

ECE 340

Solid State Electronic Devices

M,W,F 12:00-12:50 (X), 2015 ECEB

Professor John Dallesasse

Department of Electrical and Computer Engineering

2114 Micro and Nanotechnology Laboratory

Tel: (217) 333-8416

E-mail: jdallesa@illinois.edu

Office Hours: Wednesday 13:00 – 14:00



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Today's Discussion

- Finish General Introduction to Semiconductor Electronics
- Lattices and Crystal Structures
- Assignments
- Topics for Next Lecture

Tentative Schedule [1]

	JAN 17 Course overview	JAN 19 Intro to semiconductor electronics
JAN 22 Materials and crystal structures	JAN 24 Bonding forces and energy bands in solids	JAN 26 Metals, semiconductors, insulators, electrons, holes
JAN 29 Intrinsic and extrinsic material	JAN 31 Distribution functions and carrier concentrations	FEB 2 Distribution functions and carrier concentrations
FEB 5 Temperature dependence, compensation	FEB 7 Conductivity and mobility	FEB 9 Resistance, temperature, impurity concentration
FEB 12 Invariance of Fermi level at equilibrium	FEB 14 Optical absorption and luminescence	FEB 16 Generation and recombination

****Subject to Change****



General Introduction to Semiconductor Electronics

Continued

Current-Density Equations

Drift



Diffusion



$$J_n = q\mu_n nE + qD_n \nabla n$$

$$J_p = q\mu_p pE - qD_p \nabla p$$

$$J_{cond} = J_n + J_p$$

- In semiconductor, in addition to an electron current density there is a hole current density
- Each current consist of the drift component cause by field and the diffusion component caused by the carrier concentration gradient

Continuity Equations

$$\frac{\partial n}{\partial t} = G_n - U_n + \frac{1}{q} \nabla \cdot J_n$$
$$\frac{\partial p}{\partial t} = G_p - U_p - \frac{1}{q} \nabla \cdot J_p$$

For a given volume of semiconductor, the rate change of carrier is the net effect of current flow into the volume and generation and recombination rates within the volume.

G_n : electron generation rate

G_p : hole generation rate

U_n : electron recombination rate

U_p : hole recombination rate

Quantum Mechanics

Heisenberg Uncertainty Principle :

Position-Momentum: $(\Delta x \cdot \Delta p_x) \geq \hbar / 2$

Energy-Time: $(\Delta E \cdot \Delta t) \geq \hbar / 2$

Schrodinger's Equation :

$$-\frac{\hbar^2}{2m} \nabla^2 \Psi + V\Psi = -\frac{\hbar}{j} \frac{\partial \Psi}{\partial t} \quad (\text{Kinetic Energy} + \text{Potential Energy} = \text{Total Energy})$$

$\Psi(x,y,z,t)$ is continuous, finite, and single-valued

The derivative in space of $\Psi(x,y,z,t)$ is continuous, finite, and single-valued

The probability of finding a particle with wave function Ψ is $\Psi^* \Psi$

The particle is somewhere, so $\int_{-\infty}^{\infty} \Psi^* \Psi dx dy dz = 1$

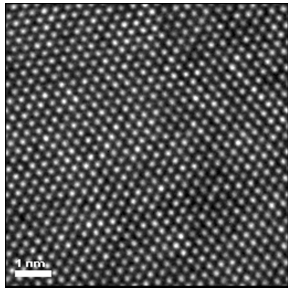
The expectation value of an operator Q is: $\langle Q \rangle = \int_{-\infty}^{\infty} \Psi^* Q_{op} \Psi dx dy dz$



Lattices and Crystal Structures

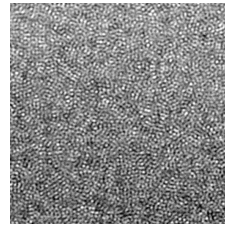
Types of Solids

HRTEM: [110] Si



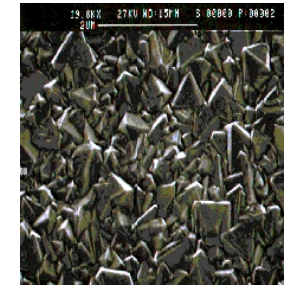
<http://spie.org/x31901.xml>

TEM: Glassy Pd

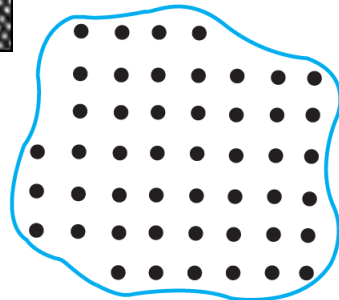


<http://www.futurity.org/science-technology>

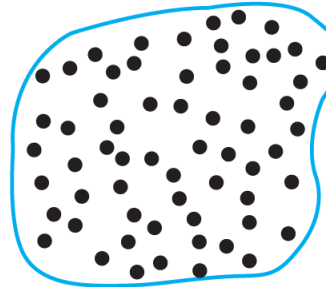
SEM: Diamond on Si



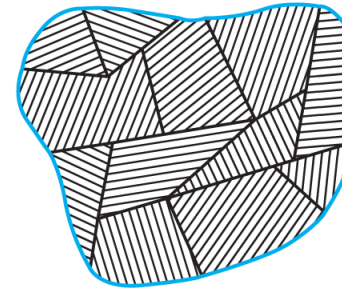
<http://isic.epfl.ch/page-53777-en.html>



(a) Crystalline



(b) Amorphous



(c) Polycrystalline

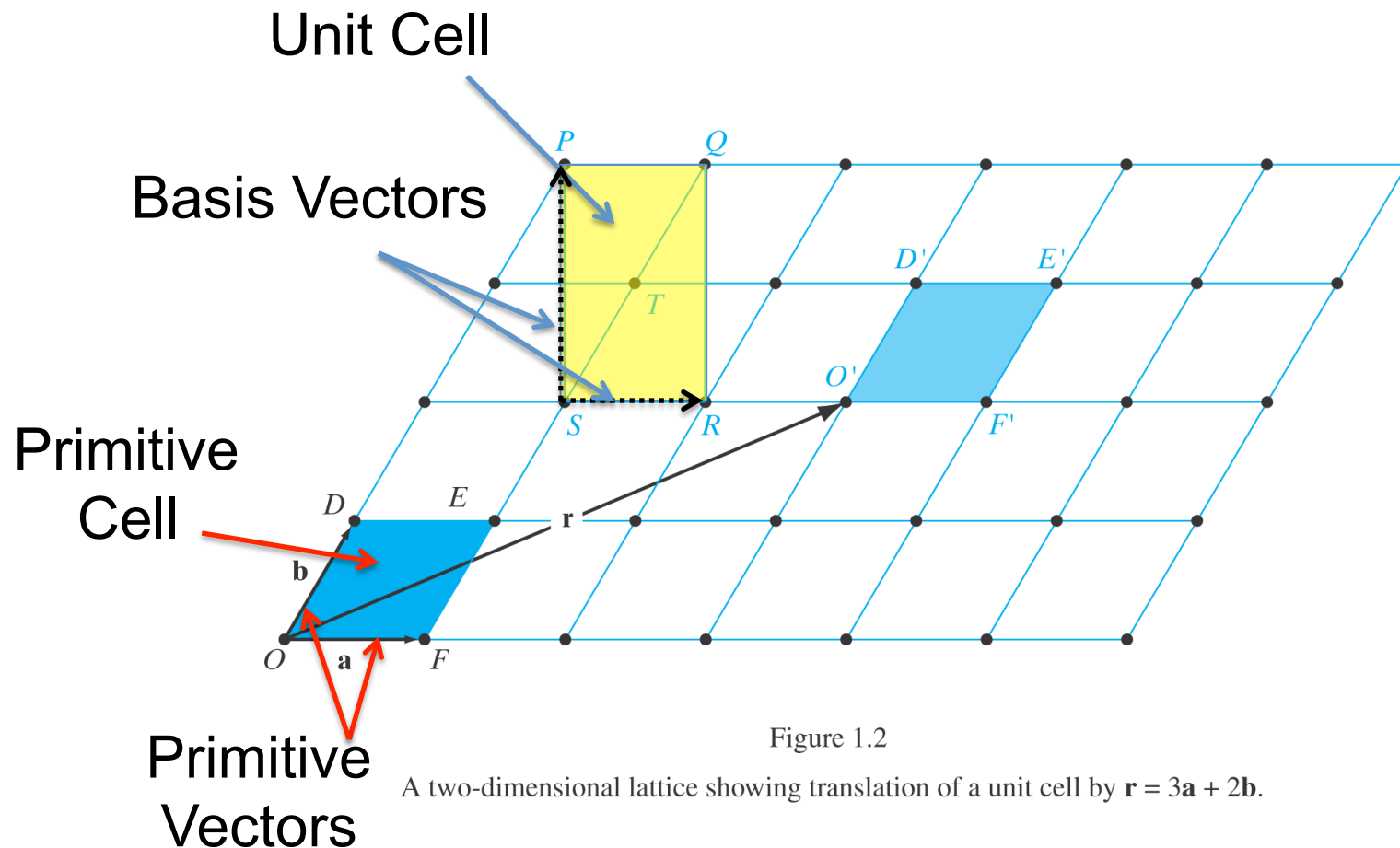
Figure 1.1

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).

Crystal Lattice

- **Lattice**: Periodic arrangement of a substance or “**basis**”
 - Atom, atomic pair, group of atoms, molecule, etc.
- **Unit Cell**: Contains a region which is representative of the lattice which can be regularly repeated to recreate the entire lattice
- **Primitive Cell**: The smallest unit cell that can be repeated in integral steps to produce the lattice
 - Contains a single lattice point
 - The Primitive Cell is a special form of the Unit Cell
- **Primitive Vectors: $\mathbf{a}$, $\mathbf{b}$, $\mathbf{c}$**
 - (1 dimension) $\mathbf{r} = p \mathbf{a}$
 - (2 dimension) $\mathbf{r} = p \mathbf{a} + q \mathbf{b}$
 - (3 dimension) $\mathbf{r} = p \mathbf{a} + q \mathbf{b} + r \mathbf{c}$
- **Basis Vectors**: Similar to primitive vectors, but used to replicate the lattice through the translation of a unit cell

Simple Lattices and Unit Cells



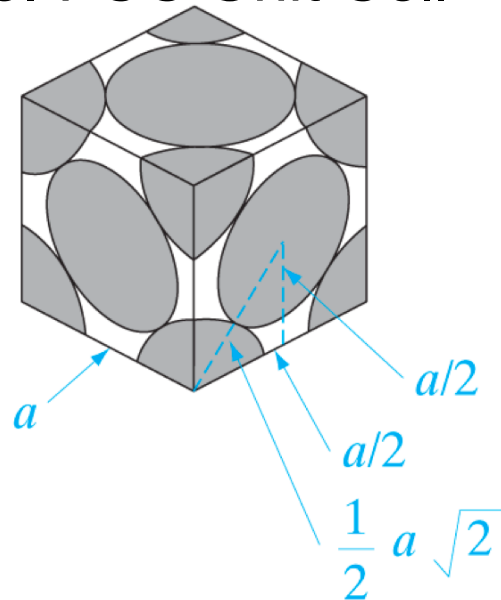
From *Solid State Electronic Devices*, Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X. © 2006 Pearson Education, Inc., Upper Saddle River, NJ. All rights reserved.

Other Important Definitions

- **Lattice Constant**: distance along the edge of a cubic unit cell (“a” in examples that follow)
 - More generally, the length of the basis vectors

NOTE: The lattice constant, in general, is **NOT** the distance between atoms (bond length).

i.e. FCC Unit Cell



Cubic Crystal Structures

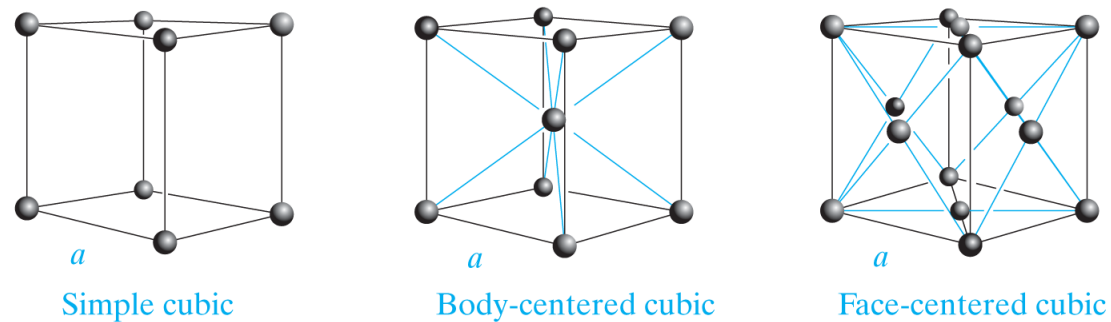


Figure 1.3

Unit cells for three types of cubic lattice structures.

FCC Lattice

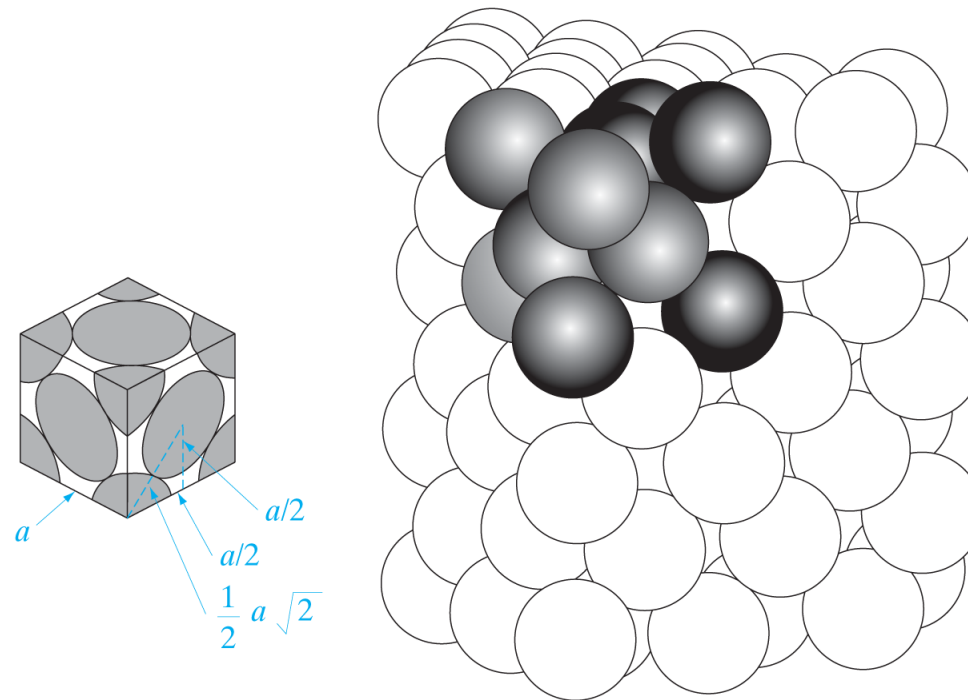


Figure 1.4

Packing of hard spheres in an fcc lattice.

Diamond Structure

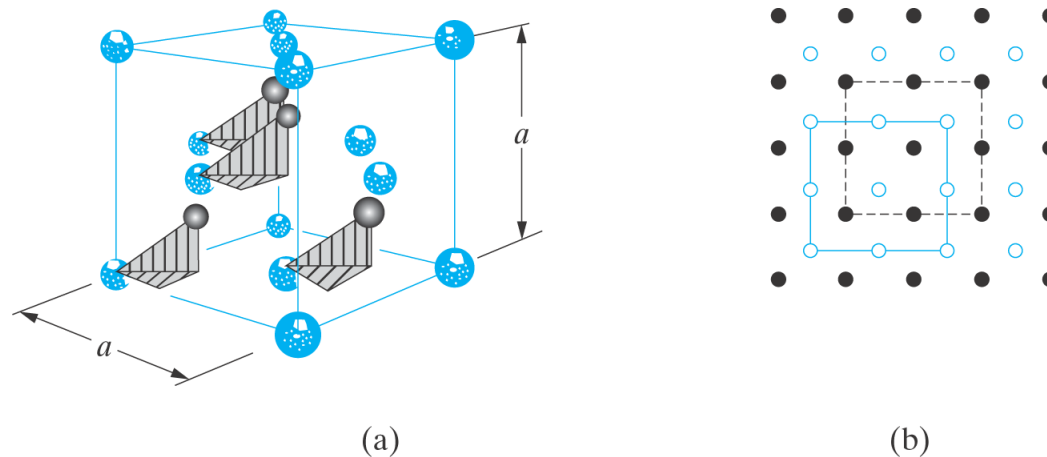


Figure 1.8

Diamond lattice structure: (a) a unit cell of the diamond lattice constructed by placing atoms $\frac{1}{4}, \frac{1}{4}, \frac{1}{4}$ from each atom in an fcc; (b) top view (along any $\langle 100 \rangle$ direction) of an extended diamond lattice. The colored circles indicate one fcc sublattice and the black circles indicate the interpenetrating fcc.

Diamond Structure Bonding

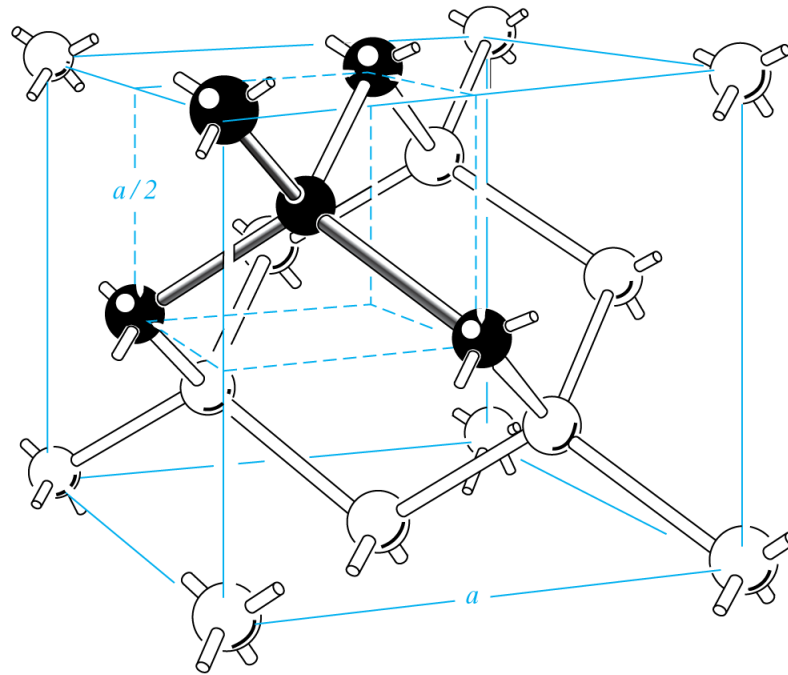


Figure 1.9

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.)

Diamond Structure Bonding

Diamond Unit Cell (not primitive cell)

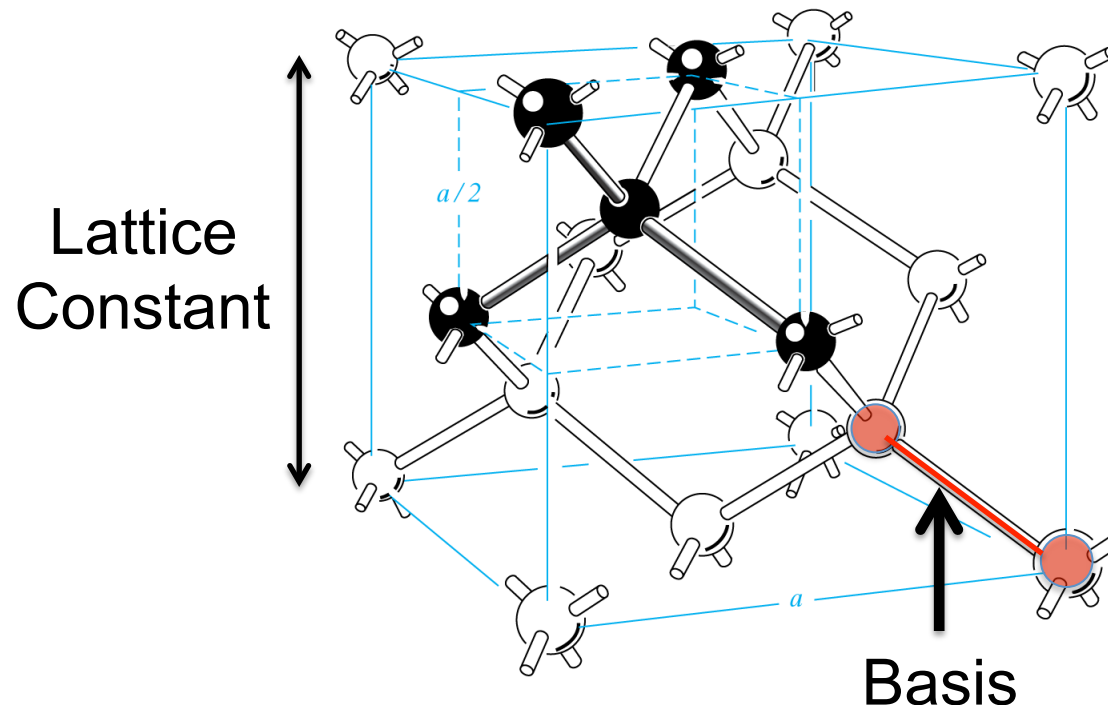


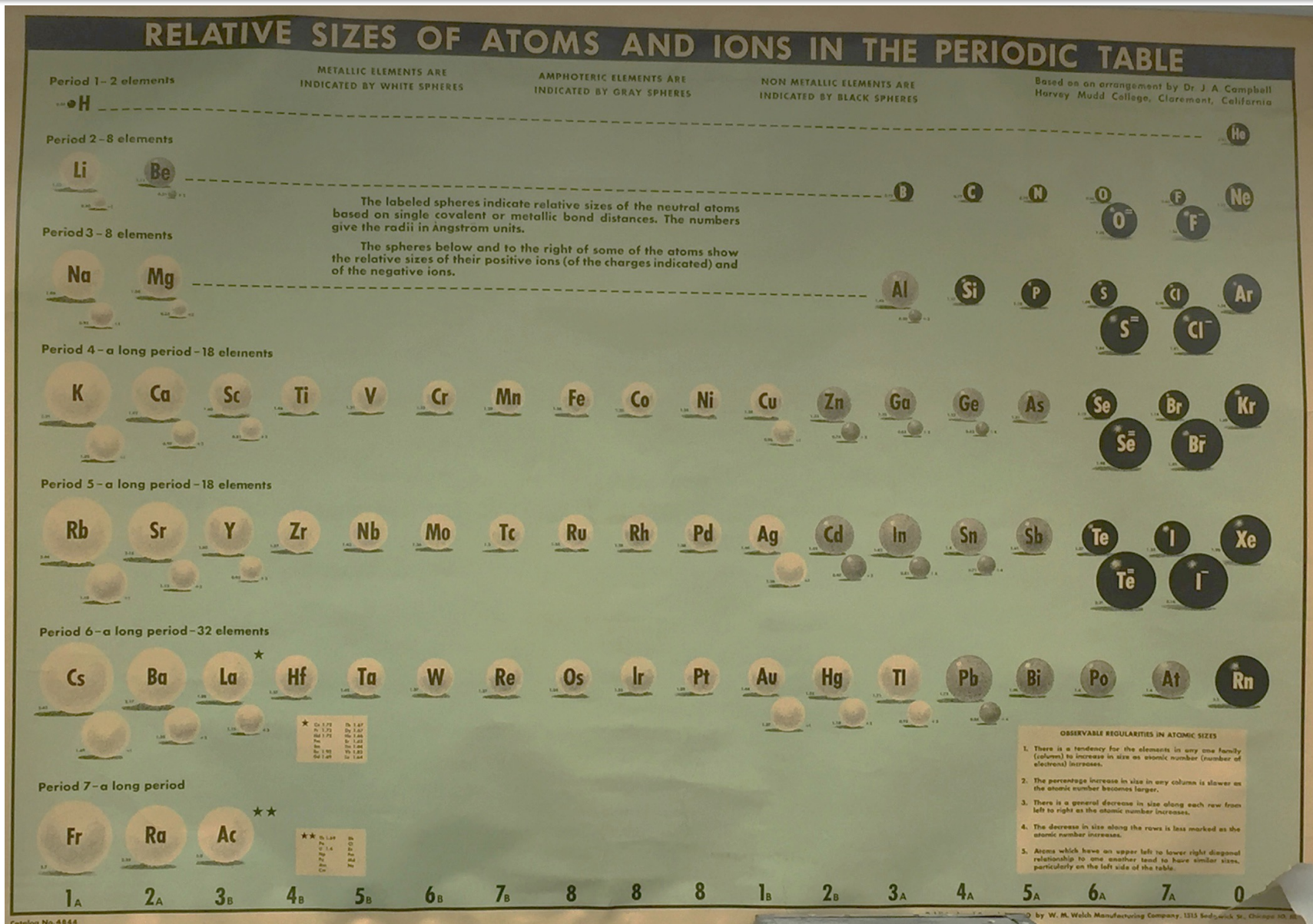
Figure 1.9

Diamond lattice unit cell, showing the four nearest neighbor structure.

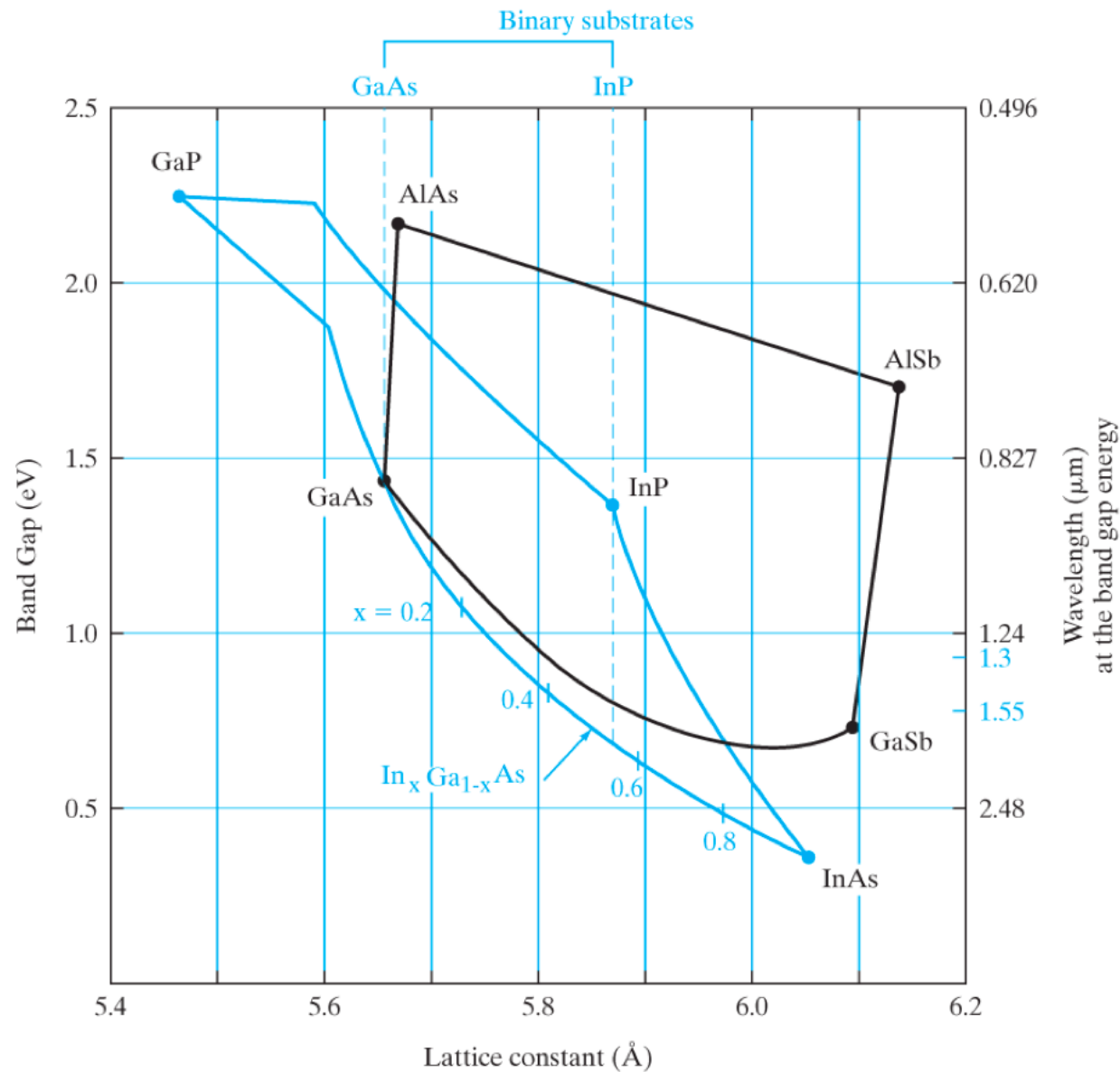
(From *Electrons and Holes in Semiconductors* by W. Shockley, © 1950 by Litton Educational Publishing Co., Inc.; by permission of Van Nostrand Reinhold Co., Inc.)

- The Diamond Structure is an FCC Lattice with a Basis of 2 atoms
- The Unit Cell has 4 Lattice Points, and 8 Atoms

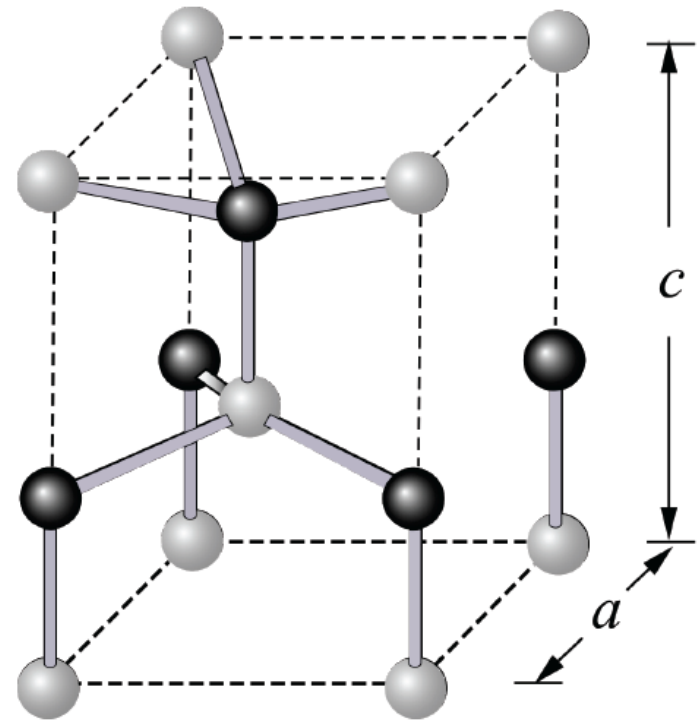
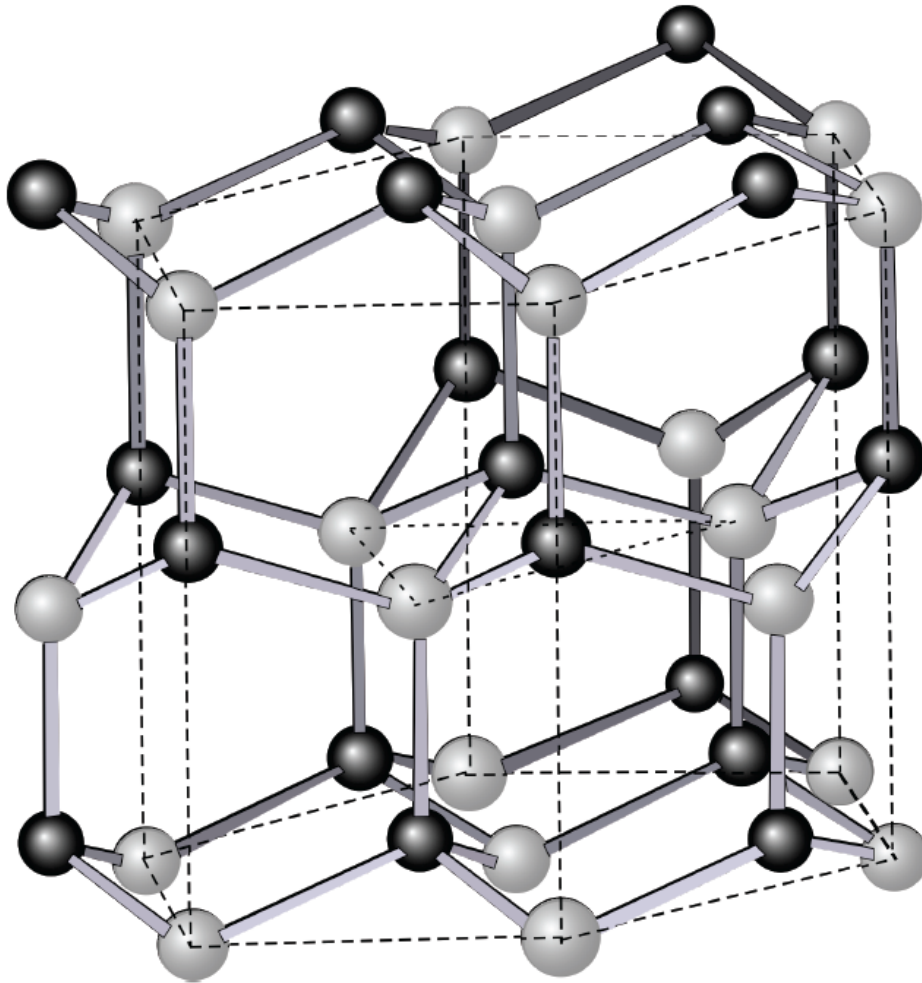
What Determines Lattice Spacing (~)



Important Material Systems



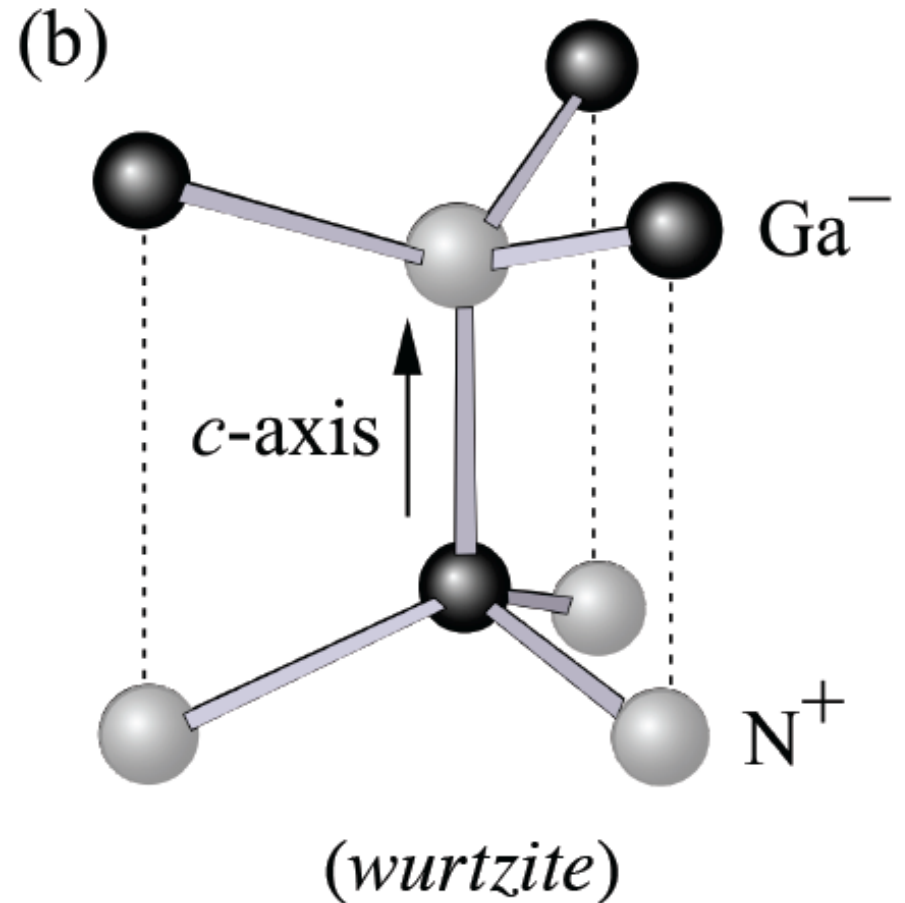
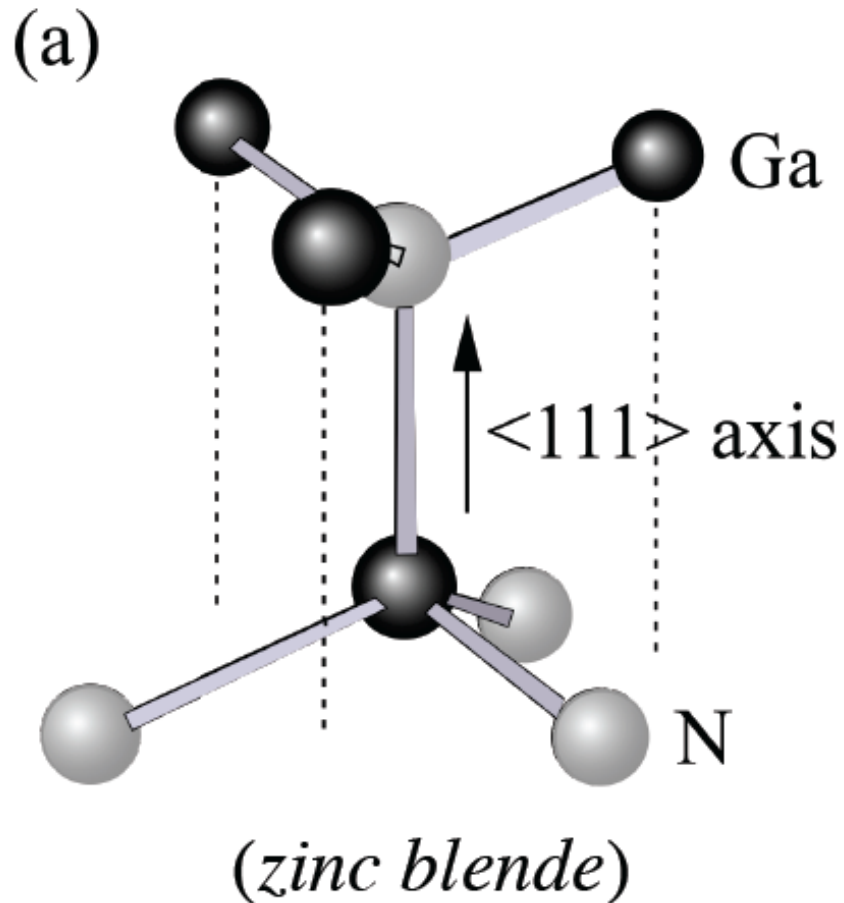
Wurtzite Structure



Unit cell of a Wurtzite structure

$$c = a\sqrt{8/3}$$

Zinc Blende Versus Wurtzite





Primitive Cells

BCC and FCC

Primitive Cell: BCC and FCC

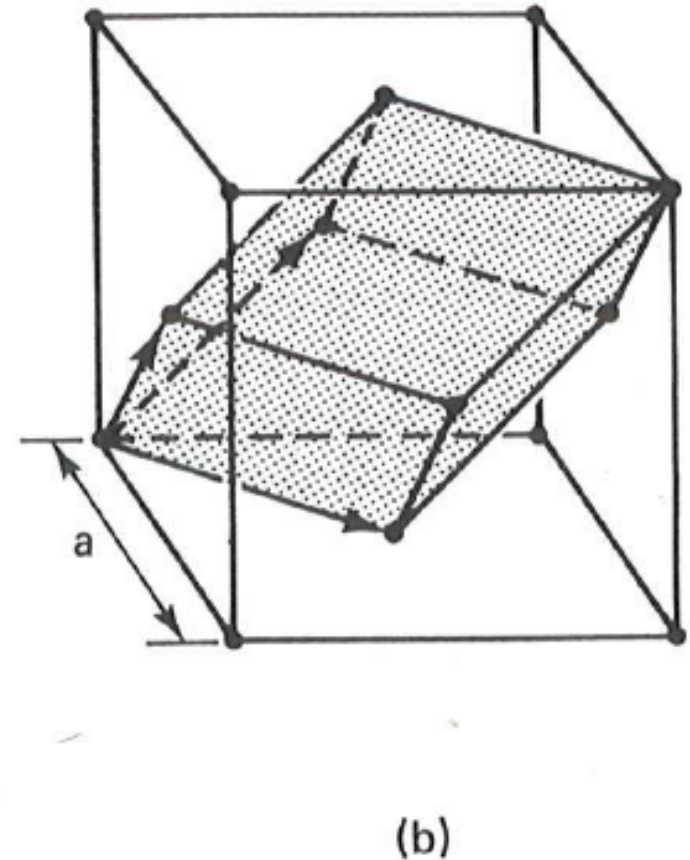
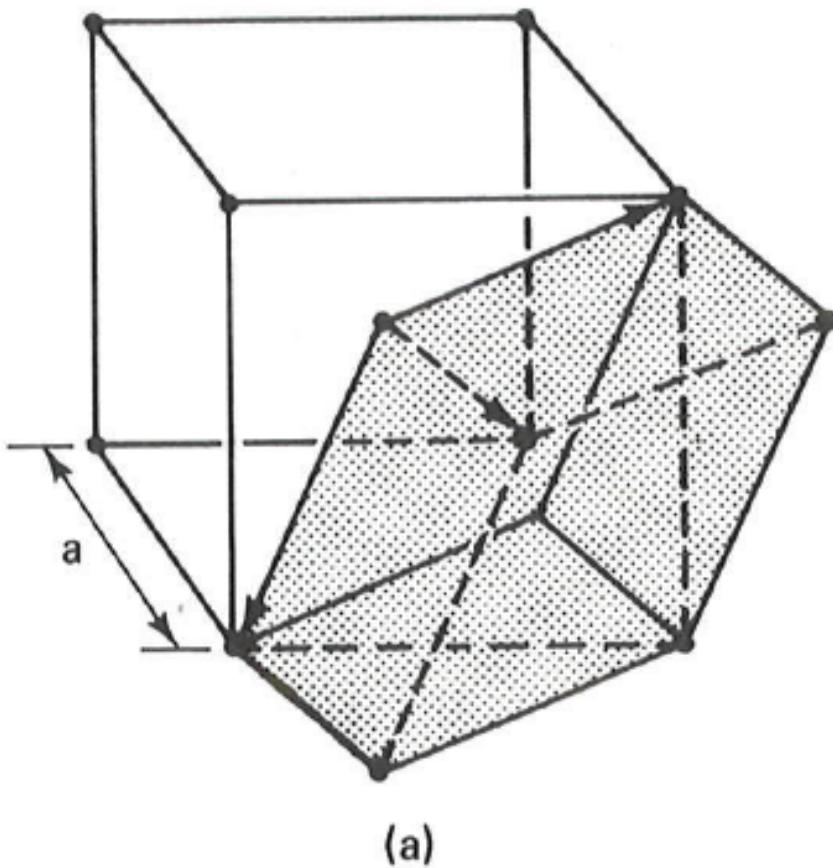


Figure 1.7 Cubic and primitive unit cells for (a) the body-centered and (b) the face-centered cubic Bravais lattices.

From: Wolfe, Holonyak, & Stillman, "Physical Properties of Semiconductors"

Wigner-Seitz Primitive Cell

- Draw a line from a given lattice point to all nearby lattice points
- Bisect the lines with orthogonal planes
- Construct the smallest polyhedron that contains the given lattice point



Assignments

Assignments

- Read info packet – key course policies and schedule are outlined here, including hourly exam dates
- Homework assigned every Friday, due following Friday
- Begin to read Chapter 1 of Streetman's book
 - Mon 1/22 Sections 1.1, 1.2, 1.3.1, 1.4
 - I suggest reading all of Chapter 1, but only the above sections are assigned
 - Wed 1/24: Review Streetman Chapter 2
 - Wed 1/24: §'s 3.1, 3.1.1, 3.1.2
 - Fri 1/26: §'s 3.1.3, 3.2.1 (HW1 Due)
 - Mon 1/29: §'s 3.2.3, 3.2.4
- Chapter 1&2 in Pierret covers similar material, and complements Streetman for another perspective



Topics for Next Lecture

Outline, 1/24/18

- Density Calculations
- Miller Indices
- Examples:
 - Determining Miller indices for various crystal planes
 - Density calculations
- Epitaxial Growth Technologies



Thank You for Listening!

Instructional Objectives (1)

By the time of exam No. 1 (after 17 lectures), the students should be able to do the following:

1. Outline the classification of solids as metals, semiconductors, and insulators and distinguish direct and indirect semiconductors.
2. Determine relative magnitudes of the effective mass of electrons and holes from an $E(k)$ diagram.
3. Calculate the carrier concentration in intrinsic semiconductors.
4. Apply the Fermi-Dirac distribution function to determine the occupation of electron and hole states in a semiconductor.
5. Calculate the electron and hole concentrations if the Fermi level is given; determine the Fermi level in a semiconductor if the carrier concentration is given.
6. Determine the variation of electron and hole mobility in a semiconductor with temperature, impurity concentration, and electrical field.
7. Apply the concept of compensation and space charge neutrality to calculate the electron and hole concentrations in compensated semiconductor samples.
8. Determine the current density and resistivity from given carrier densities and mobilities.
9. Calculate the recombination characteristics and excess carrier concentrations as a function of time for both low level and high level injection conditions in a semiconductor.
10. Use quasi-Fermi levels to calculate the non-equilibrium concentrations of electrons and holes in a semiconductor under uniform photoexcitation.
11. Calculate the drift and diffusion components of electron and hole currents.
12. Calculate the diffusion coefficients from given values of carrier mobility through the Einstein's relationship and determine the built-in field in a non-uniformly doped sample.

Instructional Objectives (2)

By the time of Exam No.2 (after 32 lectures), the students should be able to do all of the items listed under A, plus the following:

13. Calculate the contact potential of a p-n junction.
14. Estimate the actual carrier concentration in the depletion region of a p-n junction in equilibrium.
15. Calculate the maximum electrical field in a p-n junction in equilibrium.
16. Distinguish between the current conduction mechanisms in forward and reverse biased diodes.
17. Calculate the minority and majority carrier currents in a forward or reverse biased p-n junction diode.
18. Predict the breakdown voltage of a p+-n junction and distinguish whether it is due to avalanche breakdown or Zener tunneling.
19. Calculate the charge storage delay time in switching p-n junction diodes.
20. Calculate the capacitance of a reverse biased p-n junction diode.
21. Calculate the capacitance of a forward biased p-n junction diode.
22. Predict whether a metal-semiconductor contact will be a rectifying contact or an ohmic contact based on the metal work function and the semiconductor electron affinity and doping.
23. Calculate the electrical field and potential drop across the neutral regions of wide base, forward biased p+-n junction diode.
24. Calculate the voltage drop across the quasi-neutral base of a forward biased narrow base p+-n junction diode.
25. Calculate the excess carrier concentrations at the boundaries between the space-charge region and the neutral n- and p-type regions of a p-n junction for either forward or reverse bias.

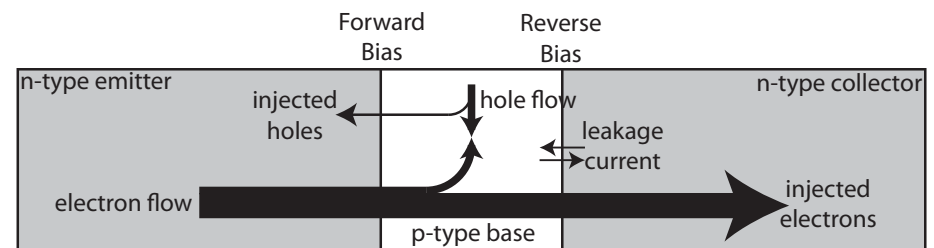
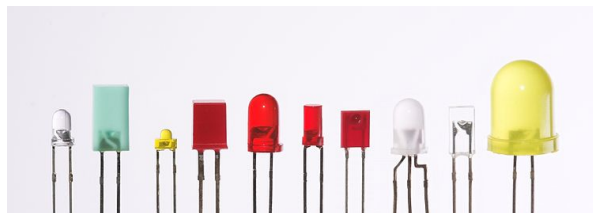
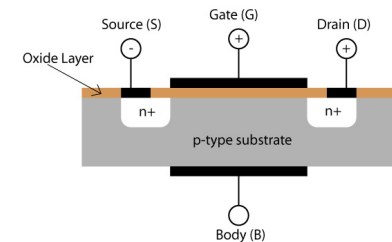
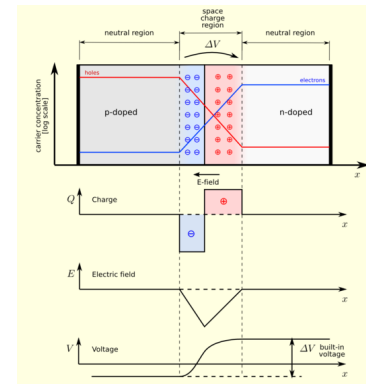
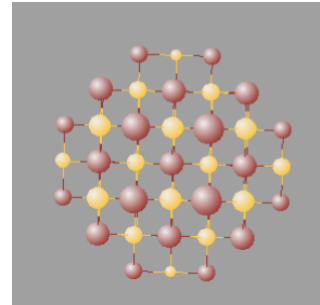
Instructional Objectives (3)

By the time of the Final Exam, after 44 class periods, the students should be able to do all of the items listed under A and B, plus the following:

26. Calculate the terminal parameters of a BJT in terms of the material properties and device structure.
27. Estimate the base transport factor “B” of a BJT and rank-order the internal currents which limit the gain of the transistor.
28. Determine the rank order of the electrical fields in the different regions of a BJT in forward active bias.
29. Calculate the threshold voltage of an ideal MOS capacitor.
30. Predict the C-V characteristics of an MOS capacitor.
31. Calculate the inversion charge in an MOS capacitor as a function of gate and drain bias voltage.
32. Estimate the drain current of an MOS transistor above threshold for low drain voltage.
33. Estimate the drain current of an MOS transistor at pinch-off.
34. Distinguish whether a MOSFET with a particular structure will operate as an enhancement or depletion mode device.
35. Determine the short-circuit current and open-circuit voltage for an illuminated p/n junction solar cell.

Course Purpose & Objectives

- Introduce key concepts in semiconductor materials
- Provide a basic understanding of p-n junctions
- Provide a basic understanding of light-emitting diodes and photodetectors
- Provide a basic understanding of field effect transistors
- Provide a basic understanding of bipolar junction transistors



Tentative Schedule [2]

FEB 19 Quasi-Fermi levels and photoconductive devices	FEB 21 Carrier diffusion	FEB 23 Built-in fields, diffusion and recombination
Feb 26 Review, discussion, problems (2/27 exam)	FEB 28 Steady state carrier injection, diffusion length	MAR 2 p-n junctions in equilibrium & contact potential
MAR 5 p-n junction Fermi levels and space charge	MAR 7 Continue p-n junction space charge	MAR 9 NO CLASS (EOH)
MAR 12 p-n junction current flow	MAR 14 Carrier injection and the diode equation	MAR 16 Minority and majority carrier currents
3/19-3/23 Spring Break MAR 26 Reverse-bias breakdown	MAR 28 Stored charge, diffusion and junction capacitance	MAR 30 Photodiodes, I-V under illumination

****Subject to Change****

Tentative Schedule [3]

APR 2 LEDs and Diode Lasers	APR 4 Metal-semiconductor junctions	APR 6 MIS-FETs: Basic operation, ideal MOS capacitor
APR 9 MOS capacitors: flatband & threshold voltage	APR 11 Review, discussion, problems (4/12 exam)	APR 13 MOS capacitors: C-V analysis
APR 16 MOSFETs: Output & transfer characteristics	APR 18 MOSFETs: small signal analysis, amps, inverters	APR 20 Narrow-base diode
APR 23 BJT fundamentals	APR 25 BJT specifics	APR 27 BJT normal mode operation
APR 30 BJT common emitter amplifier and current gain	MAY 2 (LAST LECTURE) Review, discussion, problem solving	FINAL EXAM **Date & time to be announced**

****Subject to Change****

Tentative Schedule [2]

FEB 19 Quasi-Fermi levels and photoconductive devices	FEB 21 Carrier diffusion	FEB 23 Built-in fields, diffusion and recombination
Feb 26 Review, discussion, problems (2/27 exam)	FEB 28 Steady state carrier injection, diffusion length	MAR 2 p-n junctions in equilibrium & contact potential
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3/19-3/23 Spring Break MAR 26 Reverse-bias breakdown	MAR 28 Stored charge, diffusion and junction capacitance	MAR 30 Photodiodes, I-V under illumination

****Subject to Change****



Schedule & Policies

Important Information

- Course Website:
 - <http://courses.engr.illinois.edu/ece340/>
- Download and Review Syllabus / Course Information from Website!
- Course Coordinator: Prof. John Dallesasse
 - jdallesa@illinois.edu
 - Coordinates schedule, policies, absence issues, homework, quizzes, exams, etc.
- Contact Information and Office Hours for All ECE340 Professors & TAs in Syllabus
- Lecture Slides: Click on “(Sec. X)” next to my name in instructor list
- DRES Students: Contact Prof. Dallesasse ASAP
- Textbook:
 - “Solid State Electronic Devices,” Streetman & Banerjee, 7th Edition
 - Supplemental: “Semiconductor Device Fundamentals,” Pierret
 - Additional reference texts listed in syllabus

Key Points

- Attend Class!
 - 3 unannounced quizzes, each worth 5% of your grade
 - **You must take the quiz in your section**
 - Excused absences must be **pre-arranged** with the course director
 - Absences for illness, etc. need a note from the Dean
 - See policy on absences in the syllabus
- No Late Homework
 - Homework due on the date of an excused absence must be turned in ahead of time
 - You must turn in homework in your section
 - No excused absences for homework assignments
 - Top 10 of 11 homework assignments used in calculation of course grade
 - Do all of them to best prepare for the exams!
- No Cheating
 - Penalties are severe and will be enforced
- Turn Off Your Phone
 - No video recording, audio recording, or photography

Homework

- Assigned Friday, Due Following Friday
 - Due dates shown in syllabus
- Due at Start of Class
- Follow Guidelines in Syllabus
- Peer Discussions Related to Homework are Acceptable and Encouraged
- Directly Copying Someone Else's Homework is Not Acceptable
 - Graders have been instructed to watch for evidence of plagiarism
 - Both parties will receive a “0” on the problem or assignment

Absences

- The absence policy in the syllabus will be strictly enforced
- To receive an excused absence (quiz), you must:
 - Pre-arrange the absence with the course director (valid reason and proof required)
 - Complete an Excused Absence Form at the Undergraduate College Office, Room 207 Engineering Hall (333-0050)
 - The form must be signed by a physician, medical official, or the Emergency Dean (Office of the Dean of Students)
 - The Dean's Office has recently put a strict policy in place (3 documented days of illness)
 - Excused quiz score will be prorated based upon average of completed scores
 - No excused absences are given for homework, but only the best 10 of 11 are used to calculate your final grade
 - Excused absences are not given for exams, except in accordance with the UIUC Student Code
 - Unexcused work will receive a "0"
- Failure to take the final will result in an "incomplete" grade (if excused) or a "0" (if unexcused)

Exams

- Exam I: Tuesday February 27th, 7:30-8:30 pm
- Exam II: Thursday April 12th, 7:30-8:30 pm
- Final Exam: Date/Time To Be Announced
 - Determined by University F&S

Grading

Grading Criterion

Homework	10 %
Quizzes	15 %
Hour Exam I	20 %
Hour Exam II	20 %
Final Exam	35 %
Total	100 %

Historical Grade Trends*

	Spring 2016	Fall 2016	Spring 2017
A's	27 %	28 %	27 %
B's	37 %	26 %	38 %
C's	27 %	25 %	27%
D's	6 %	16 %	4 %
F's	3 %	5 %	4 %

*Past performance is not necessarily
indicative of future results

My Recommendations

- Read the syllabus and information posted on the course website
- **Attend class** & participate
- Attend office hours (TA and Professors)
- **Read the book**
- Re-read the book
- Look at and read selected portions of the supplemental texts
- Form study groups to review concepts and discuss high-level approaches for solving homework problems
 - Don't form study groups to copy homework solutions
- **Don't miss any homework, quizzes, or exams**
 - It's hard to overcome a zero
- Ask questions in class!