EE415/515 Fundamentals of Semiconductor Devices Fall 2012

Lecture 1: Introduction, General Information, and Chapters 1 & 2

Today

- Introduction & motivation
  - Why study semiconductor devices?
  - General course information.
  - What's going on: (Semiconductor History)
- Chapter 1: Crystal Lattices and Growth
- Chapter 2: Quantum Mechanics
  - Both revision of PH 319 (pre-requisite with ECE 322)

You should take this course if you…

- are interested in semiconductor devices (duh..)
- would like a career in fab processing, device physics, device design or integration as an option.
- would like to be an IC designer who understands devices and can communicate with fab personnel.
- would like to be an IC designer who can understand the limitations of real devices and take advantage of real device performance.
- would like to be an electronics/systems/anything designer who needs to understand real world devices in real world applications.
- like physics
- are interested in modeling (abstraction)

You should still take this course if you …

- hate physics, (even if you want a dual degree)
- feel like you never really understood solid state after taking previous courses.
- have always found physics and math courses extremely difficult.

… but recognize that it may be harder for you than for others, and that you may need to work harder for it

Why work in semiconductors?

- Part of leading edge technology
- Industry that is *always* new, interesting and challenging
- Try your hand at doing the “impossible”
- Growth and high rate of change can lead to opportunities for high responsibility positions early in your career
- Meritocracies: pay and advancement are driven by your performance
- Access to great resources
- Did I mention fun ☺ ?

Semiconductor jobs

- Designers: Chip architects, circuit designers, mask designers
- Fab/Sort Engineers: process, integration, device, equipment, test
- Assembly/Test
- Automation is everywhere
- System level engineering
- Other support: materials, equipment, environmental, fab design, analytical labs, …
- Technical liaisons to customers.

Why Study Device Physics?

- Essential to understand theory *thoroughly* to be an integration, device, or reliability engineer.
- Essential to understand device operation (output) to be a good designer.
- Extremely valuable for all other jobs, especially in technology development.

Course information

- Tuesday, Thursday 12:00-1:50pm
- James E. Morris
  - Office FAB 160-13
  - Office hours Tues 9–10am, Thur 4–5pm, or by appointment.
  - Email: jmorris@cecs.pdx.edu
- Required textbook: Donald A. Neaman. *Semiconductor Physics & Devices*, McGraw-Hill, **Fourth** Edition
- See syllabus for reference books.
  - Especially: Streetman & Bannerjee (previous text), Dimitrijev, Modular Series, .
  - See on-line textbook: http://ecee.colorado.edu/~bart/book/start.htm
- Course information at www.ece.pdx.edu/~jmorris
  - Lecture slides (download or print out before the lecture)
  - Assignments will be at the end of the lecture before due date
  - Model answers (for one week until next posting)

Topics Covered

- Intrinsic/extrinsic Semiconductors
- Energy Bands
- Carrier Transport
- P-N Junctions
- MOS Capacitor
- MOS Field Effect Transistors (MOSFET)
- Bipolar Junction Transistors
- LEDs, solar cells
- PNPN and other power devices

Grading

Undergraduates

20% Homework (10 assignments, 1% per lecture +3% bonus)
20% TWO "on-line lab" device characterization projects
30% Mid-term exam (covering lectures 1-9/chapters 1-9)
30% Final exam (covering lectures 10-18/chaps 10-12, 14 & 15)

Graduate students

20% Homework (10 assignments, 1% per lecture, +3% bonus)
20% TWO "on-line lab" device characterization projects
25% Mid-term exam (covering lectures 1-9)
25% Final exam (covering lectures 10-18)
10% Literature review: written report and presentation

ALL grading components must be completed as "satisfactory," but LATE satisfactory submissions will still earn zero grades.

ANY academic dishonesty will make the submission "unsatisfactory."

Note: This includes the unauthorized use of model answers!

Homework due dates: See schedule
Hard copies to be turned in at the START of class

- See on line for assignments (in lecture notes.)
- Most assignments cover two classes (~4 problems/lecture)
- Solutions posted on-line immediately after homework due, so no late homework can be accepted.
  - Note also "deadlines"
- Some collaboration is acceptable.
  - You can give or receive suggestions.
  - You can check each other's work.
  - This does not mean copying work. You must turn in your own work that you have completed and understood. You may not copy line for line. Work together to figure out HOW TO DO IT, but then actually DO IT YOURSELF ALONE.
  - Any indications of cheating will result in a "unsatisfactory" and potential course failure, and will be reported.
  - See http://www.pdx.edu/dos/codeofconduct and ECE policy
- Classroom etiquette: No talking/texting, turn off cell phones

Projects

- Two projects: characterizing real PN diodes and MOSFETs using the MIT Microelectronics WebLab over the internet.
  - Weblab can be accessed at http://ilab.mit.edu
  - Manual can be found in ilab
  - Projects are not due for a few weeks, about one week after the last topic lecture
  - Nevertheless, request an account soon and test that it works on the computer of interest.

Course outcomes

Ability to:

1. Understand and analyze performance of intrinsic and extrinsic semiconductors
2. Understand and analyze operation of p-n junction
3. Understand and analyze performance of MOS capacitor, FET and MOS transistor
4. Model semiconductor devices and to examine accuracy and limits of models
5. Trade-off device design parameters based on understanding of device operation and design goals
6. Understand and analyze bipolar transistors for dc and ac operation
7. Understand and analyze performance of MOS devices fabricated in sub-micron technology
8. Understand and analyze performance of selected optoelectronic and power devices
9. Write succinct, accurate and complete technical reports

Course outcomes (graduate)

Ability to:

1. Understand and analyze performance of intrinsic and extrinsic semiconductors
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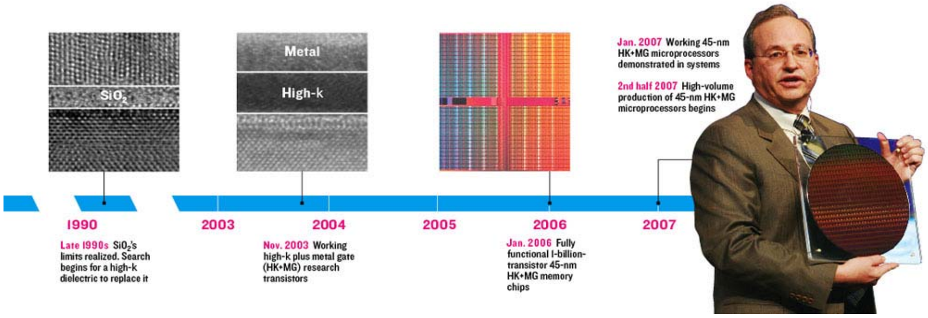
6. Understand and analyze bipolar transistors for dc and ac operation
7. Understand and analyze performance of MOS devices fabricated in sub-micron technology
8. Write succinct, accurate and complete technical reports
9. Understand and analyze performance of selected optoelectronic and power devices
10. Ability to compare pros and cons of various devices in different applications and present the findings in a short, informative way

Some history …



Late 1990s SiO$_2$'s limits realized. Search begins for a high-k dielectric to replace it

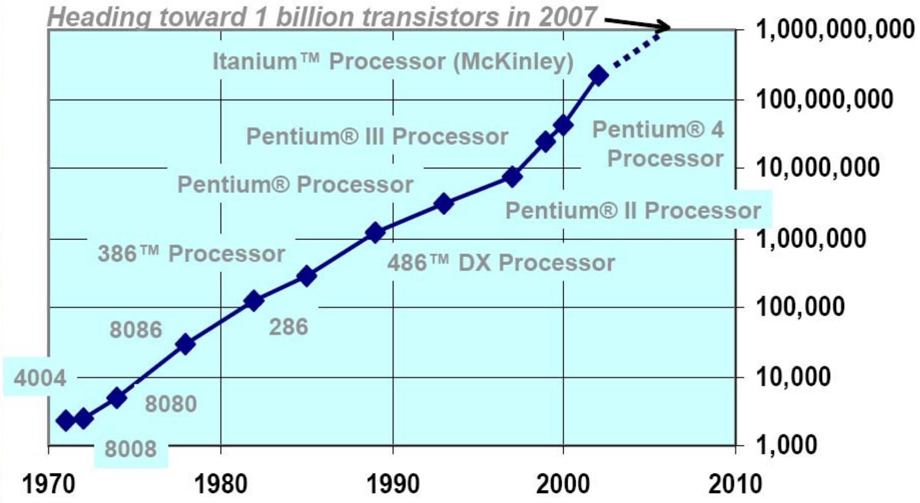
Nov. 2003 Working high-k plus metal gate (HK+MG) research transistors

Jan. 2006 Fully functional 1-billion-transistor 45-nm HK+MG memory chips

Jan. 2007 Working 45-nm HK+MG microprocessors demonstrated in systems

2nd half 2007 High-volume production of 45-nm HK+MG microprocessors begins

Moore's Law Continues



From 90nm SRAM Press Briefing

This chip contains 330 million transistors

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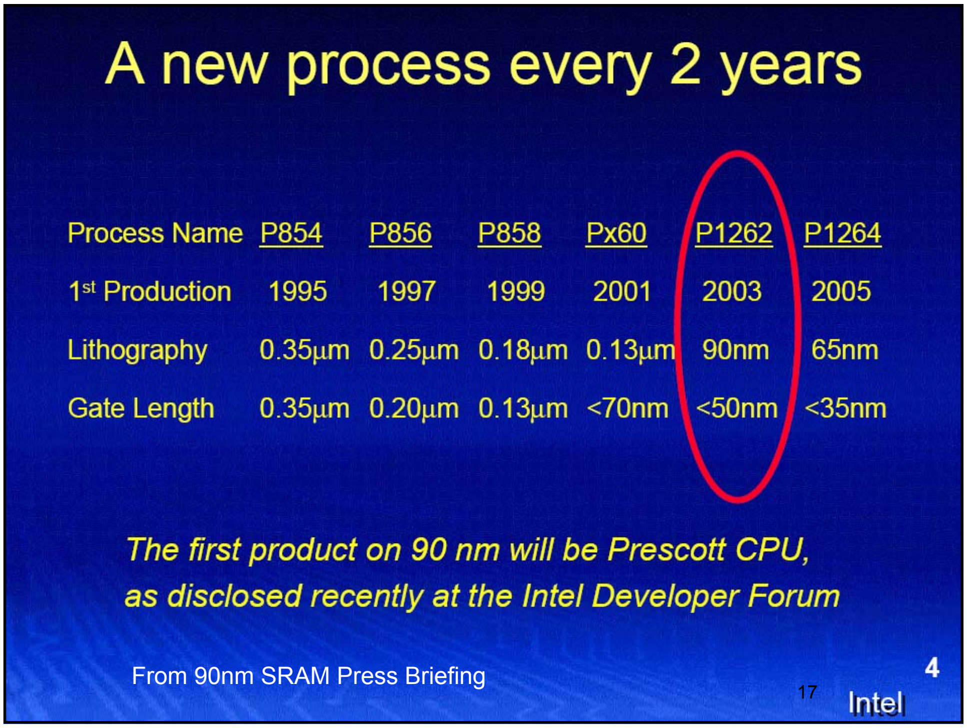
Intel

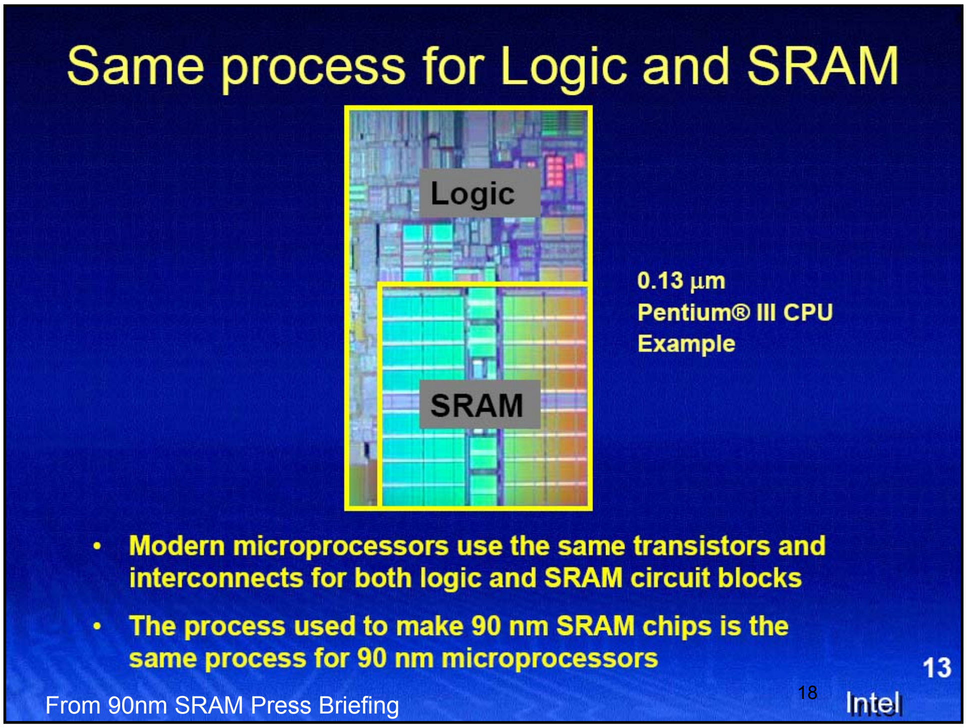


A new process every 2 years

Process Name	P854	P856	P858	Px60	P1262	P1264
1st Production	1995	1997	1999	2001	2003	2005
Lithography	0.35µm	0.25µm	0.18µm	0.13µm	90nm	65nm
Gate Length	0.35µm	0.20µm	0.13µm	<70nm	<50nm	<35nm

The first product on 90 nm will be Prescott CPU, as disclosed recently at the Intel Developer Forum

From 90nm SRAM Press Briefing



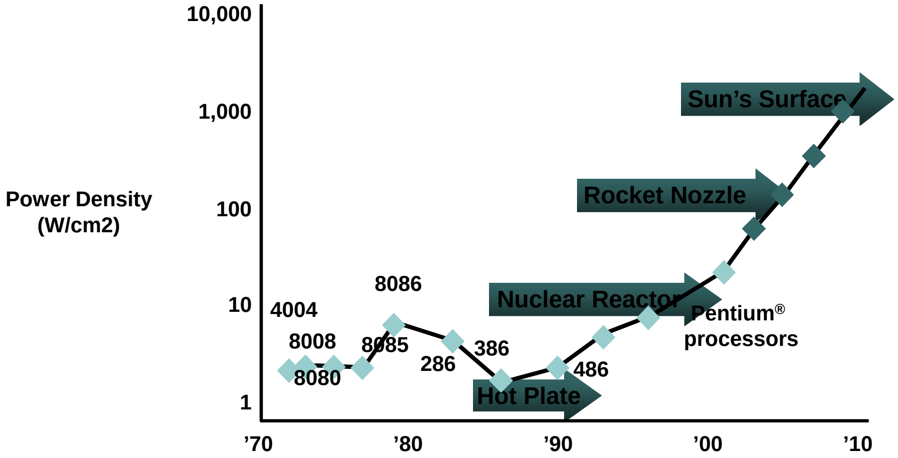
Same process for Logic and SRAM

**0.13 µm
Pentium® III CPU
Example**

- **Modern microprocessors use the same transistors and interconnects for both logic and SRAM circuit blocks**
- **The process used to make 90 nm SRAM chips is the same process for 90 nm microprocessors**

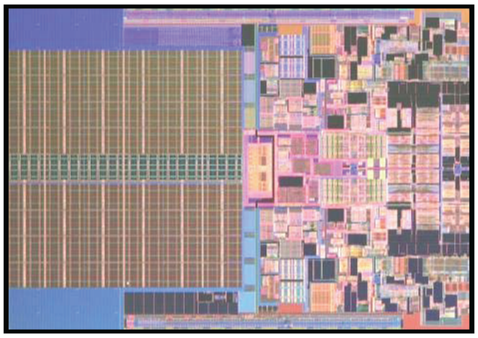
From 90nm SRAM Press Briefing

Power Density Extrapolation



- Can't continue business as usual
- What have you noticed about recent microprocessors?
- Note: Scaling has been great for digital circuits but for analog ???

Penryn Die Photo



45 nm next generation Intel® Core™2 family processor

410 million transistors for dual core, 820 million for quad core

World's first working 45 nm CPU

Intel's Logic Technology Evolution

Process Name:	P1262	P1264	P1266	P1268	P1270
Lithography:	90 nm	65 nm	45 nm	32 nm	22 nm
1st Production:	2003	2005	2007	2009	2011

Moore's Law continues!

Intel continues to develop a new technology generation every 2 years

Semiconductors

Table 1.1 | A portion of the periodic table

III	IV	V
5 **B** Boron	6 **C** Carbon	
13 **Al** Aluminum	14 **Si** Silicon	15 **P** Phosphorus
31 **Ga** Gallium	32 **Ge** Germanium	33 **As** Arsenic
49 **In** Indium		51 **Sb** Antimony

Table 1.2 | A list of some semiconductor materials

Elemental semiconductors	
Si	Silicon
Ge	Germanium
Compound semiconductors	
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
GaP	Gallium phosphide
GaAs	Gallium arsenide
InP	Indium phosphide

Structure of Solids

- Some solids are *amorphous* with no periodic structure. Atoms or molecules are randomly oriented.
- Crystalline solids are *periodic.*
  - Atoms or molecules are arranged in an orderly and repeating fashion.
  - They have definite shapes with clearly defined faces.
- Polycrystalline solids have small regions of crystalline material.

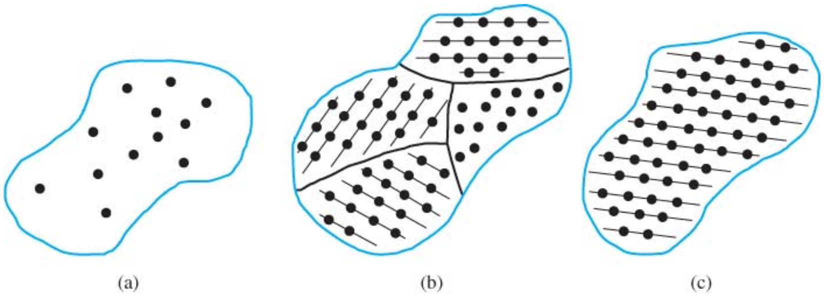


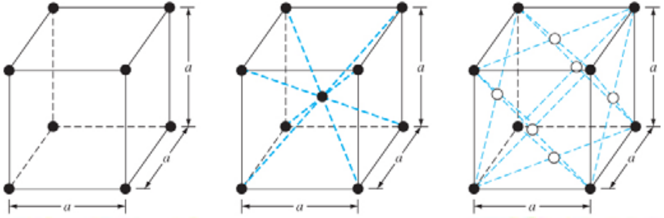
Figure 1.1 | Schematics of three general types of crystals: (a) amorphous, (b) polycrystalline, (c) single.

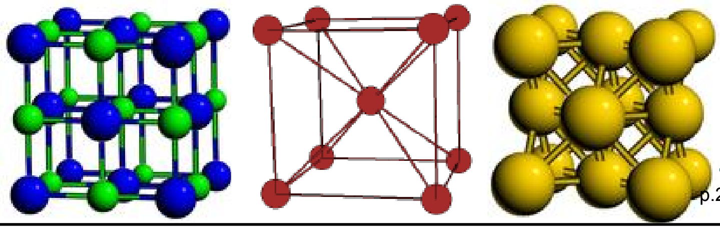
Lattice Types

Simple cubic (sc): atom at each corner of cube.
(NaCl, AgCl, NaF)

Body-centered cubic (bcc): additional atom at center. (Na, K, Fe)

Face-centered cubic (fcc): additional atom in the center of each face. (Cu, Al, Ni, Au)





Unit cells

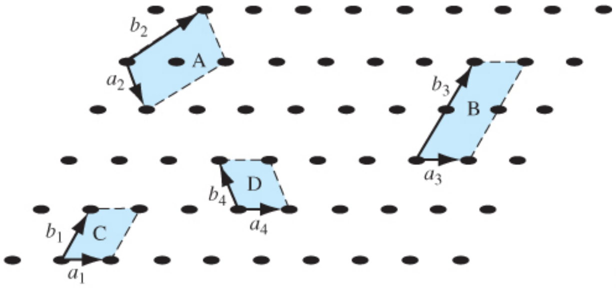


Figure 1.3 | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

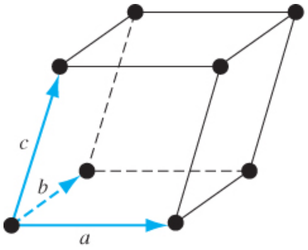


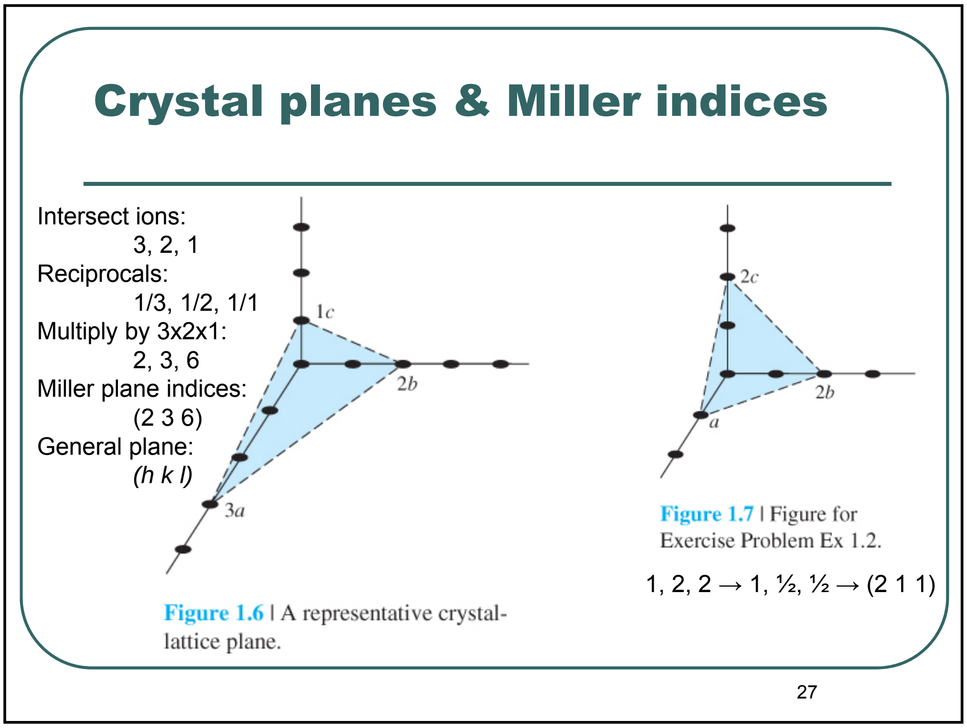
Figure 1.4 | A generalized primitive unit cell.

Crystalline Structure

- A *unit cell* can represent the entire lattice.
- When shifted by an integral number of basis vectors **a, b, c** a new cell is found identical to the original.

  i.e. points indistinguishable when shifted by

  r= p**a**+q**b**+s**c,** where p,q,s are integers.
- The arrangement dictates the properties of the material, including electrical properties



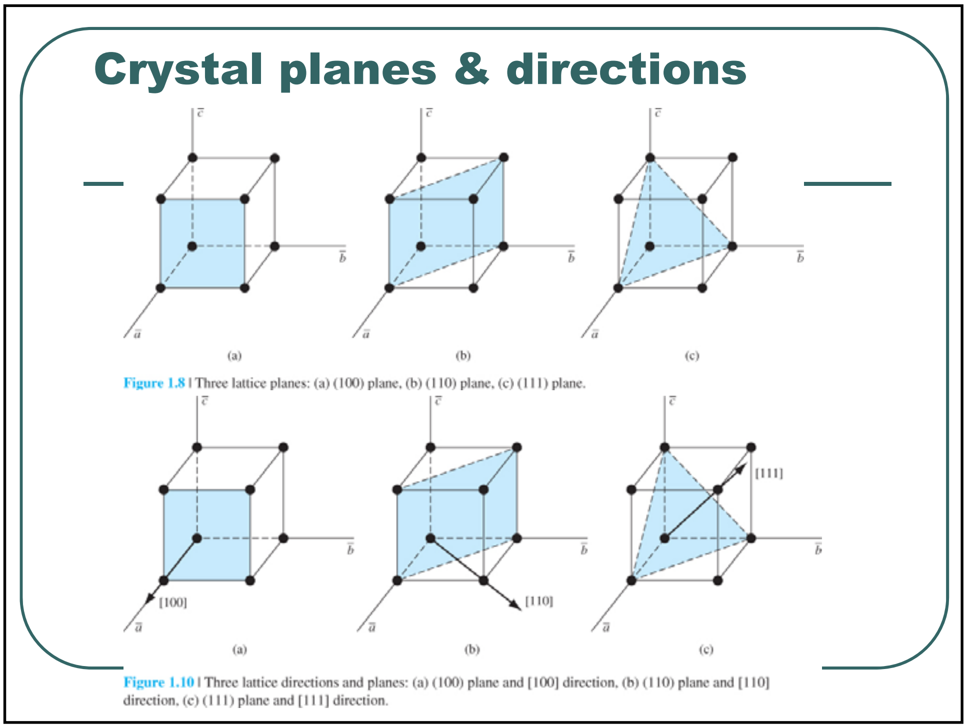
Crystal planes & Miller indices

Intersect ions:
3, 2, 1
Reciprocals:
1/3, 1/2, 1/1
Multiply by 3x2x1:
2, 3, 6
Miller plane indices:
(2 3 6)
General plane:
(h k l)

Figure 1.6 | A representative crystal-lattice plane.

Figure 1.7 | Figure for Exercise Problem Ex 1.2.

1, 2, 2 → 1, ½, ½ → (2 1 1)



Crystal planes & directions

Figure 1.8 | Three lattice planes: (a) (100) plane, (b) (110) plane, (c) (111) plane.

Figure 1.10 | Three lattice directions and planes: (a) (100) plane and [100] direction, (b) (110) plane and [110] direction, (c) (111) plane and [111] direction.

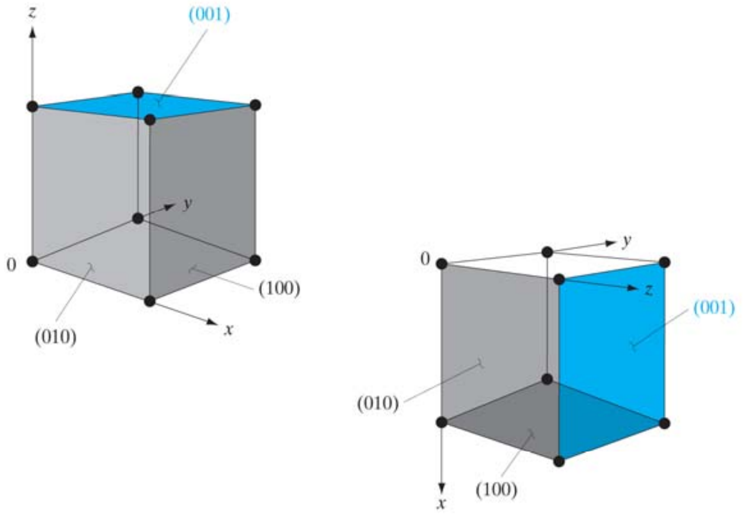


Figure 1.6

Equivalence of the cube faces ({100} planes) by rotation of the unit cell within the cubic lattice.

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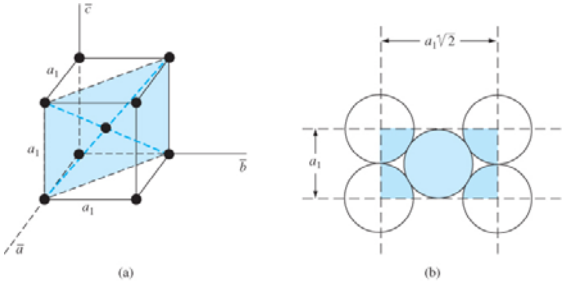
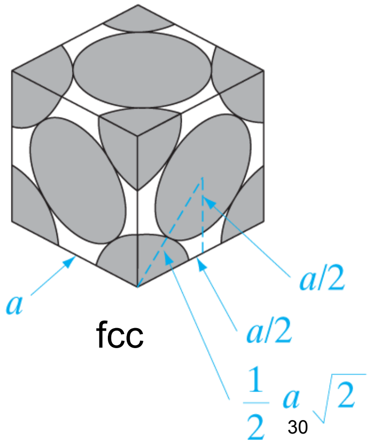


Figure 1.9 | (a) The (110) plane in a body-centered cubic and (b) the atoms cut by the (110) plane in a body-centered cubic.



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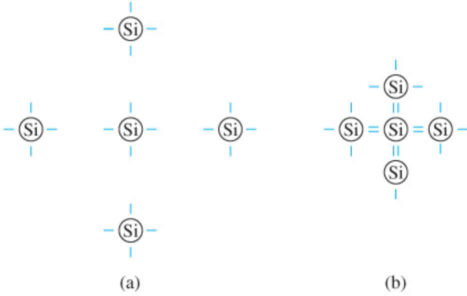
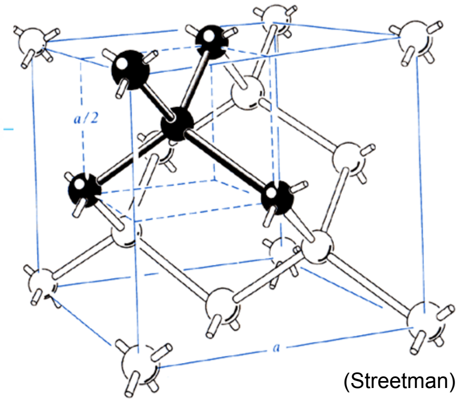
Diamond Lattice (Silicon, Germanium, and Carbon sp^3)



(a)

(b)

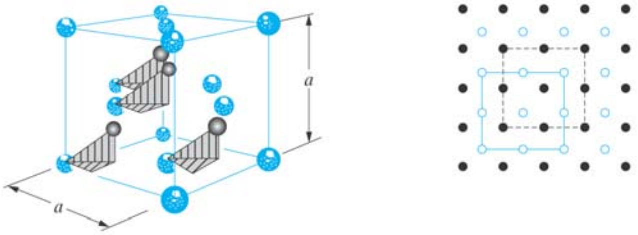
Figure 1.17 | Representation of (a) silicon valence electrons and (b) covalent bonding in the silicon crystal.



(Streetman)

Diamond lattice: fcc with an extra atom placed at **a**/4+**b**/4+**c**/4 from each atom

Can also be thought of as two interpenetrating fcc sublattices



(a)

(b)

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 ⟨100⟩ direction) of an extended diamond lattice. The colored circles indicate one fcc sublattice and the black circles indicate the interpenetrating fcc.

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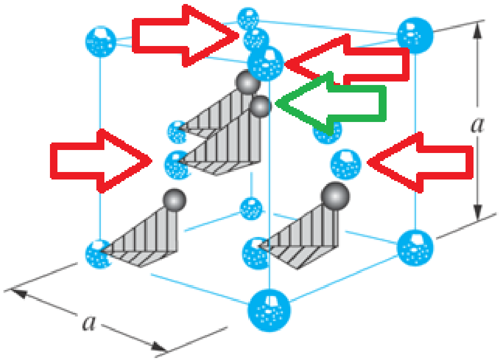
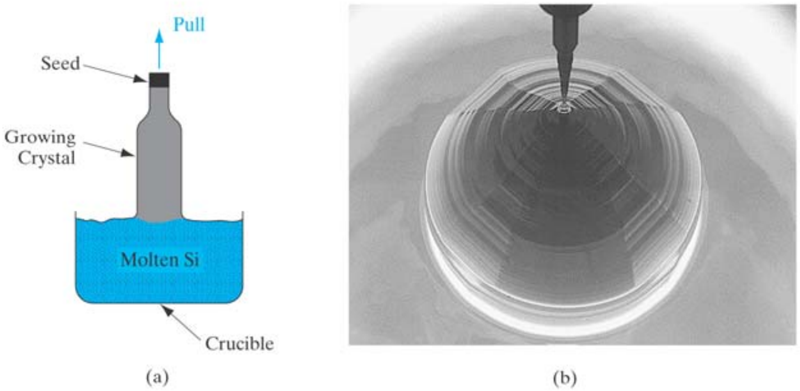
Tetragonal “diamond” structure: 4 atoms from original fcc cell + 1





(a) (b)

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.)

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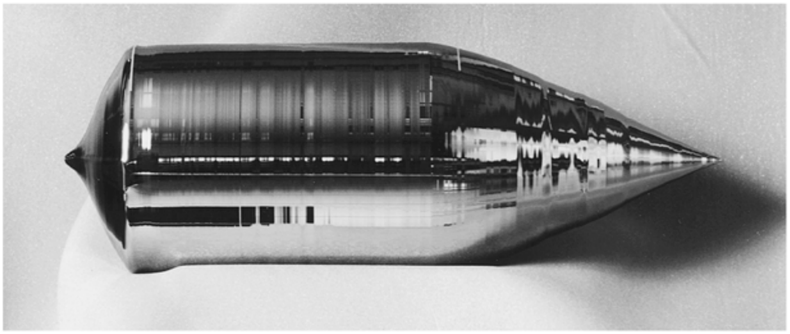

Figure 1.11

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 1.0 m long (including the tapered regions), and weighs about 140 kg. (Photograph courtesy of MEMC Electronics Intl.)

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Crystal defects

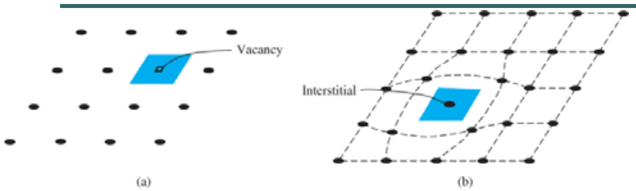


Figure 1.18 | Two-dimensional representation of a single-crystal lattice showing (a) a vacancy defect and (b) an interstitial defect.

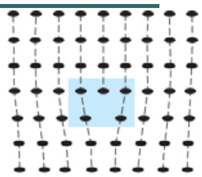


Figure 1.19 | A two-dimensional representation of a line dislocation.

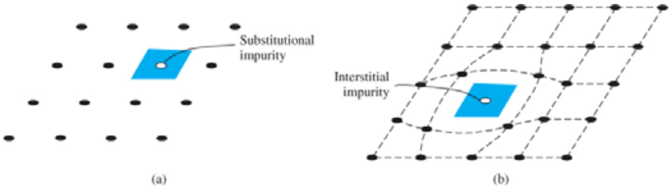
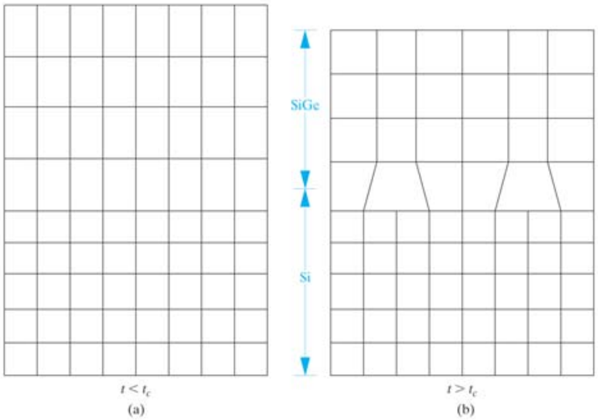


Figure 1.20 | Two-dimensional representation of a single-crystal lattice showing (a) a substitutional impurity and (b) an intersitital impurity.



$t < t_c$
(a)

$t > t_c$
(b)

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.

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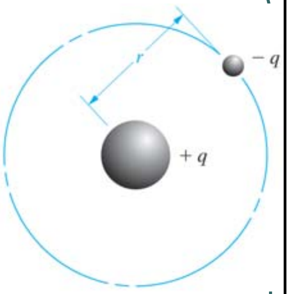
Single atom energy levels



$$-\frac{q^2}{4\pi\varepsilon r^2} = -\frac{mv^2}{r} \;\&\; p_\theta = mvr = n\hbar = n\frac{h}{2\pi}$$

$$E_n = \frac{mq^4}{2(4\pi\varepsilon)^2\hbar^2}\cdot\frac{1}{n^2}$$

- Electrons in an atom have certain allowed energies: $E_n = -\frac{Z^2 m_o q^4}{8\varepsilon_0{}^2 h^2 n^2}$
- At low temperatures the electrons fill the allowed levels starting with the lowest energies.
- Gaps exist between levels.
- Pauli exclusion ➔ at most two electrons of opposite spin may occupy any energy level.

Photoelectric effect

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{c}{\nu}$$

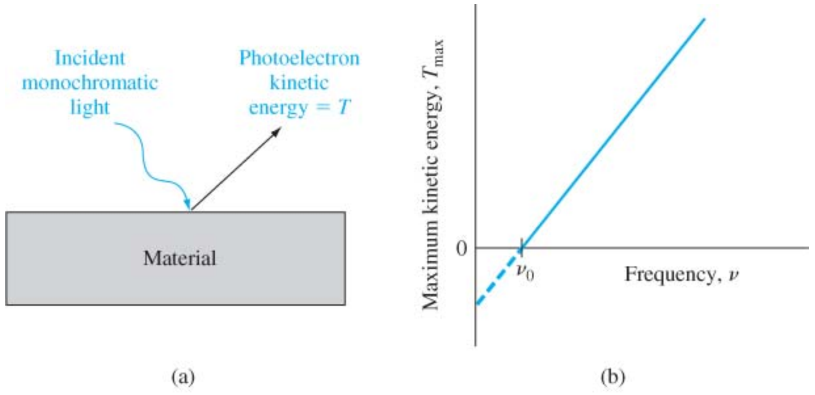
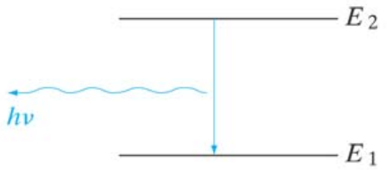


Figure 2.1 | (a) The photoelectric effect and (b) the maximum kinetic energy of the photoelectron as a function of incident frequency.

Optical emission: $h\vartheta = E_2 - E_1$



Lyman: $i = 1$,
Balmer: $i = 2$,
Paschen: $i = 3$,
Brackett: $i = 4$

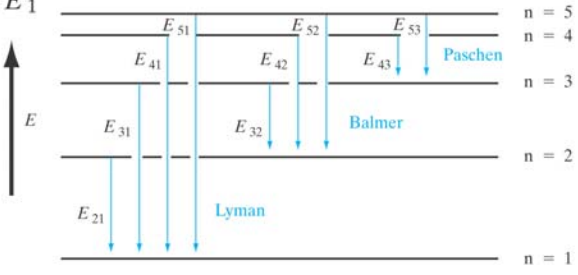


Figure 2.3

Relationships among photon energies in the hydrogen spectrum.

$$\nu_{ij} = cR\left[\frac{1}{i^2} - \frac{1}{j^2}\right] \text{where } j = i+1, i+2, ...$$

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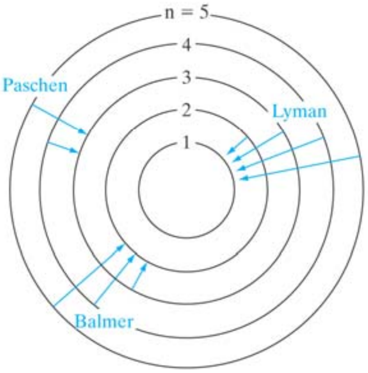

Figure 2.4

Electron orbits and transitions in the Bohr model of the hydrogen atom. Orbit spacing is not drawn to scale.

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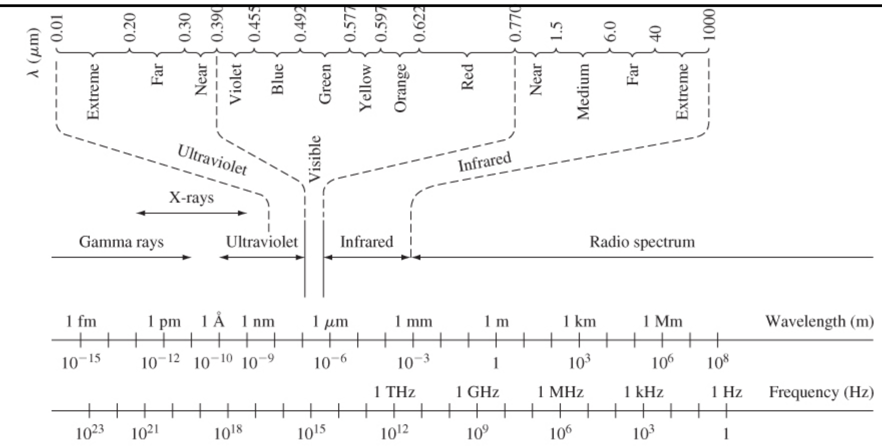
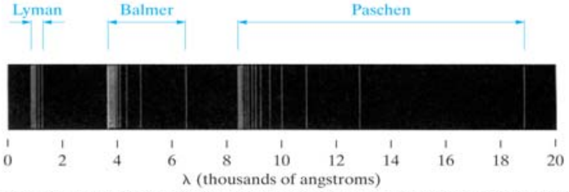


Figure 2.4 | The electromagnetic frequency spectrum.



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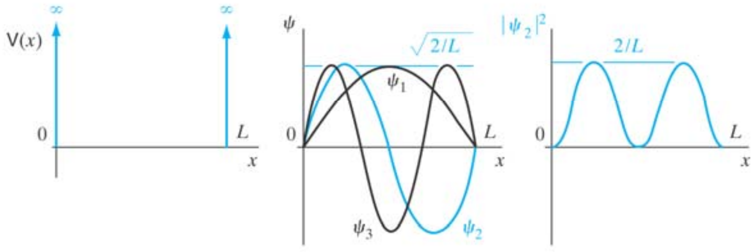
Schroedinger & Potential well
→ Wave function & probability solutions



(a) (b) (c)

Figure 2.5

The problem of a particle in a potential well: (a) potential energy diagram; (b) wave functions in the first three quantum states; (c) probability density distribution for the second state.

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$r \rightarrow n$
$\Phi \rightarrow m$
$\Theta \rightarrow \ell$
+ spin

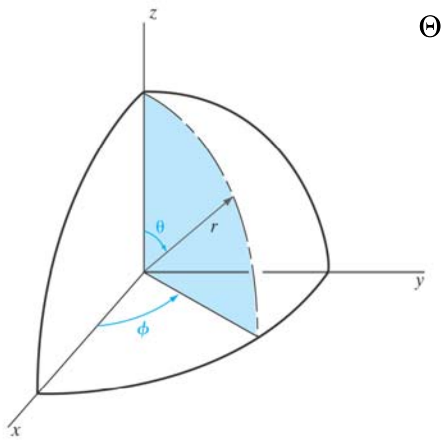

Figure 2.7

The spherical coordinate system.

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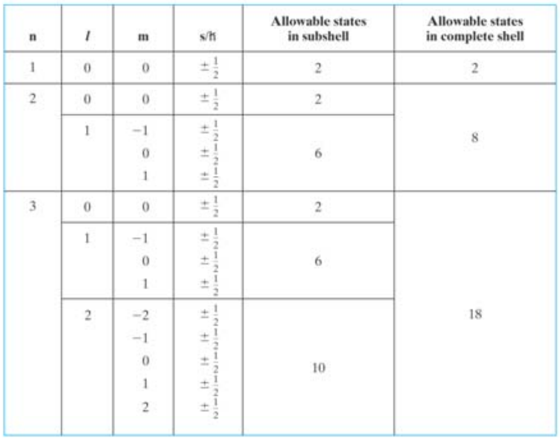
Hydrogen atom



n	*l*	m	s/ħ	Allowable states in subshell	Allowable states in complete shell
1	0	0	$\pm\frac{1}{2}$	2	2
2	0	0	$\pm\frac{1}{2}$	2	8
	1	−1	$\pm\frac{1}{2}$	6	
		0	$\pm\frac{1}{2}$		
		1	$\pm\frac{1}{2}$		
3	0	0	$\pm\frac{1}{2}$	2	18
	1	−1	$\pm\frac{1}{2}$	6	
		0	$\pm\frac{1}{2}$		
		1	$\pm\frac{1}{2}$		
	2	−2	$\pm\frac{1}{2}$	10	
		−1	$\pm\frac{1}{2}$		
		0	$\pm\frac{1}{2}$		
		1	$\pm\frac{1}{2}$		
		2	$\pm\frac{1}{2}$		

Table 2.1

Quantum numbers to **n** = 3 and allowable states for the electron in a hydrogen atom: The first four columns show the various combinations of quantum numbers allowed by the selection rules of Eq. (2–46); the last two columns indicate the number of allowed states (combinations of **n**, ***l***, **m**, and **s**) for each ***l*** (subshell) and **n** (shell, or Bohr orbit).

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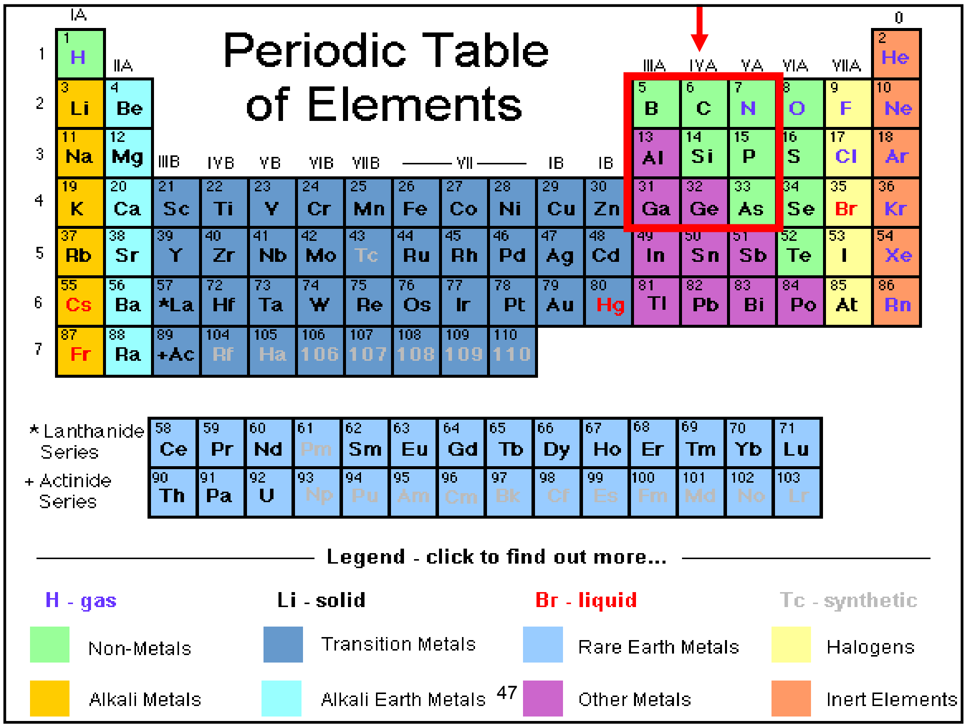
Atomic properties

- An atom's chemical properties, or how it interacts with other atoms, are determined by the shell structure.
  - They fill from the bottom up.
- In particular it is the number of electrons in the *outer* shell that matters.
  - Called *valence* electrons.
- Periodic table organized by valence electrons.



Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Legend - click to find out more...

H - gas
Li - solid
Br - liquid
Tc - synthetic

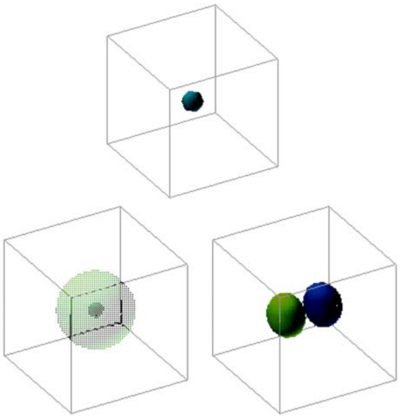
🟩 Non-Metals
🟦 Transition Metals
🟦 Rare Earth Metals
🟨 Halogens
🟧 Alkali Metals
🟦 Alkali Earth Metals
🟪 Other Metals
🟧 Inert Elements

Silicon is in Column IV of the periodic table

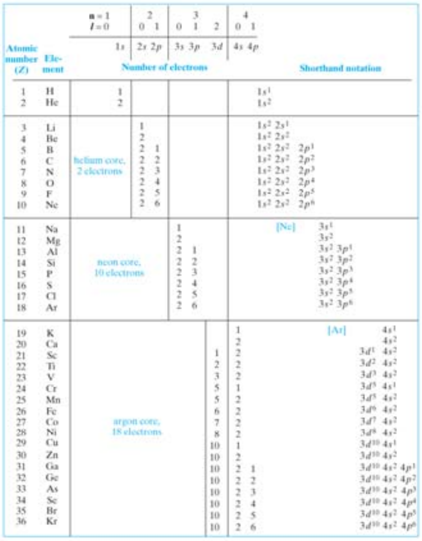
Memorize This!

IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

First atomic orbitals



- 1s shell=2 electrons
- 2s shell=2 electrons
- 2p shells=total of 6 electrons
  - $2p_x$ shell = 2 electrons
  - $2p_y$ shell = 2 electrons
  - $2p_z$ shell = 2 electrons
- So 8 electrons in (n=2) second shell



		$n = 1$	2		3			4		
		$l = 0$	0	1	0	1	2	0	1	
		$1s$	$2s$	$2p$	$3s$	$3p$	$3d$	$4s$	$4p$	
Atomic number (Z)	Element	Number of electrons								Shorthand notation
1	H	1								$1s^1$
2	He	2								$1s^2$
3	Li	helium core, 2 electrons	1							$1s^2\ 2s^1$
4	Be		2							$1s^2\ 2s^2$
5	B		2	1						$1s^2\ 2s^2\ 2p^1$
6	C		2	2						$1s^2\ 2s^2\ 2p^2$
7	N		2	3						$1s^2\ 2s^2\ 2p^3$
8	O		2	4						$1s^2\ 2s^2\ 2p^4$
9	F		2	5						$1s^2\ 2s^2\ 2p^5$
10	Ne		2	6						$1s^2\ 2s^2\ 2p^6$
11	Na	neon core, 10 electrons			1					[Ne] $3s^1$
12	Mg				2					$3s^2$
13	Al				2	1				$3s^2\ 3p^1$
14	Si				2	2				$3s^2\ 3p^2$
15	P				2	3				$3s^2\ 3p^3$
16	S				2	4				$3s^2\ 3p^4$
17	Cl				2	5				$3s^2\ 3p^5$
18	Ar				2	6				$3s^2\ 3p^6$
19	K	argon core, 18 electrons						1		[Ar] $4s^1$
20	Ca							2		$4s^2$
21	Sc						1	2		$3d^1\ 4s^2$
22	Ti						2	2		$3d^2\ 4s^2$
23	V						3	2		$3d^3\ 4s^2$
24	Cr						5	1		$3d^5\ 4s^1$
25	Mn						5	2		$3d^5\ 4s^2$
26	Fe						6	2		$3d^6\ 4s^2$
27	Co						7	2		$3d^7\ 4s^2$
28	Ni						8	2		$3d^8\ 4s^2$
29	Cu						10	1		$3d^{10}\ 4s^1$
30	Zn						10	2		$3d^{10}\ 4s^2$
31	Ga						10	2	1	$3d^{10}\ 4s^2\ 4p^1$
32	Ge						10	2	2	$3d^{10}\ 4s^2\ 4p^2$
33	As						10	2	3	$3d^{10}\ 4s^2\ 4p^3$
34	Se						10	2	4	$3d^{10}\ 4s^2\ 4p^4$
35	Br						10	2	5	$3d^{10}\ 4s^2\ 4p^5$
36	Kr						10	2	6	$3d^{10}\ 4s^2\ 4p^6$

Table 2.2

Electronic configurations for atoms in the ground state.

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Silicon orbits/shells

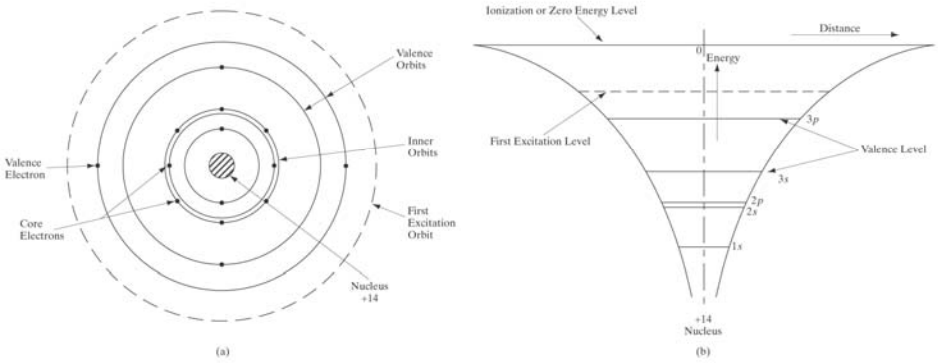

Figure 2.8

Electronic structure and energy levels in a Si atom: (a) The orbital model of a Si atom showing the 10 core electrons (**n** = 1 and 2), and the 4 valence electrons (**n** = 3); (b) energy levels in the coulombic potential of the nucleus are also shown schematically.

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Chapter 2

Read Sections 2.2 & 2.3:
- Schrödinger wave equation
- Applications
  - Free electrons
  - Potential wells
  - Electron tunneling

(Revision? Covered in ECE417/517 Nanoelectronics)

Table 1.2 | A list of some semiconductor materials

Elemental semiconductors	
Si	Silicon
Ge	Germanium
Compound semiconductors	
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
GaP	Gallium phosphide
GaAs	Gallium arsenide
InP	Indium phosphide

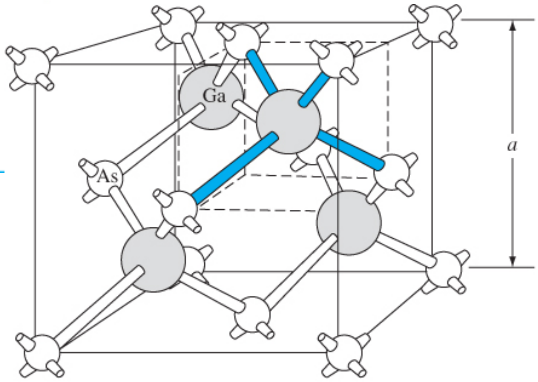

Figure 1.14 | The zincblende (sphalerite) lattice of GaAs.

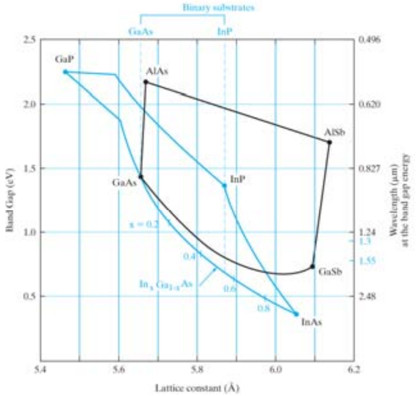

Figure 1.13

Relationship between band gap and lattice constant for alloys in the InGaAsP and AlGaAsSb systems. The dashed vertical lines show the lattice constants for the commercially available binary substrates GaAs and InP. For the marked example of $In_xGa_{1-x}As$, the ternary composition $x = 0.53$ can be grown lattice-matched on InP, since the lattice constants are the same. For quaternary alloys, the compositions on both the III and V sublattices can be varied to grow lattice-matched epitaxial layers along the dashed vertical lines between curves. For example, $In_xGa_{1-x}As_yP_{1-y}$ can be grown on InP substrates, with resulting band gaps ranging from 0.75 eV to 1.35 eV. In using this figure, assume the lattice constant a of a ternary alloy varies linearly with the composition x.

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