University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

# VE 320 – Summer 2012
# Introduction to Semiconductor Device

Instructor: Professor Hua Bao



## Introduction

## Course Information

Time: Tuesday 8:00 - 9:40 AM / Thursday 4:00 – 5:40 PM
Friday 8:55 – 9:40 AM
Location: Dong Xia Yuan 200

Instructor: Professor Hua Bao
JI Building Office 302
Tel: 34206765 – 3021
Email: hua.bao@sjtu.edu.cn
Teaching Assistant: Guiyu Tian
Email: redrivertgy@sjtu.edu.cn



## Textbook, Office Hours, Pre-Requisites

- Textbook

  ***Semiconductor Device Fundamentals*** by Robert F. Pierret
- Reference

  ***Introduction of Solid State Physics*** by C. Kittel or any similar solid state physics textbook
- Office Hours

  Prof. Hua Bao: JI 302, TF 9:40-10:40 AM

  Guiyu Tian: JI reading room, M 6:00-8:00 PM, Th 4:00-5:00 PM
- Prerequisites

  Ve215, Vp240 or Vp260. If you do not meet this requirement, see your instructor immediately after class.

## Assignments, In-Class Participation

- Assigned weekly on Thursday. Due the following Friday. Graded assignments will be returned during lecture.
- Homework problems due at the start of the class. ***Late homework is not accepted.***
- Solutions will be posted after the homework is due.

- In-class exercises given periodically
  -- 5-15 minutes duration
  -- Textbook essential
- Class attendance mandatory



## Exams and Grading

- One mid-term exam during the week of Jun 25 (week 7 of this semester).
- Final exam during the week of Aug 6 (week 13).
- Review session will be provided before mid-term and final exam. Exact exam time will be announced.
- There will be **no** written make-up exams. If you have a good excuse for missing an exam, you will be given an oral exam

**Grading Policy**
- Quiz and in-class performance 10%
- Homework 15%
- Mid-term 35%
- Final 40%

?

## Unethical Conduct

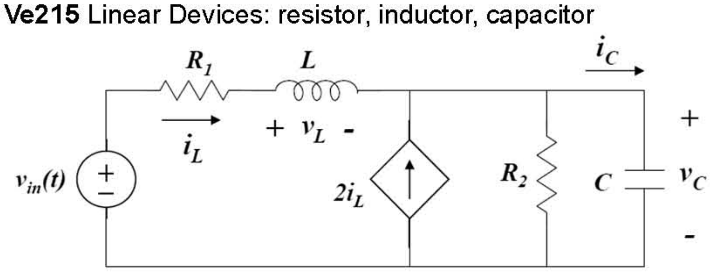
- You are free to discuss homework with each other. However, the work that you submit must be your own.
- Any cheating behavior will result in failing this class and other serious consequences.



## Course Objective

- To introduce students to the fundamentals of semiconductor devices.

**Ve215** Linear Devices: resistor, inductor, capacitor

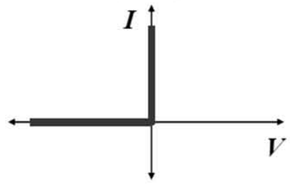



**Ve320** Nonlinear Devices: diodes and transistors. “How” and “Why”.

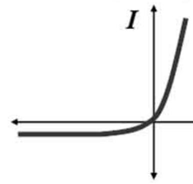
# Diode

A one way valve for current flow

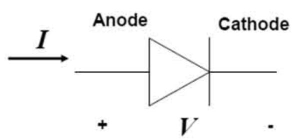
**Ideal**

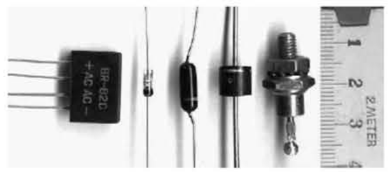



**Actual**




$$I = I_0\left(e^{qV/kT} - 1\right)$$



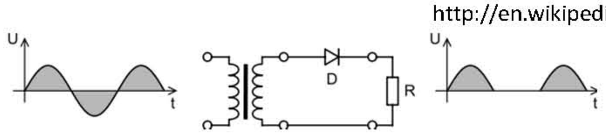



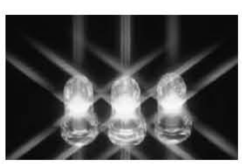


# Diode Applications

- Rectifier
- Over voltage protection
- Light emitter (Light emitting diode)
- Light detector (solar cell)

http://en.wikipedia.org/wiki/Rectifier



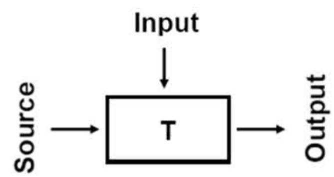



## Transistor

**tran•sis•tor (trán-zìs′ter)**
A solid-state electronic device that is used to control the flow of electricity in electronic equipment and consists of a small block of a semiconductor with at least three electrodes

**Trans(fer) + (res)istor**

**Idea: control large output with small input**

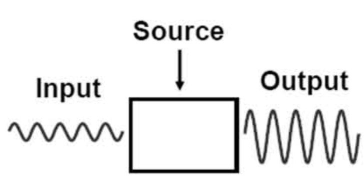


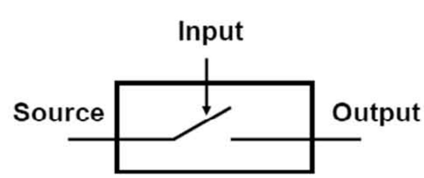

**This device should exhibit *gain***



## What is a Transistor Used for?

| Analog | Digital |
| --- | --- |
| **Gain: Signal amplification** | **Switch: on or off** |
| **Realization of signal processing electronically** | **Realization Of Boolean logic electronically** |

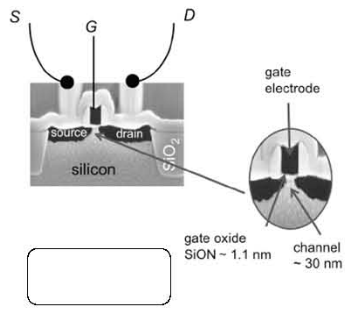


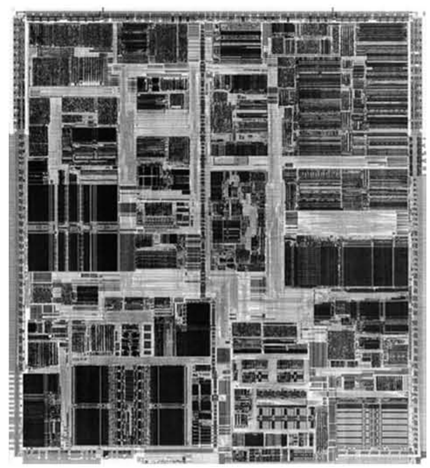

**Integrate many devices into a circuit**

## Integrated Circuits

- Billions of transistors in a small area

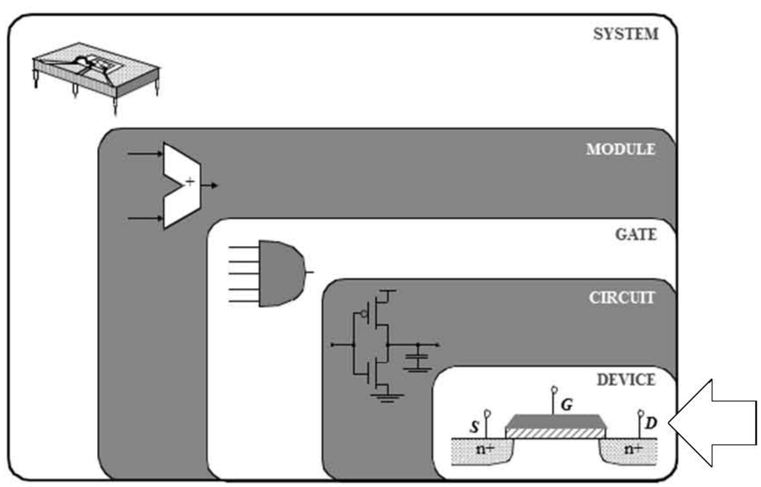



Intel Pentium (IV) microprocessor

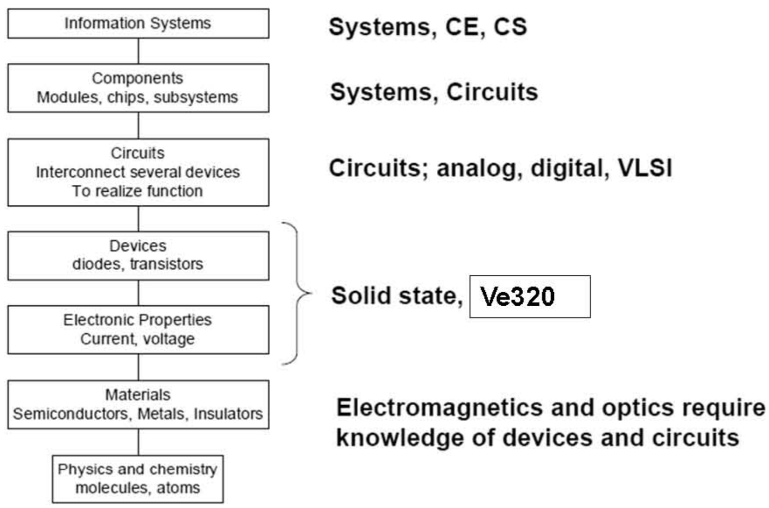




## Where we are?



## Why should I Take This Course?






## Course Outline and Learning Strategy

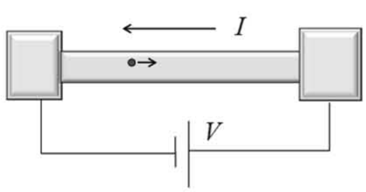
| | | |
|---|---|---|
| **Part I** | **Semiconductor Fundamentals** | **~ 4 weeks, 20 lectures** |
| **Part II** | **PN Junction Diode, MS Diode, LED** | **~ 3 weeks, 15 lectures** |
| **Part III** | **Transistors, BJT, FET** | **~ 4 weeks, 20 lectures** |

- Part I: knowledge of quantum mechanics, statistical mechanics, and solid state physics is needed to fully understand this part. Try to accept those as facts.
- Part II and III: a lot of assumptions will be made. Try to think about how and why these assumptions are made. Repeat the mathematical derivation.

# Crystal Structures



# Current Flow in Semiconductor




$$I = G \times V$$
$$= q \times n \times v \times A$$

Carrier Density

Velocity

Depends on chemical composition, crystal structure, temperature, doping, etc

**Quantum Mechanics + Equilibrium Statistical Mechanics**
-→ Encapsulated into concepts of effective mass and occupation factors

**Transport with scattering, non-equilibrium Statistical Mechanics**
-→ Encapsulated into drift-diffusion equation with recombination-generation

## Computing Carrier Density and Velocity

**Atomic composition**

- *number of electrons per atom*

**Arrangement of atoms**

- *not all electrons are available for conduction*

**For Periodic Arrays**

- *simplification for computation*

  ⇒ Concept of Unit Cells

  ⇒ Simple 3-D Unit Cells



## Chemical Composition

Q: What is a semiconductor?

| II | III | IV | V | VI |
|---|---|---|---|---|
| 4 Be | 5 B | 6 C | 7 N | 8 O |
| 12 Mg | 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 |
| 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po |

**Elemental** (e.g., Si, C)

**Compound**

IV-IV: Si-Ge, Si-C

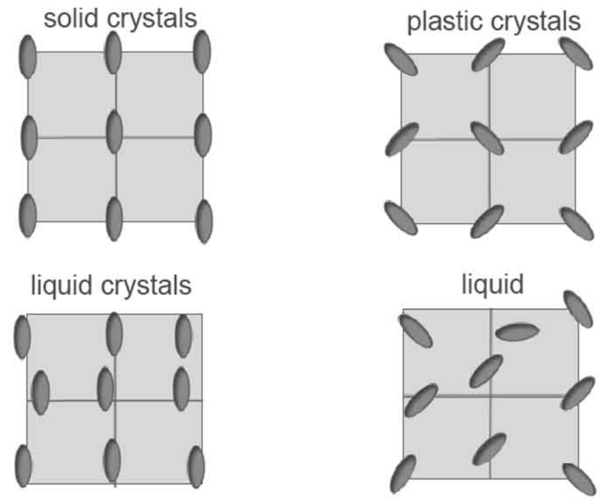
III-V: InP, GaAs, $(In_xGa_{1-x})(As_yP_{1-y})$

II-VI: CdTe

IV-VI: PbS

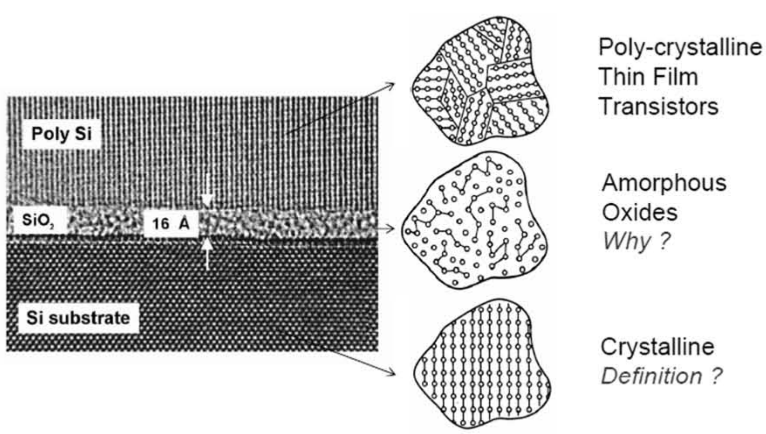
Not all combinations are possible:
Lattice mismatch, room temp. instability, etc. are concerns

## Arrangement of Atoms: orientation vs. position



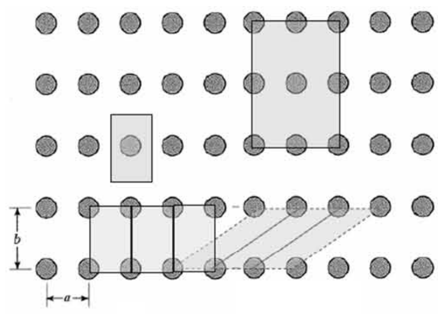



## Arrangement of Atoms




- Quantitative definition: correlation spectrum and diffraction pattern
- Modern solid state devices use all forms of these forms of materials

## Unit Cell of a Periodic Lattice

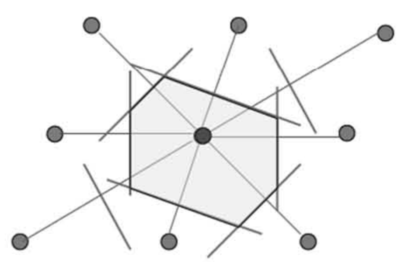



- Unit cell is not unique
- Unit cell can be primitive or non-primitive
- Properties of one cell define the properties of the crystal



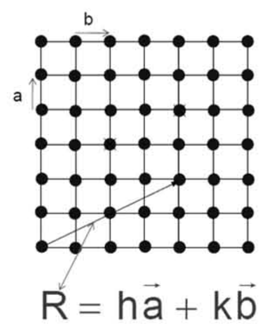
## Wigner-Seitz Primitive Cell

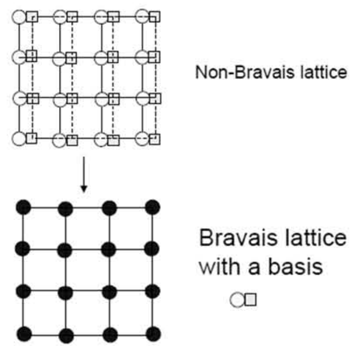
- Choose a reference atom
- Connect to all its neighbors by straight lines
- Draw lines (in 2D) or planes (in 3D) normal to and at the midpoints of lines drawn in step 2
- Smallest volume enclosed is the Wigner-Seitz primitive cell



## Bravais Lattice

- Bravais lattice is an infinite array of discrete points generated by a set of discrete translation operations
- In Bravais Lattice, every point has the same environment as any other point (same number of neighbors, etc)



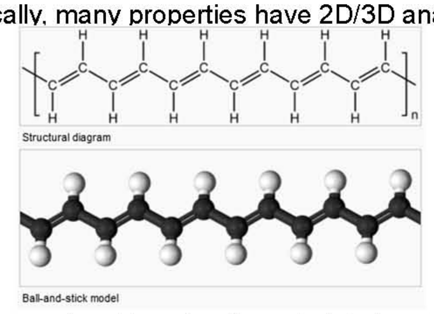



## Unit Cells in One-dimensional Crystals

No system is truly 1-D, but…

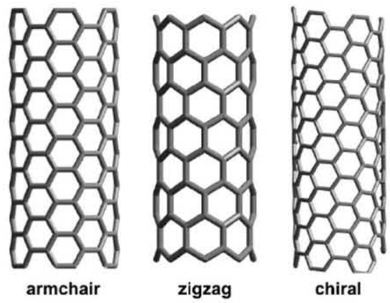
- 1D properties dominate behavior in some materials (e.g., polymers)
- Can be solved analytically, many properties have 2D/3D analogs

Polyacetylene




http://en.wikipedia.org/wiki/Polyacetylene

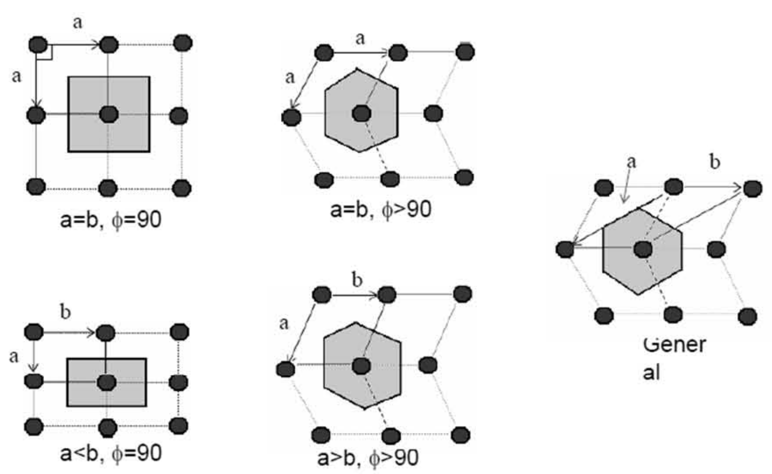
## Carbon Nanotube




- Quasi 1D structure.
- High mechanical strength.
- High electric conductivity
- High thermal conductivity ( ~10 times of copper)
- Generally believed first found by Iijima Sumio (饭岛澄男)

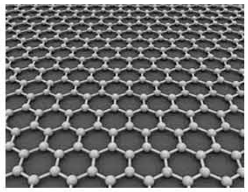


## Periodic Lattice in 2D




- Many systems have 2D lattice (e.g. Graphene)

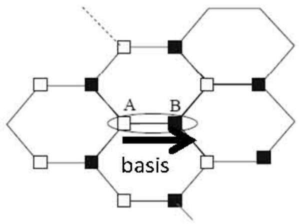
## Graphene



**Nobel Prize Physics in 2010**

http://en.wikipedia.org/wiki/Graphene

**0D: Fullerene**
Nobel Prize in Chemistry 1996




This is a Graphene sheet which has recently been isolated from Graphite by adhesive tape stamping.

Ref. Novoselov, Geim, et al. Nature, 438, 197, 2005.

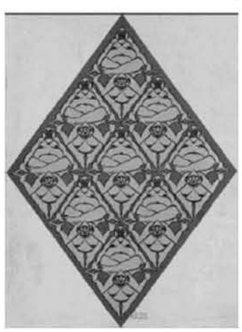
A and B do not have identical environments

Not a Bravais lattice… but either A or B forms a Bravais lattice. The graphene structure can be constructed by a Bravais lattice + a basis vector

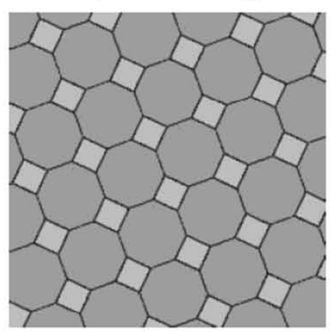


## Not a Bravais Lattice, but …

Escher Tiling



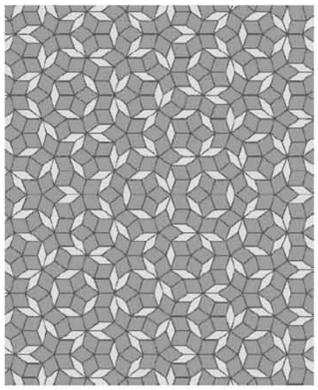
Kepler Tiling



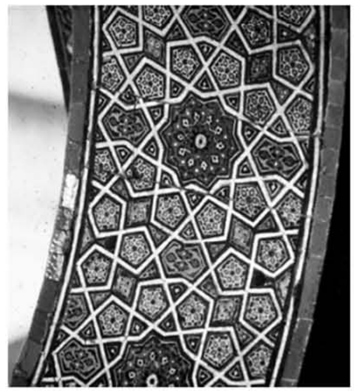
… but these can be converted into Bravais Lattice

## Not a Bravais Lattice, and …

**Penrose Tiles**



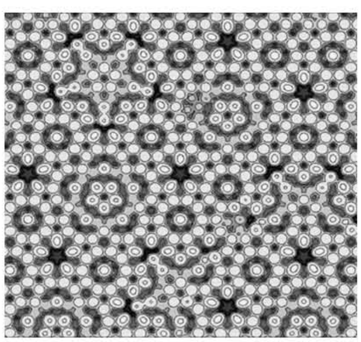
**Ancient Tiles**



- These CANNOT be transformed into Bravais lattice.



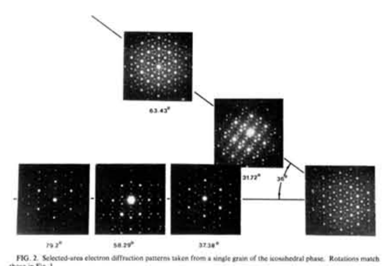
## Quasicrystals



Atomic model of an aluminium-palladium-manganese (Al-Pd-Mn) quasicrystal surface.

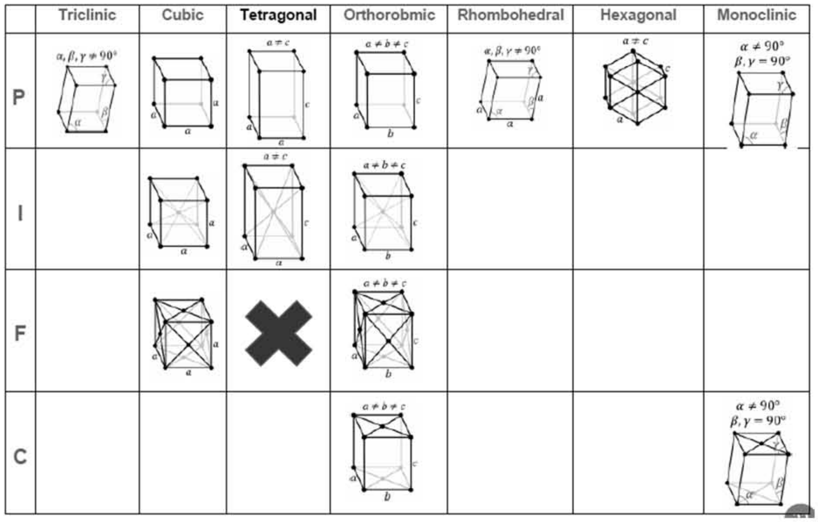
http://en.wikipedia.org/wiki/Quasicrystal

- First found by Dan Shechtman
- 2011 Nobel Prize in Chemistry



Diffraction pattern publised in their original paper in 1984 on *Physical Review Letters*

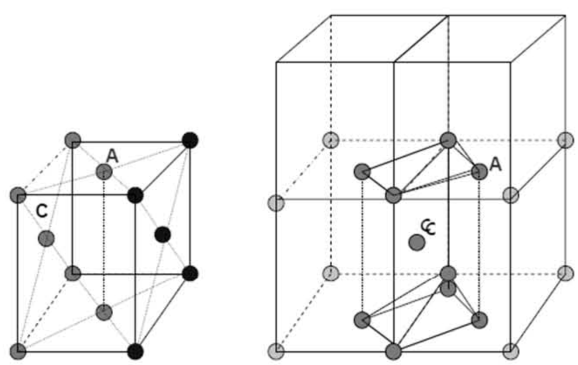
# Types of 3D Bravais Lattice





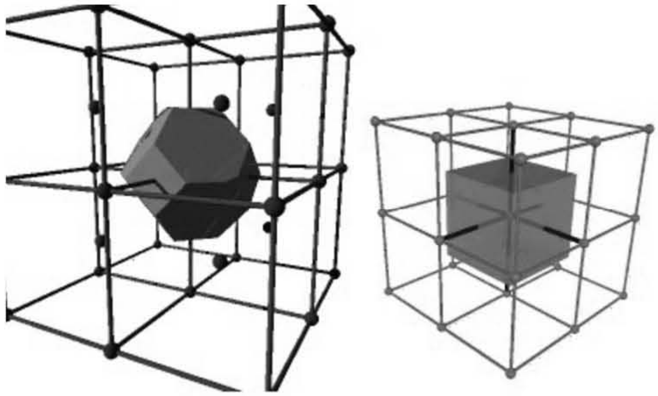

# Duplicated Bravais Lattice

Unlucky Frankenheim (1842)!




Tetragonal BC = Tetragonal FC

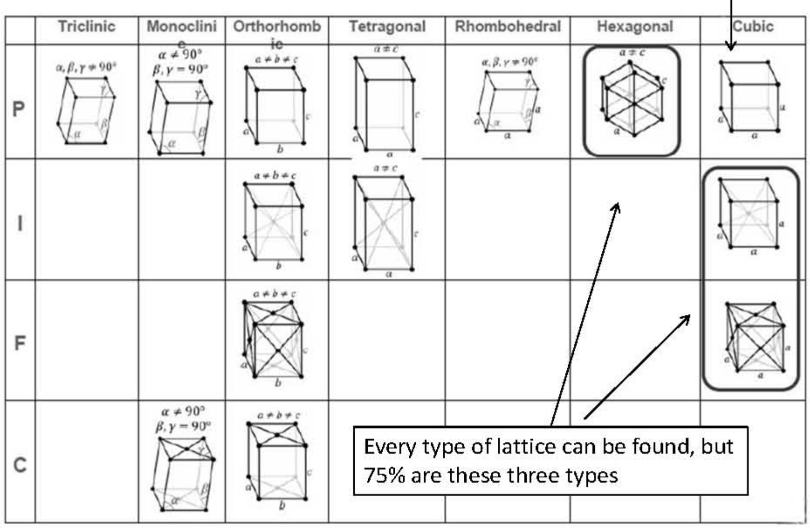
## Wigner-Seitz cells for BCC and Cubic Lattices





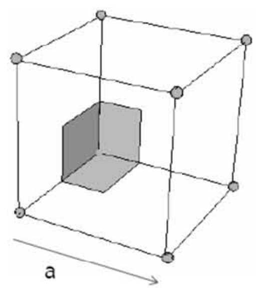
## Important Bravais Lattices

Polonium84

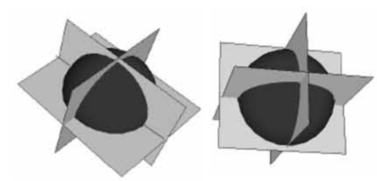



Every type of lattice can be found, but 75% are these three types

## Cubic Cell: Volume Issues



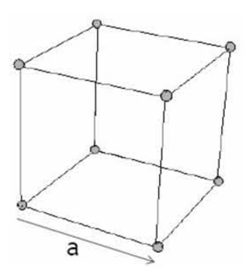

Points per cell
=1/8 points/corner x 8 corners
=1 Point/cell.
(depends on definition of cell)



Number density
= $(1/a^3)$ points/$cm^3$.
(does not depend on cell definition)



## Cubic Cell: volume issues



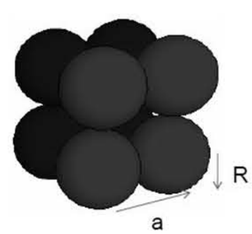

Packing density
=volume filled/total volume

R=a/2

$P= (1/8)x(4/3)\pi R^3$ x (8 corners) $/a^3$

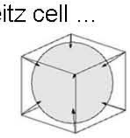
$=\pi/6$

(does not depend on cell definition)

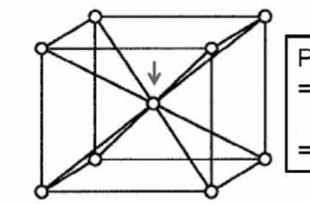



If you choose a Wigner-Seitz cell ...

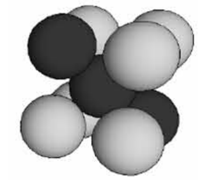
P=V_sphere / V_cube

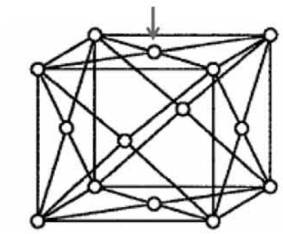


# BCC and FCC Lattices

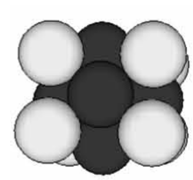


Points per cell
= 1/8 x 8 @corners
+ 1 @inside
=2



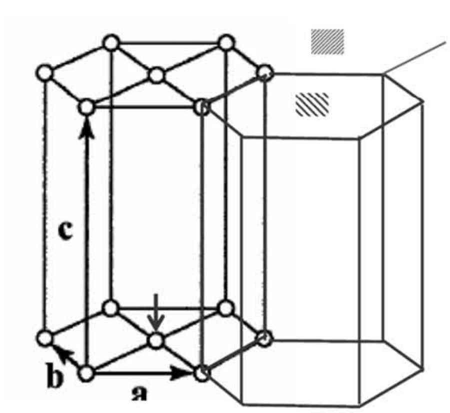


Points per cell
= 1/8 x 8 @corners
+ 1/2 x 6 @faces
=4



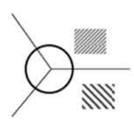


# Hexagonal Closed-Packed




Points per cell

1/2 x 2 @faces =1

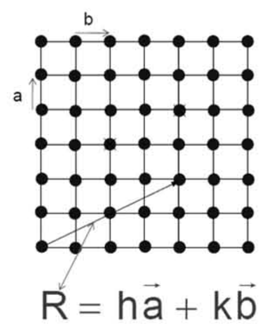


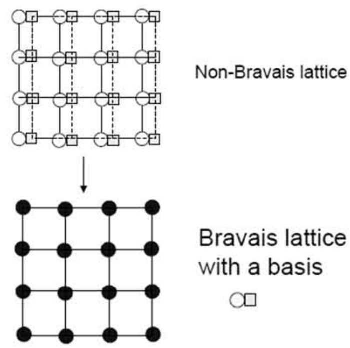
1/2x1/3 x 12 @corners =2

3 points/cell

## Geometry of Lattice Points

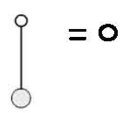
- Bravais lattice is an infinite array of discrete points generated by a set of discrete translation operations
- Crystal can be constructed by the Bravais lattice + basis

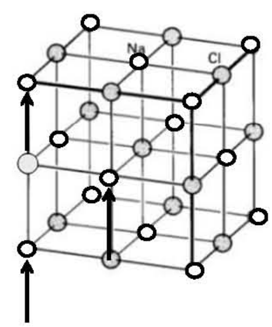




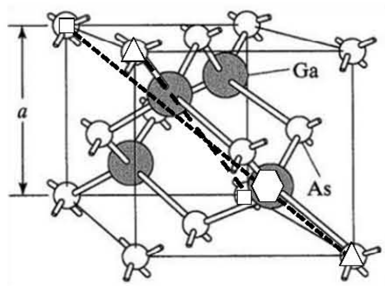

## Rocksalt FCC Structure






- This is not a simple cubic structure!
- Only looking at the Na atoms. This is the Bravais lattice. It forms an FCC structure.

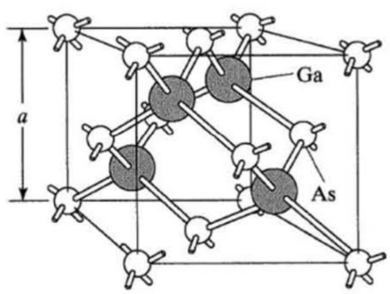
## Zinc-Blende FCC Lattice for GaAs

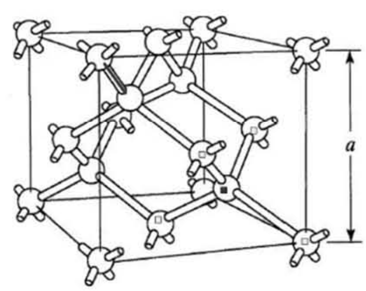



Atoms/cell=(1/8)x8 + (1/2)x6 + 4=8
FCC Lattice with a basis
Tetrahedral structure



## Diamond FCC Lattice for Silicon



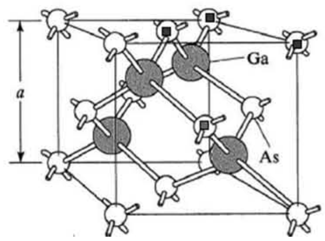

Zinc-blende: GaAs, InP…

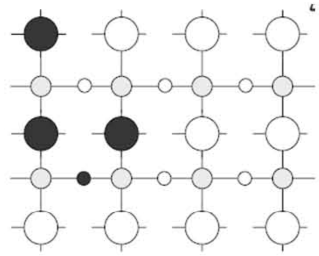
Diamond: Si, Ge…

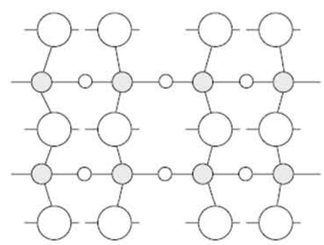
**Lattice constant a is a material property!**

Eg. a_Si ~ 5.43 Angstrom and a_GaAs ~ 5.65 Angstrom at room temperature.

## Surface Reconstruction



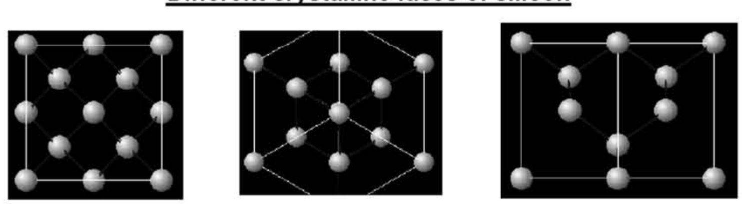




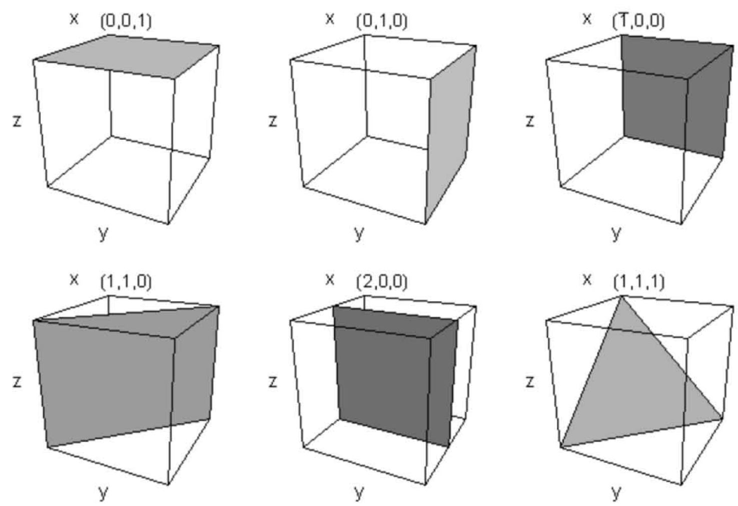
## Crystal Surfaces

- Atomic arrangement not symmetric in all directions
- Chemical and electronic properties will depend on atomic arrangement
- Need a method of specifying atomic arrangement or orientation

**Different crystalline faces of silicon**

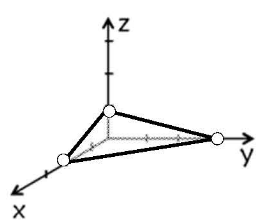


## Miller Indices and Definition of Planes





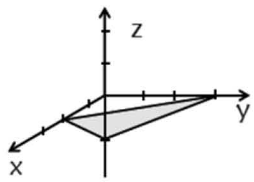

## Miller Indices: Rules




1. Set up axes along the edges of the unit cell
2. Normalize intercepts … 2, 3, 1
3. Invert/rationalize intercepts … 1/2, 1/3, 1
   3/6, 2/6, 6/6
4. Enclose the numbers in curvilinear brackets
   (3,2,6)

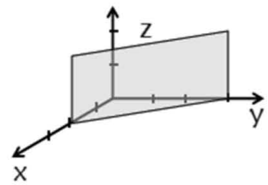
# Few More Rules …

Negative Intercept




| |
|---|
| 2, 3, -2 |
| 1/2, 1/3, -1/2 |
| 3, 2, -3 |
| $(3\ 2\ \bar{3})$ |

Intercept at infinity

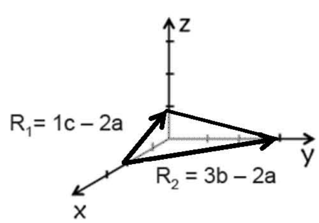



| |
|---|
| 2, 3, ∝ |
| 1/2, 1/3, 0 |
| 3, 2, 0 |
| (3 2 0) |



# Where does Miller Indices come from?

Miller indices: (326)



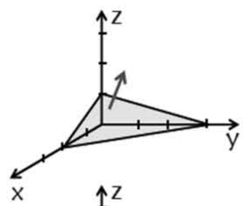

Cross Product of the two vectors
(what does it mean?)

$$R_2 x R_1 = \begin{vmatrix} a & b & c \\ -2 & 3 & 0 \\ -2 & 0 & 1 \end{vmatrix} = 3a + 2b + 6c$$

Vector index
[326]

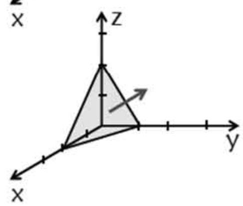
The same as Miller indices!

## Angle between Two Planes




Unit vector normal to plane 1:

$$N_1 = (h_1\vec{a} + k_1\vec{b} + l_1\vec{c})/(h_1^2 + k_1^2 + l_1^2)^{1/2}$$



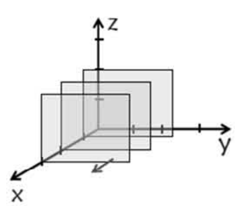

Unit vector normal to plane 2:

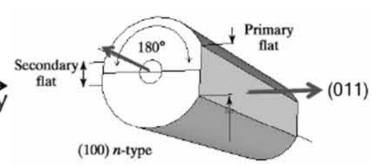
$$N_2 = (h_2\vec{a} + k_2\vec{b} + l_2\vec{c})/(h_2^2 + k_2^2 + l_2^2)^{1/2}$$

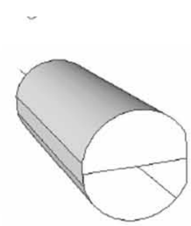
$$Cos(\theta) = N_1 \bullet N_2$$
$$= (h_2h_1 + k_2k_1 + l_2l_1)/(h_2^2 + k_2^2 + l_2^2)^{1/2}(h_2^2 + k_2^2 + l_2^2)^{1/2}$$



## Examples



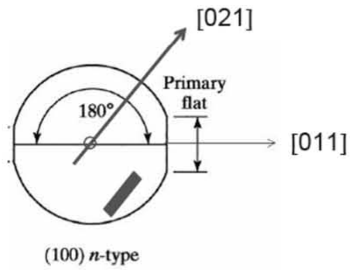



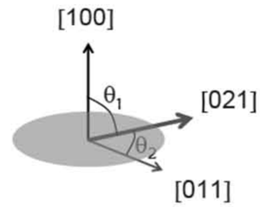
cos(θ)=(1x0+0x1+0x1)/(√1x√2) = 0

so θ=90 degrees

(011) surface is normal to (100) surface

# Example use of Miller Indices




$\cos(\theta_1)=(1x0+0x2+0x1)/(1x\sqrt{5}) = 0$, so $\theta_1=90$ degrees

[021] vector lies on (100) plane.

$\cos(\theta_2)=(0x0+2x1+1x1)/(\sqrt{5}\ \sqrt{2})$ , so $\theta_2=18.5$ degrees with respect to [011] direction.



# Conclusions

- In order to understand the transport property of semiconductor, we need to understand the chemical composition and atomic arrangements.
- Crystalline structure can be built by repeating basic building blocks… Bravais lattice, basis
- Diamond and zinc-blende structure
- To identify crystal planes…Miller Indices, vector indices

References:
1. Lecture notes of ECE606 (Alam) and ECE315 (Lundstrom) at Purdue University
2. Lecture notes of EECS320 (Zhong) at UM

## Looking ahead …

Number of atoms/volume from crystal structure

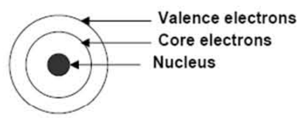
Number of electrons available for conduction

Number of electrons/atoms

$$n \neq \rho \times N$$

| II | III | IV | V | VI |
|---|---|---|---|---|
| 4 Be | 5 B | 6 C | 7 N | 8 O |
| 12 Mg | 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 |
| 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po |

**Classical Model (Drude Model)**




“Free” valence electrons contribute to conductivity

?