VE 320 Fall 2021

Introduction to Semiconductor Devices

Instructor: Rui Yang （杨睿）

Office: JI Building 434

rui.yang@sjtu.edu.cn

Lecture 1

Information session &
Introduction to solids and crystal structures
(Chapter 1)

About the instructor

- 2011.08 – 2016.05. Ph.D., Electrical Engineering, Case Western Reserve University
- 2016.07 – 2018.07. Postdoc Fellow, Electrical Engineering, Stanford University
- 2018.08 – present. Assistant Professor, UM-SJTU Joint Institute, Shanghai Jiao Tong University, Shanghai, China
  - Instructor of VE215
  - Instructor of VE320
  - Instructor of VE510

Course schedule

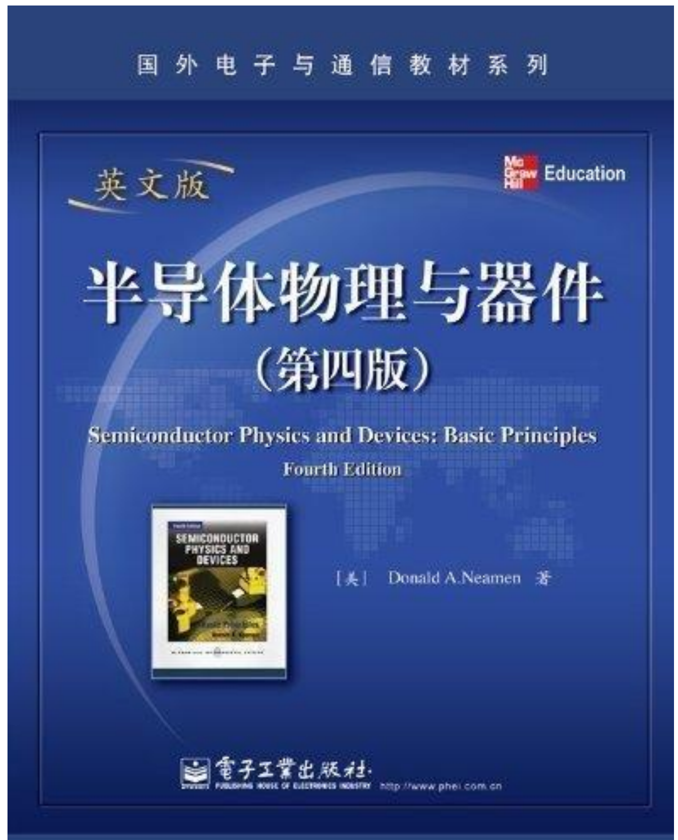
- Lectures: Tuesday 10:00 – 11:40
  Thursday 10:00 – 11:40
  Friday 10:00-11:40 (even weeks)
- Recitation: TBD
- Location: Dong Shang Yuan D308(Tu), D408(Th/F)
- My office hours: Tuesday 13:00 – 15:00, Rm. 434
- Prerequisites: Ve215, Vp240 (old) or VP 245/250 (new), or Vp260
  - If you do not meet this requirement, please see the instructor immediately after class
- TA:
  - Wang Xingyuan, 王兴远, xingyuan_wang@sjtu.edu.cn
  - Wu Haochen, 武昊辰, wuhaochen2018@sjtu.edu.cn

Instructor's contact

- Office location:
  Rm. 434, UM-SJTU JI Building
- Office tel:
  3420-8540 ext. 4341
- Email:
  rui.yang@sjtu.edu.cn

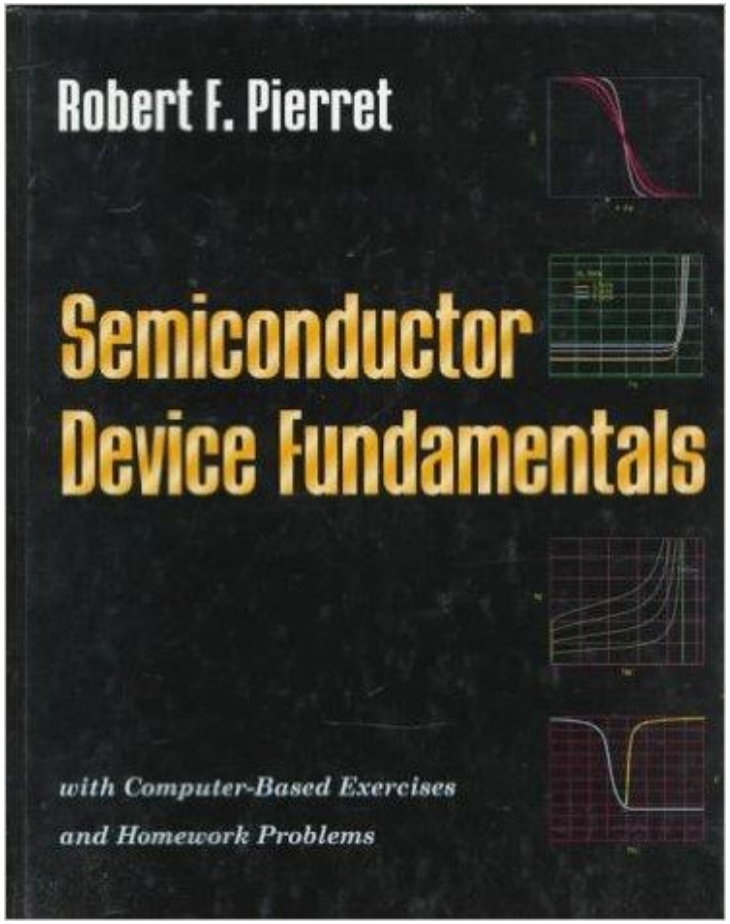
Textbook 1

Semiconductor Physics and Devices: Basic Principles 4th ed.
Donald A. Neamen
Publishing house of electronic industry



Textbook 2

Semiconductor Device Fundamentals, 2^{nd} Ed.
Robert F. Pierret, (available JI library)



Grading policy

- Ve320 has around 8 problem sets (homework assignments), and 3 exams
- Random in-class quizzes: 10%
- Problem sets: 10%
- Exam 1(Midterm Exam 1): 25%
- Exam 2(Midterm Exam 2): 25%
- Exam 3(Final Exam): 30%
- Curve to be centered at B or B+
- If the total grade is below 50, that will lead to fail (F)

The JI Honor Code

- Personal integrity as students and professionals.
- Respect other people and their work.
- Respect yourself and your own efforts.
- Mutual trust.
- Applicable to all your academic activities here, including homework, quizzes, lab reports, projects and exams.
- Special honor code for online learning.
- Violations will be reported to the Honor Council.
  - Copy other student’s homework, quizzes, lab reports, exams.
  - Illegal copy of online resource and academic literatures.
  - Helping others on the abovementioned activities.
  - Fake ID for exams.

Class rules

- Please do not come in late and do not get up to leave until the class is dismissed.
- You are responsible for all material covered in class, whether or not it is in the book.
- Read the book after the class.
- Problem sets (homework assignments) may be discussed with partners, but the work you submit must be your own.
- Homework will be assigned online at Canvas as scheduled. They are usually due one week later or specified otherwise. One day automatic grace period. Second day late penalty -25%, later no credit.
- If the total grade is below 50, that will lead to fail (F).

Exam rules

- There will be two midterm exams and one final exam.
- Students should complete the exam independently. No talk and collaboration are allowed.
- Closed book, cheat sheet may be allowed.
- No electronic devices except basic calculators will be allowed to use.
- Random quizzes are open book and open discussion
- Any suspicious violation of the honor code will be reported to the honor council.

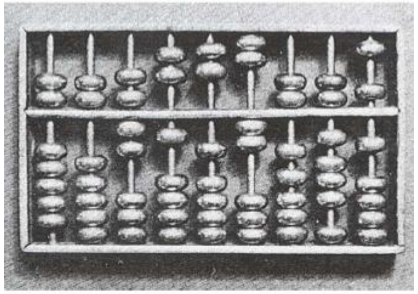
Tentative schedule: (subject to change)

Week	Date	Lecture Topics	Homework
1	Sept. 14	Introduction to solids	
	Sept. 16	Introduction to quantum mechanics	HW1
2	Sept. 21	No Lecture, National Holiday	
	Sept. 23	Energy band	
	Sept. 24	Energy band	HW2
3	Sept. 28	DOS and Fermi distribution	
	Sept. 30	DOS and Fermi distribution	HW3
4	Oct. 5	No Lecture, National Holiday	
	Oct. 7	No Lecture, National Holiday	
	Oct. 8	Carrier transport	
5	Oct. 12	Carrier transport	HW4
	Oct. 14	No Lecture, Midterm Exam 1	
6	Oct. 19	Carrier transport	
	Oct. 21	PN junction	
	Oct. 22	PN junction	
7	Oct. 26	PN junction	
	Oct. 28	PN junction	
8	Nov. 1	PN junction	HW5
	Nov. 3	BJT	
	Nov. 5	BJT	
9	Nov. 9	BJT	
	Nov. 11	BJT	HW6
10	Nov. 16	No Lecture, Midterm Exam 2	
	Nov. 18	Schottky diode	
	Nov. 19	Schottky diode	HW7
11	Nov. 23	MOS capacitor	
	Nov. 25	MOS capacitor	
12	Nov. 30	MOS capacitor	
	Dec. 2	MOSFET	
	Dec. 3	MOSFET	HW8
13	Dec. 7	MOSFET	
	Dec. 9	MOSFET	
14	Dec. 14	No Lecture, Final Exam	

Semiconductor Devices

- The abacus, ancient digital memory

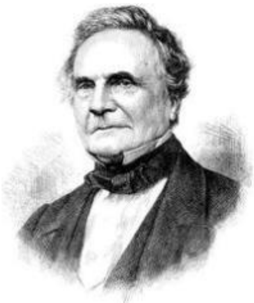
Roman Abacus (ca. 200BC)



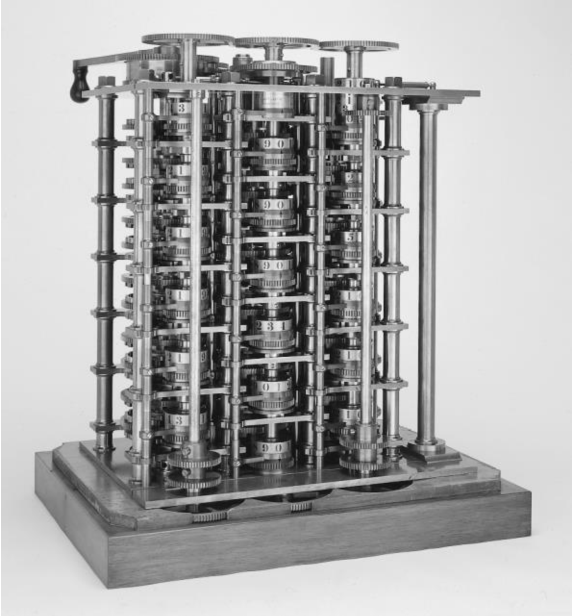
Chinese Abacus (ca. 190AD)

  – Information represented in digital form
  – Each rod is a decimal digit (units, tens, etc.)
  – Can store information, and do calculation

- An early mechanical computer
  – The Babbage difference engine, 1832
  – 25,000 parts



Charles Babbage (Wikipedia)



- Ohm's law: V = I x R
  - Georg Ohm, 1827

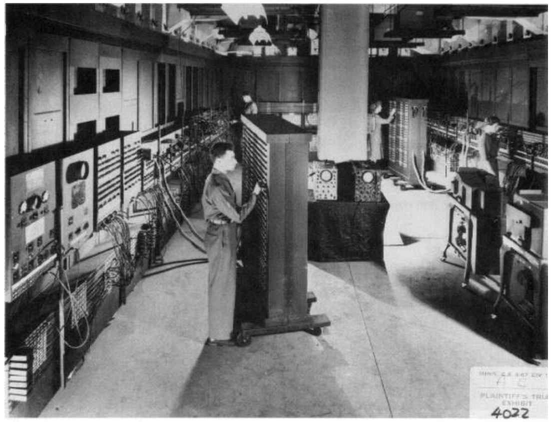
- Semiconductors are not metals
  - Semiconductor resistance decreases with temperature
  - Michael Faraday, 1834

- Discovery of the electron
  - J.J. Thomson, measured only charge/mass ratio, 1897
  - "To the electron, may it never be of any use to anybody." – J.J. Thomson's favorite toast.

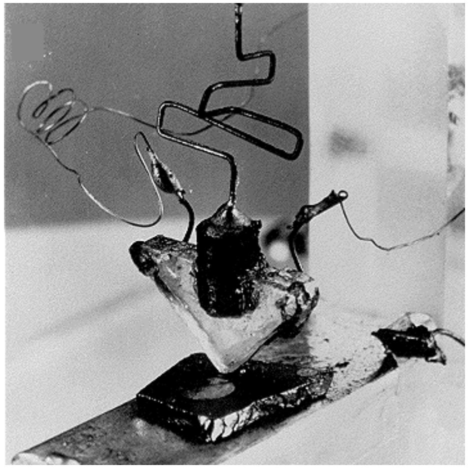
- Measuring the electron charge: 1.6×10^{-19} C
  - Robert Millikan, oil drops, 1909

- ENIAC: The first electronic computer (1946)
  - 30 tons, including ~20,000 vacuum tubes, relays
  - Punch card inputs, ~5 kHz speed
  - It failed ~every five days

Note: ILLIAC @ UIUC
5 tons, 2800 vacuum tubes
64k memory (1952)

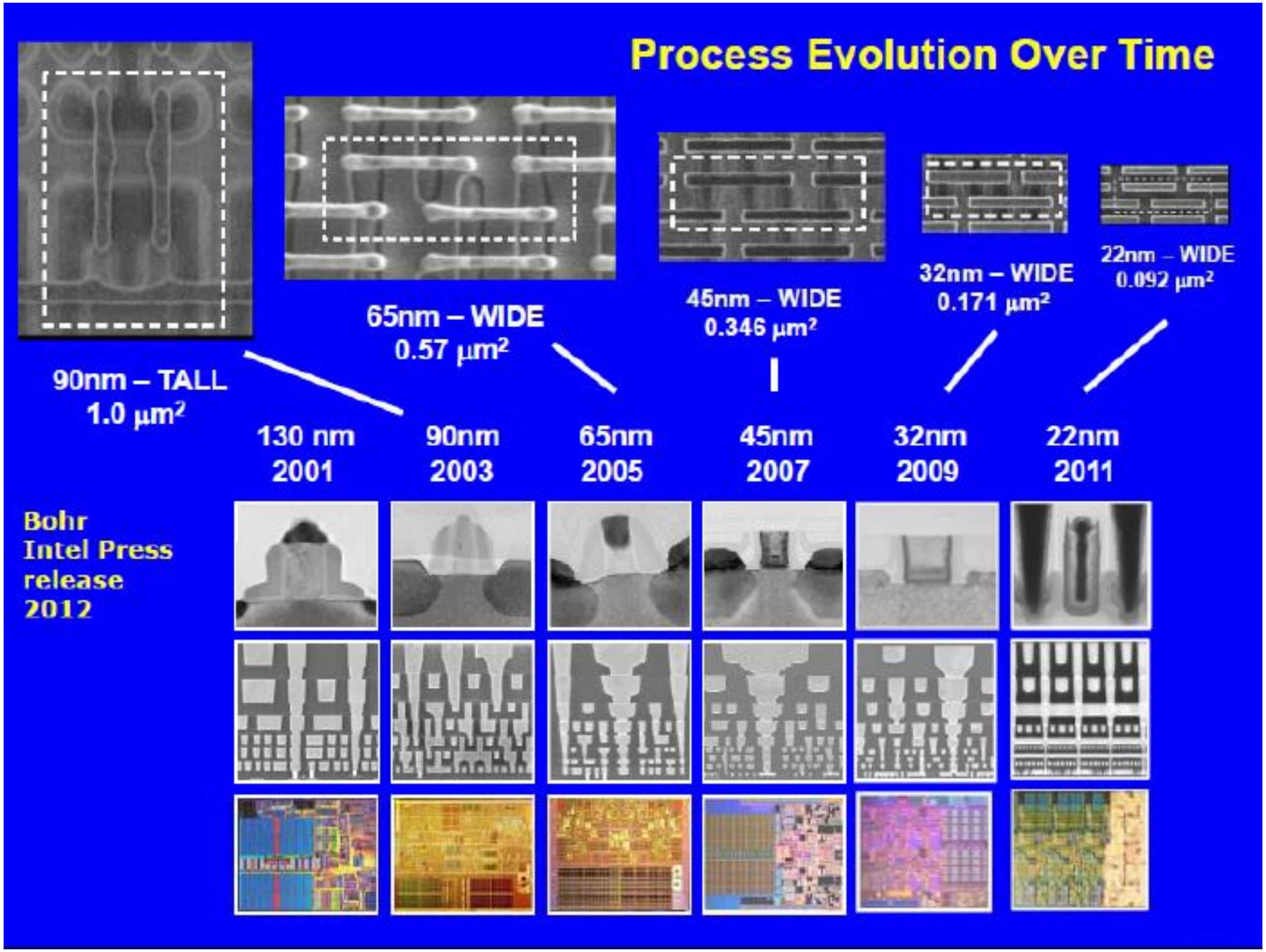


- Modern age begins in 1947:
  - The first semiconductor transistor
  - AT&T Bell Labs, Dec 1947
  - J. Bardeen, W. Brattain, W. Shockley
  - Germanium base, gold foil contacts



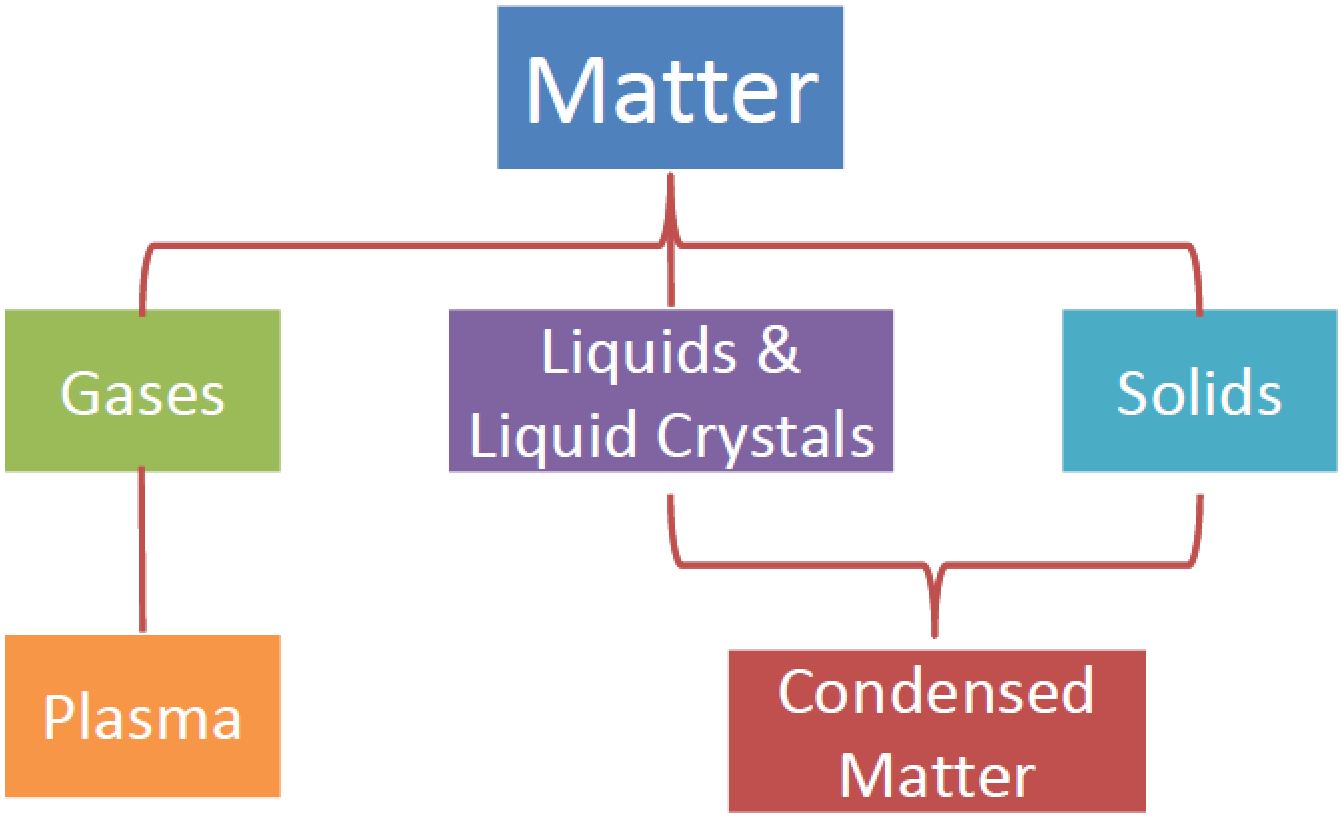
Note: ILLIAC II @ UIUC
Built with discrete transistors (1962)

Semiconductor processing



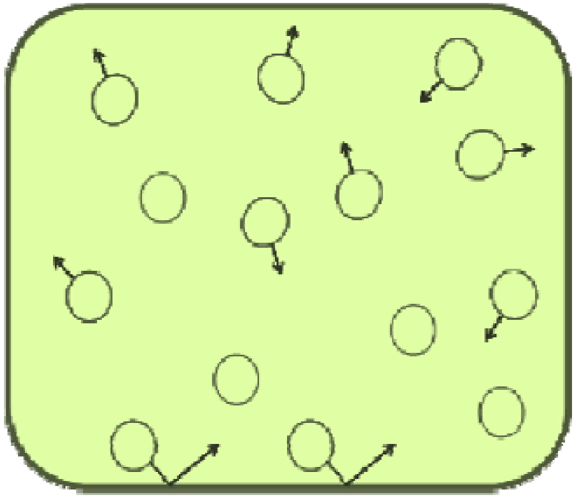
Introduction to solids

States, phases of matter



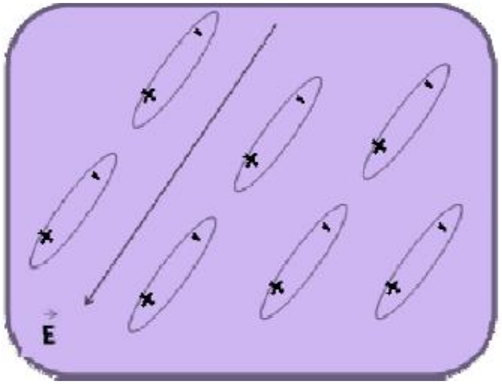
Gases

- ***Gases*** have atoms or molecules that do not bond to one another in a range of pressure, temperature & volume.
- These molecules haven’t any particular order & move freely within a container.



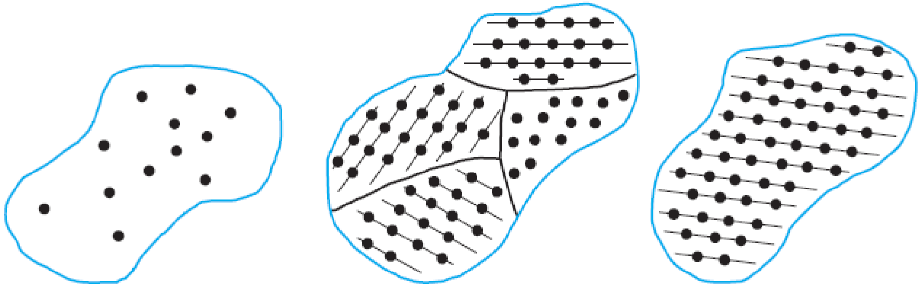
Liquids & liquid crystals

- Similar to gases, ***Liquids*** have no atomic/molecular order & they assume the shape of their containers.
- Applying low levels of thermal energy can easily break the existing weak bonds.
- ***Liquid Crystals*** have mobile molecules, but a type of long range order can exist; the molecules have a permanent dipole. Applying an electric field rotates the dipole & establishes order within the collection of molecules.



Solids

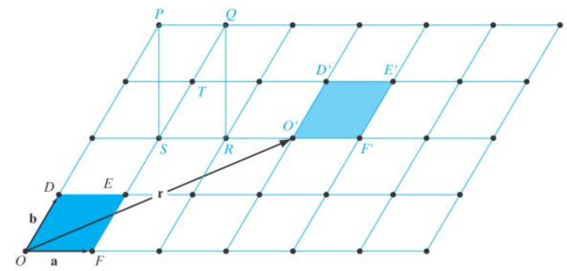
- ***Solids*** consist of atoms or molecules *undergoing thermal motion* about their equilibrium positions, which are at *fixed points* in space.
- *Solids* can be amorphous, polycrystalline, or single crystal.



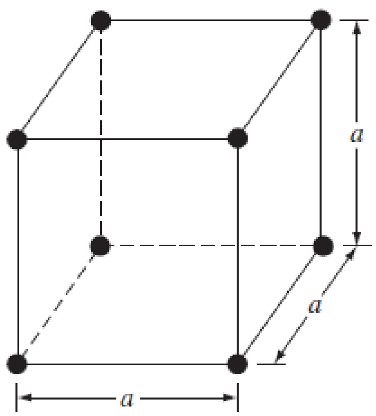
amorphous polycrystalline single crystal

- *Solids* (at a given temperature, pressure, volume) have stronger interatomic bonds than liquids.
- So, solids require more energy to break the interatomic bonds than liquids.

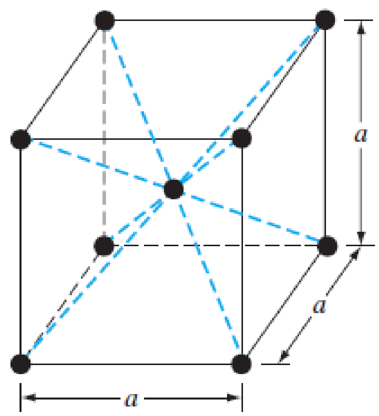
- The periodic lattice
  - Unit cell: can reproduce the crystal
  - Primitive cell: the smallest unit cell



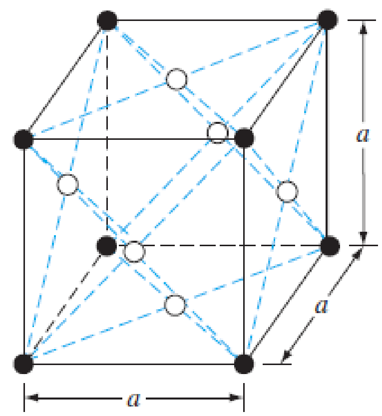
- Stuffing atoms into unit cells:



Simple cubic

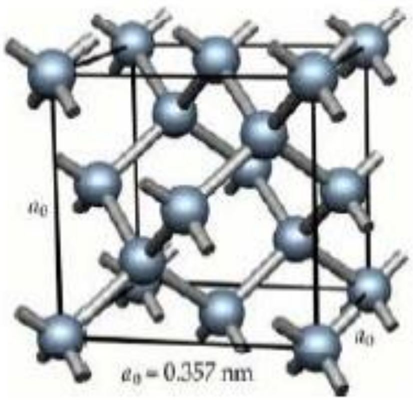


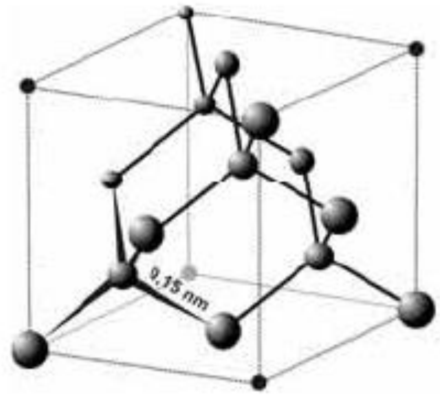
Body-centered cubic

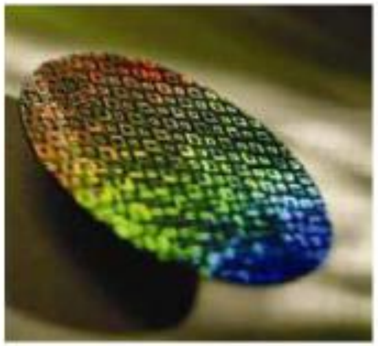


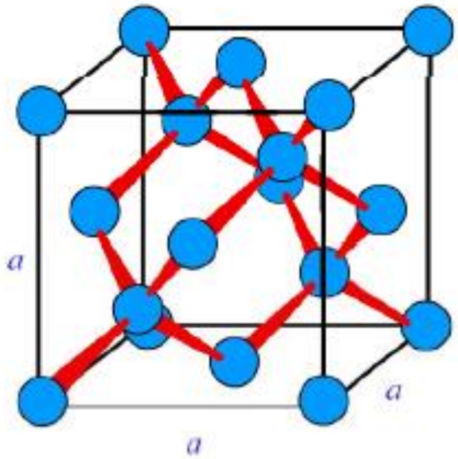
Face-centered cubic

Diamond structure – a special cubic







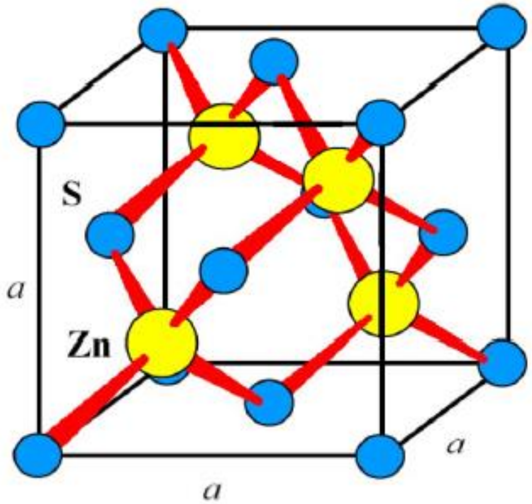


The Silicon lattice:

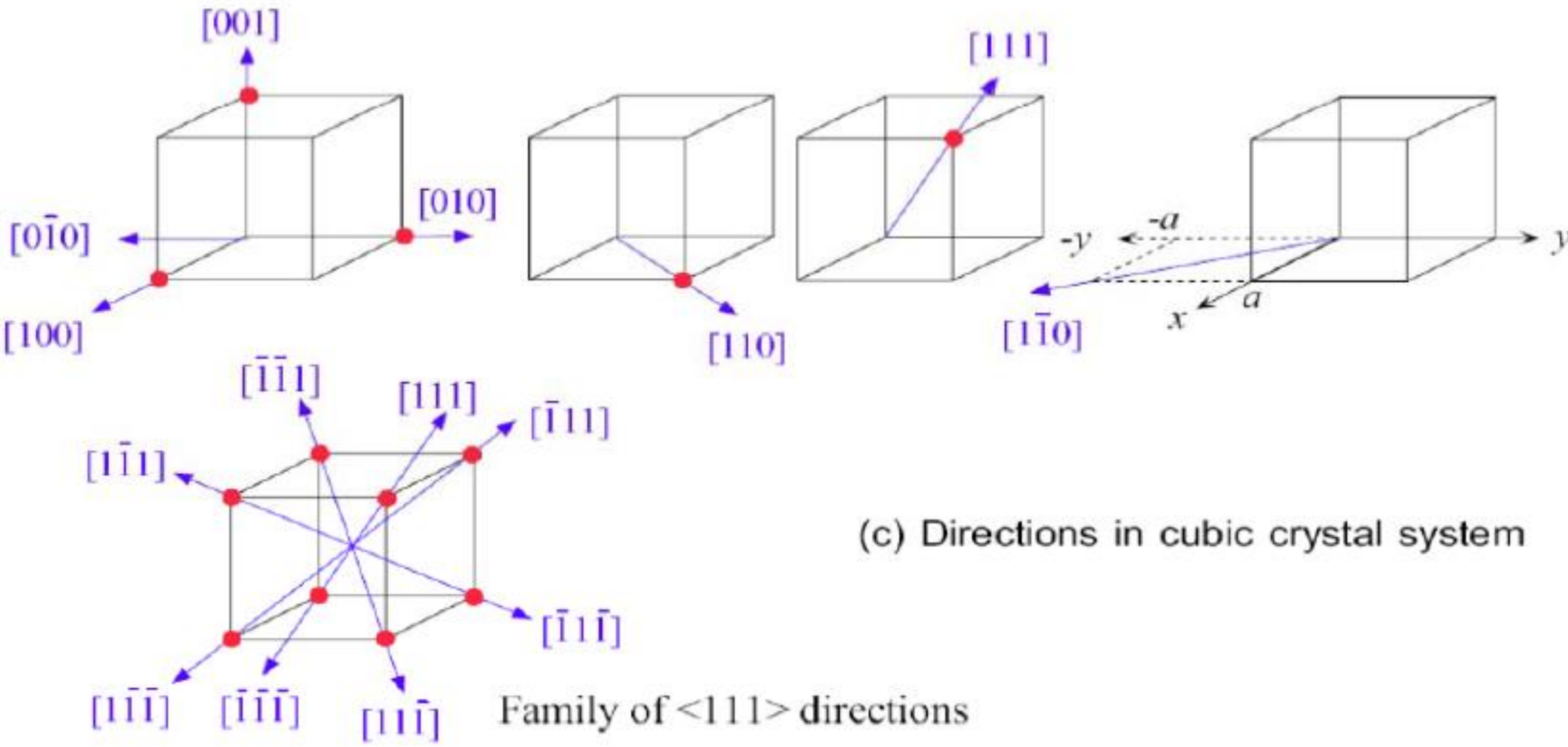
- “Diamond lattice”
- Si atom: 14 electrons occupying lowest 3 energy levels:
  - 1s, 2s, 2p orbitals filled by 10 electrons
  - 3s, 3p orbitals filled by 4 electrons
- Each Si atom has four neighbors
- Any atom within the diamond structure will have four nearest neighboring atoms
- The diamond structure refers to the particular lattice in which all atoms are of the same species, such as silicon or germanium
- How many atoms per unit cell?

Zinc blende lattice

- The Zinc blende is diamond cystal structure, w/ switching atoms
- Two intercalated fcc lattices
- Many important compound crystal
- AlN, AlAs, GaAs, GaN, GaP, GaSb, InAs, InP, InSb, ZnS, ZnTe.



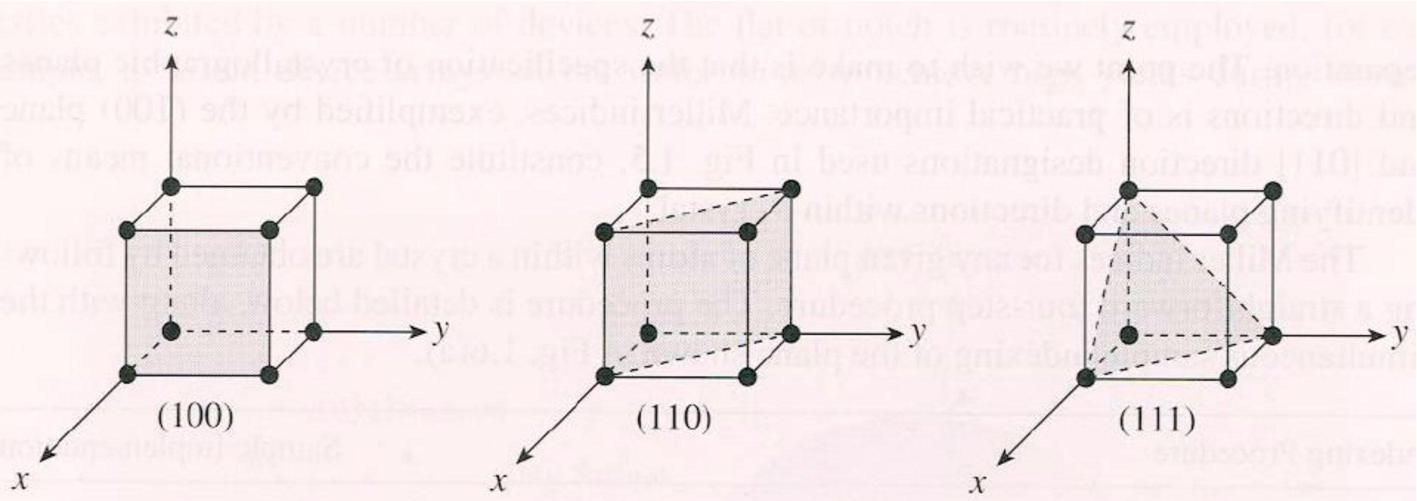
- Crystallographic notation



(c) Directions in cubic crystal system

Family of <111> directions

Crystallographic planes

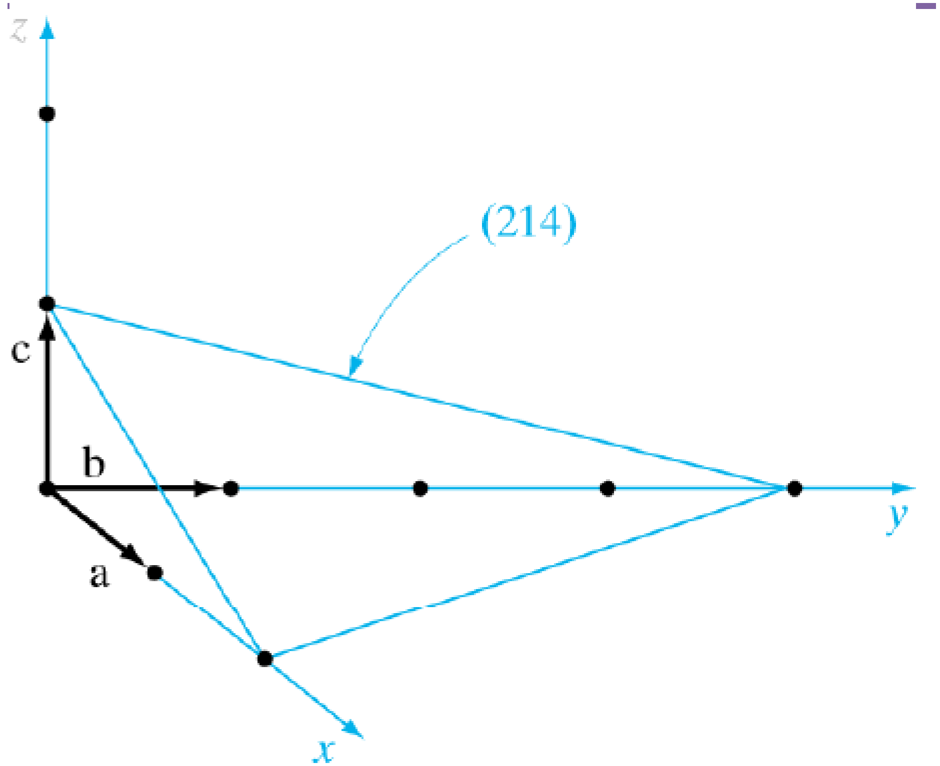


Miller Indices

(Intercept values are in multiples of the lattice constant; h, k and l are reduced to 3 integers having the same ratio.)

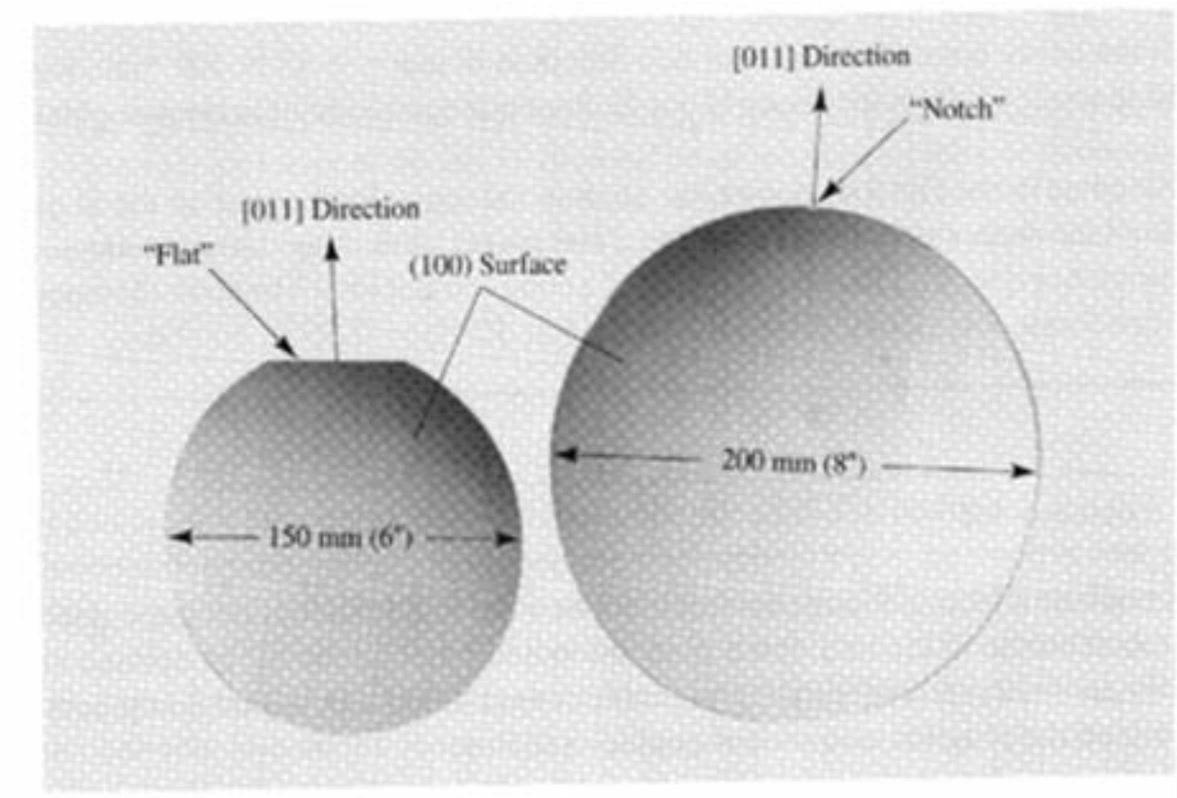
Notation	Interpretation
$(h\ k\ l)$	crystal plane
$\{h\ k\ l\}$	equivalent planes
$[h\ k\ l]$	crystal direction
$<h\ k\ l>$	equivalent directions

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

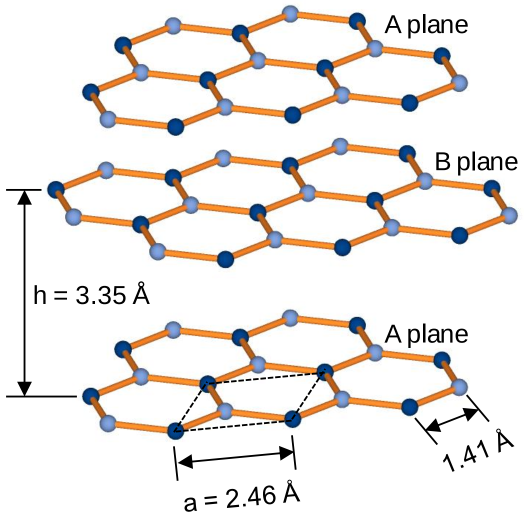


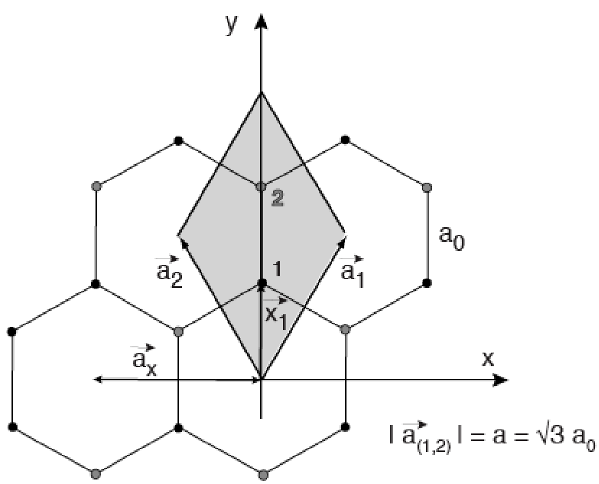
A (214) crystal plane.

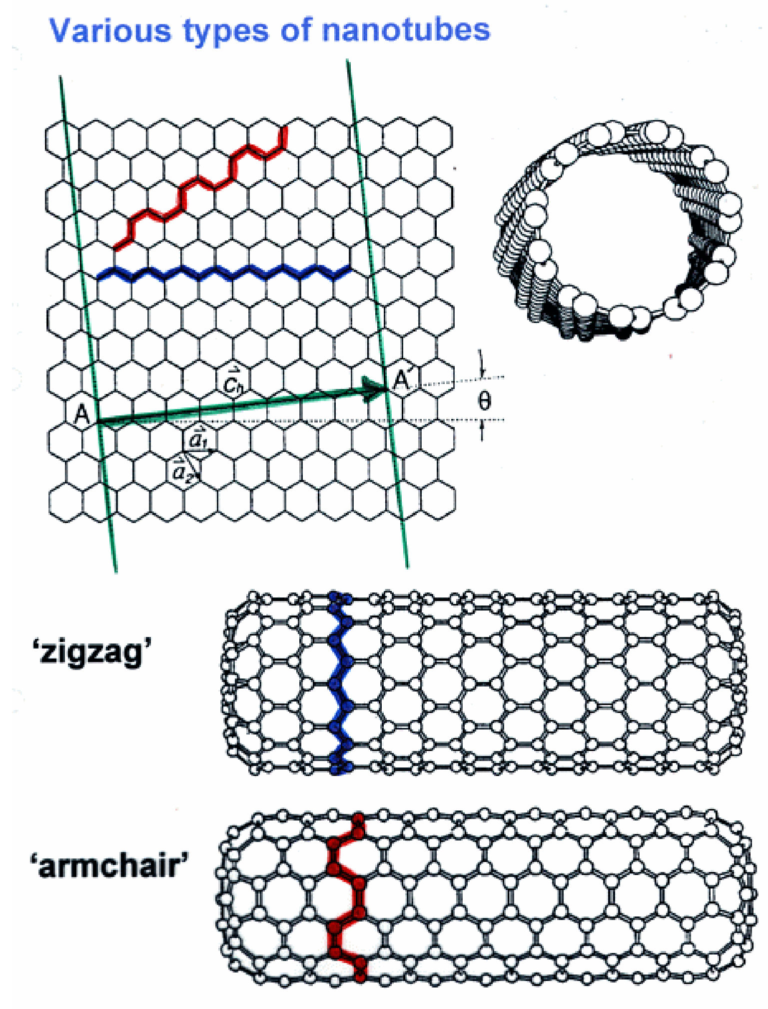
- Si wafers usually cut along {100} plane with a notch or flat side to orient the wafer during fabrication

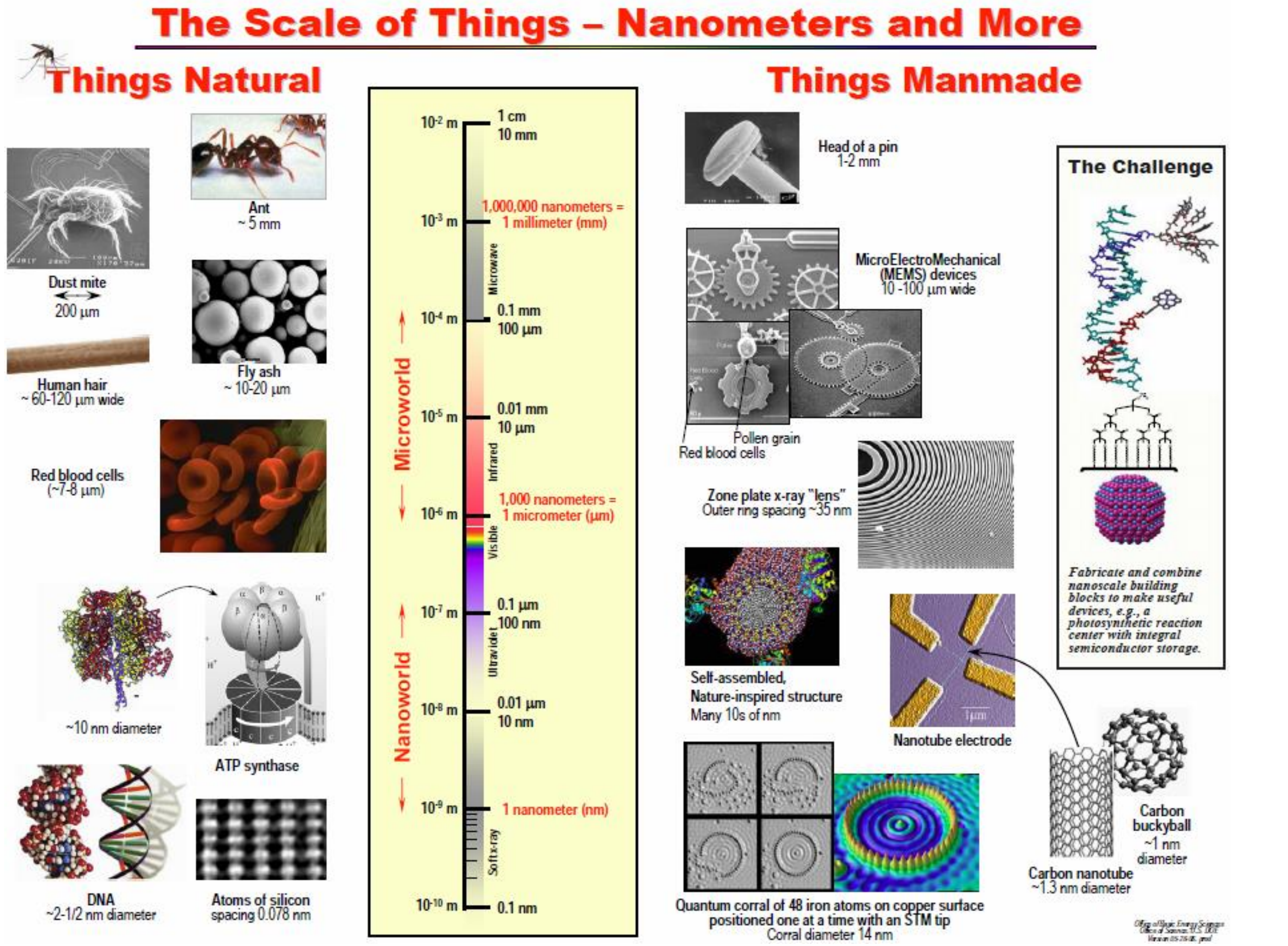


- Graphite (~pencil lead) = parallel sheets of graphene
- Carbon nanotube = rolled up sheet of graphene








The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Dust mite
200 µm
Ant
~ 5 mm
Fly ash
~ 10-20 µm
Human hair
~ 60-120 µm wide
Red blood cells
(~7-8 µm)
~10 nm diameter
ATP synthase
DNA
~2-1/2 nm diameter
Atoms of silicon
spacing 0.078 nm
Microworld
Nanoworld
10-2 m
1 cm
10 mm
10-3 m
1,000,000 nanometers =
1 millimeter (mm)
Microwave
10-4 m
0.1 mm
100 µm
10-5 m
0.01 mm
10 µm
Infrared
10-6 m
1,000 nanometers =
1 micrometer (µm)
Visible
10-7 m
0.1 µm
100 nm
Ultraviolet
10-8 m
0.01 µm
10 nm
10-9 m
1 nanometer (nm)
Soft x-ray
10-10 m
0.1 nm
Head of a pin
1-2 mm
MicroElectroMechanical
(MEMS) devices
10 -100 µm wide
Pollen grain
Red blood cells
Zone plate x-ray "lens"
Outer ring spacing ~35 nm
Self-assembled,
Nature-inspired structure
Many 10s of nm
Nanotube electrode
Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm
Carbon nanotube
~1.3 nm diameter
Carbon
buckyball
~1 nm
diameter
The Challenge
Fabricate and combine
nanoscale building
blocks to make useful
devices, e.g., a
photosynthetic reaction
center with integral
semiconductor storage.