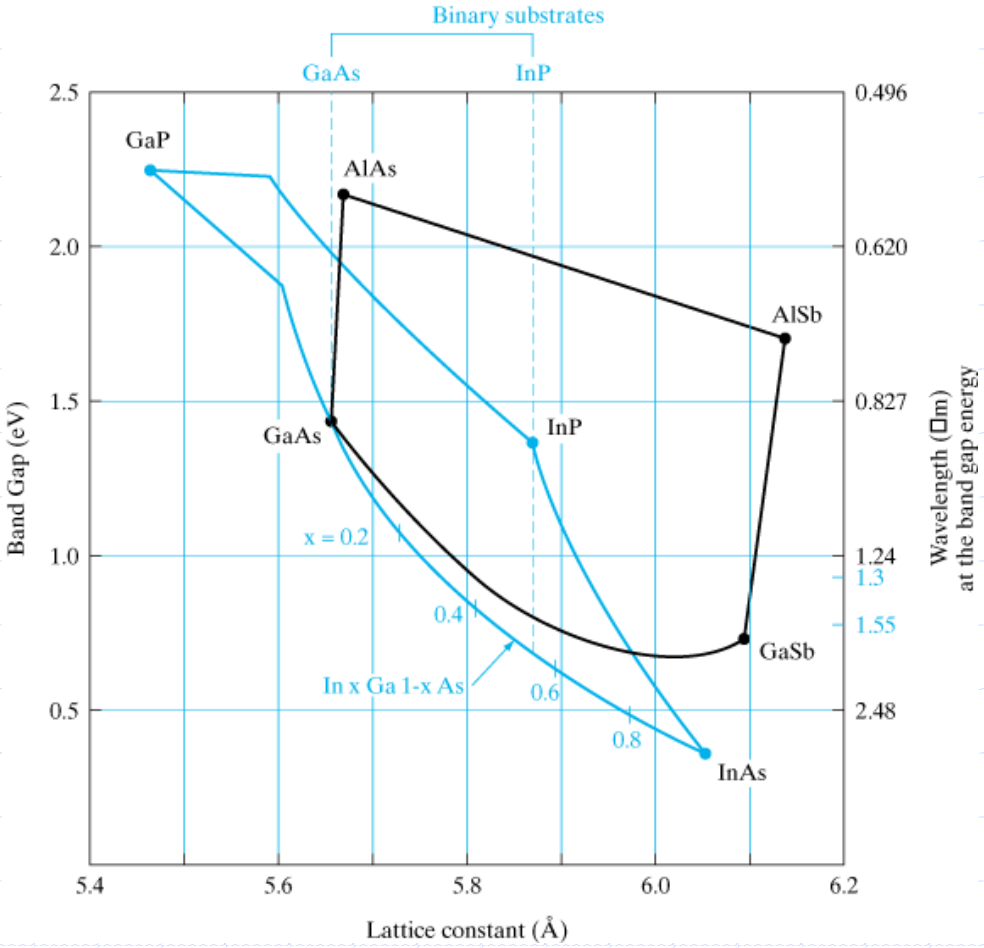
Figure 1—12
Steps involved in manufacturing Si wafers: (a) A 300 mm Si cylindrical ingot, with a notch on one side, being loaded into a wire saw to produce Si wafers; (b) a technician holding a cassette of 300 mm wafers. (Photographs courtesy of MEMC Electronics Intl.)

Silicon Run I

Band Gap

- ✓ Varying Energy Band Gaps
  - Si – 1.11 eV
  - Ge – 0.67 eV
  - SiC – 2.86 eV
  - GaP – 2.26 eV
  - GaN – 3.4 eV
  - InSb – 0.18 eV
  - ZnS – 3.6 eV
  - PbTe – 0.29 eV

…and on and on.



Compound Semiconductors used for LEDs

A breadth of crystalline properties translates to a range of emitted wavelengths. This provides a range of native colors in our LED crayon box.

Heteroepitaxy

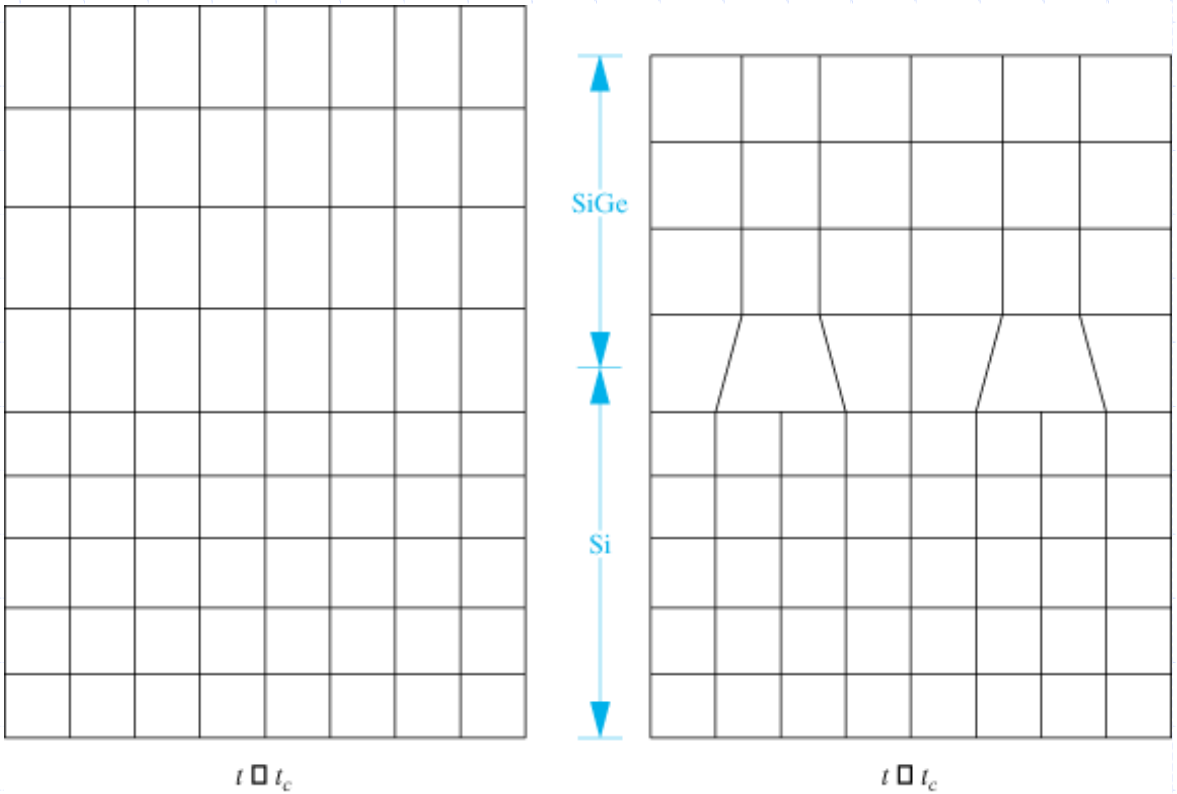


Figure 1—14

Heteroepitaxy and misfit dislocations. For example, in heteroepitaxy of a SiGe layer on Si, the lattice mismatch between SiGe and Si leads to compressive strain in the SiGe layer. The amount of strain depends on the mole fraction of Ge. (a) For layer thicknesses less than the critical layer thickness, t c , pseudomorphic growth occurs. (b) However, above t c , misfit dislocations form at the interface which may reduce the usefulness of the layers in device applications.

Vapor Phase Epitaxy

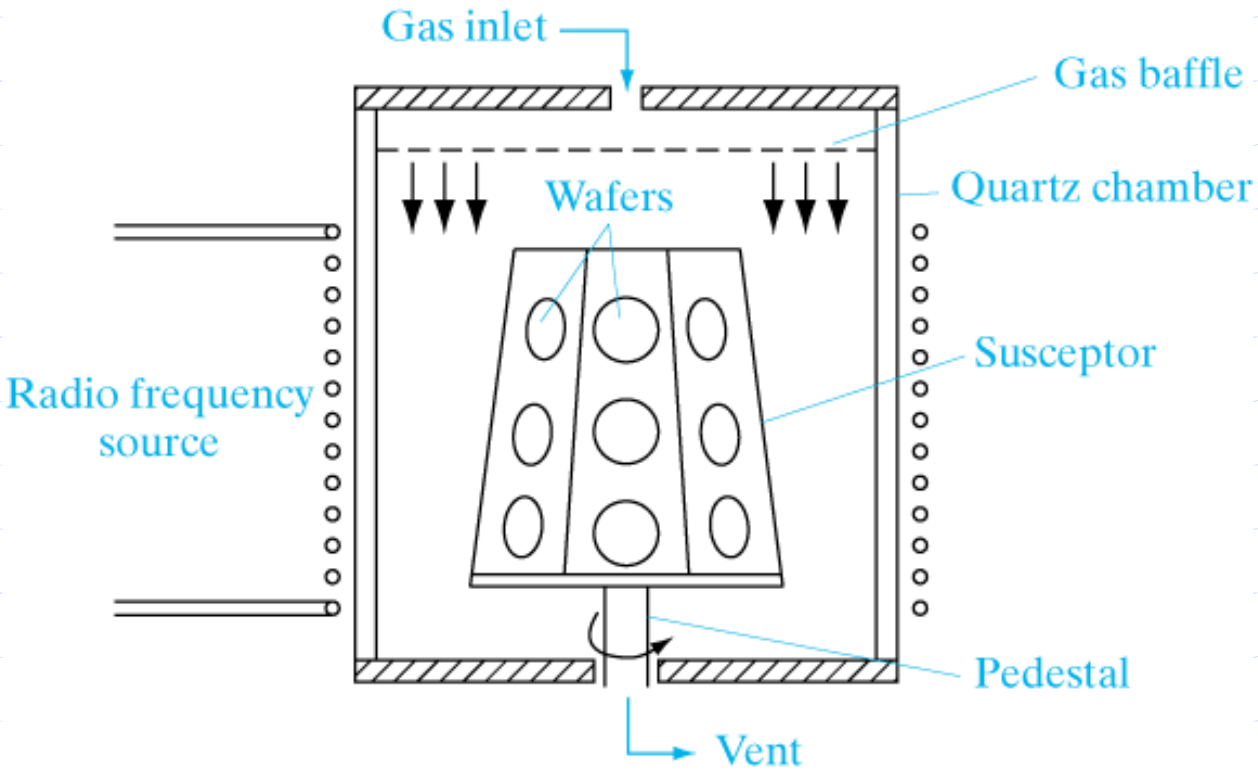


Figure 1—15

A barrel-type reactor for Si VPE. These are atmospheric pressure systems. The Si wafers are held in slots cut on the sides of a SiC-coated graphite susceptor that flares out near the base to promote gas flow patterns conducive to uniform epitaxy.

MBE

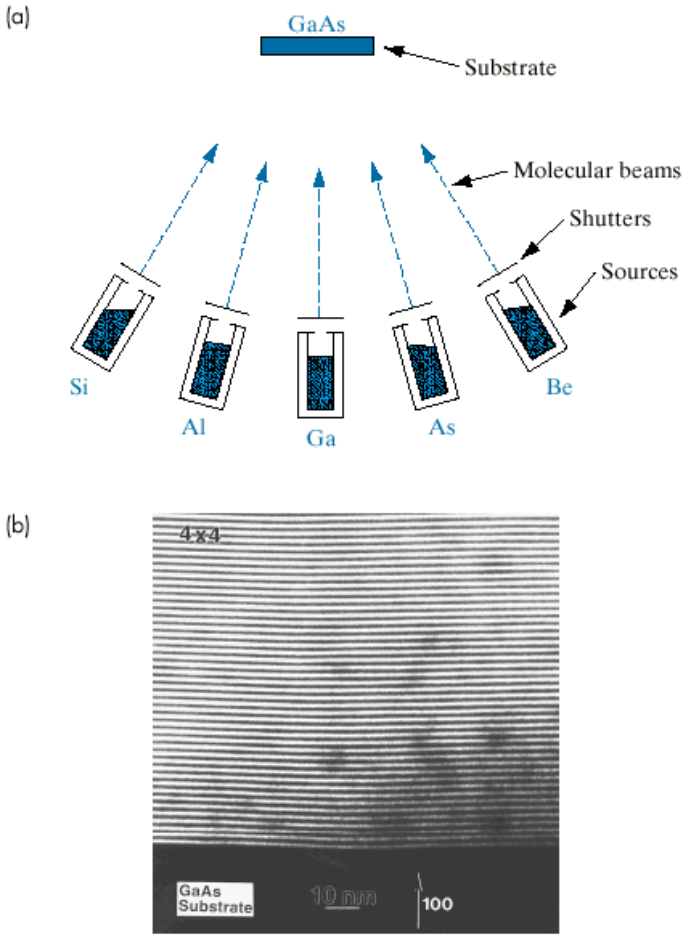


Figure 1—16
Crystal growth by molecular beam epitaxy (MBE): (a) evaporation cells inside a high -vacuum chamber directing beams of Al, Ga, As, and dopants onto a GaAs substrate; (b) scanning electron micrograph of the cross section of an MBE-grown crystal having alternating layers of GaAs (dark lines) and AlGaAs (light lines). Each layer is four monolayers (4 3 a/2 5 11.3Å) thick. (Photograph courtesy of Bell Laboratories.)

MBE

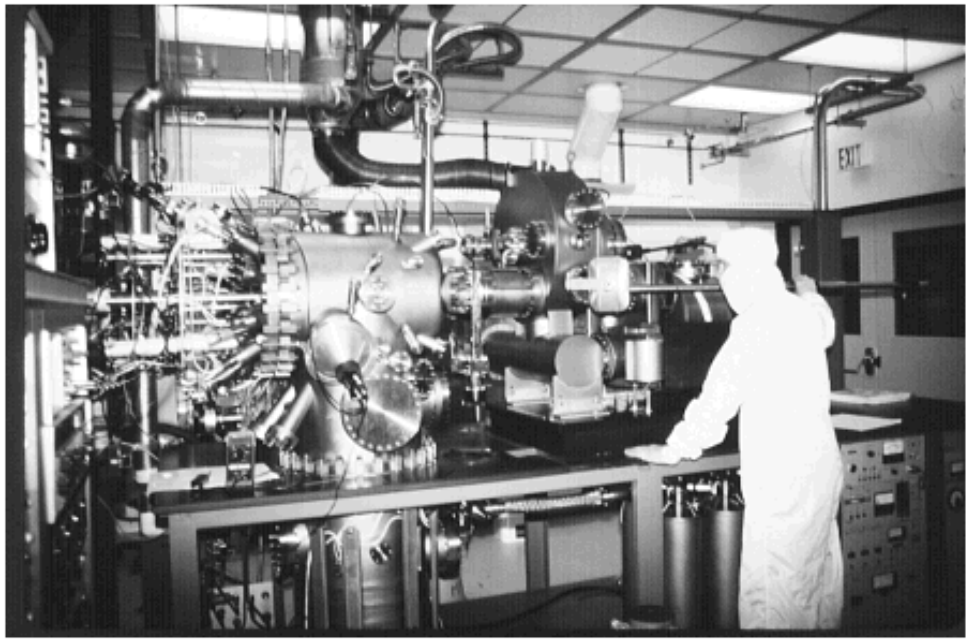


Figure 1—17
Molecular beam epitaxy facility in the MicroelectronicsResearch Center at the University of Texas at Austin.

Chapter 1 HW Assignment

1. For a face centered cubic lattice of identical atoms, with a lattice constant of 4.5 Å, find the following:
   a. Maximum packing fraction.
   b. Radius of atoms treated as hard spheres.
2. A Si crystal is to be grown by the Czochralski, and is desired to contain 1.7of x10^{16} Boron atoms per cm^3. Presuming a k_d of 0.28, how many grams of Boron must be added to the 10 *kg* Si melt to obtain this Boron concentration?

   [Hint: Example 1-4, p 17]

1. Problem 1.16, p27.

Chapter 1 HW is due (paper or email) NLT Wednesday, 5/27/2015