Semiconductor Fundamentals

Material developed by Prof. C. Z. Zhao

last lecture: 3 key points

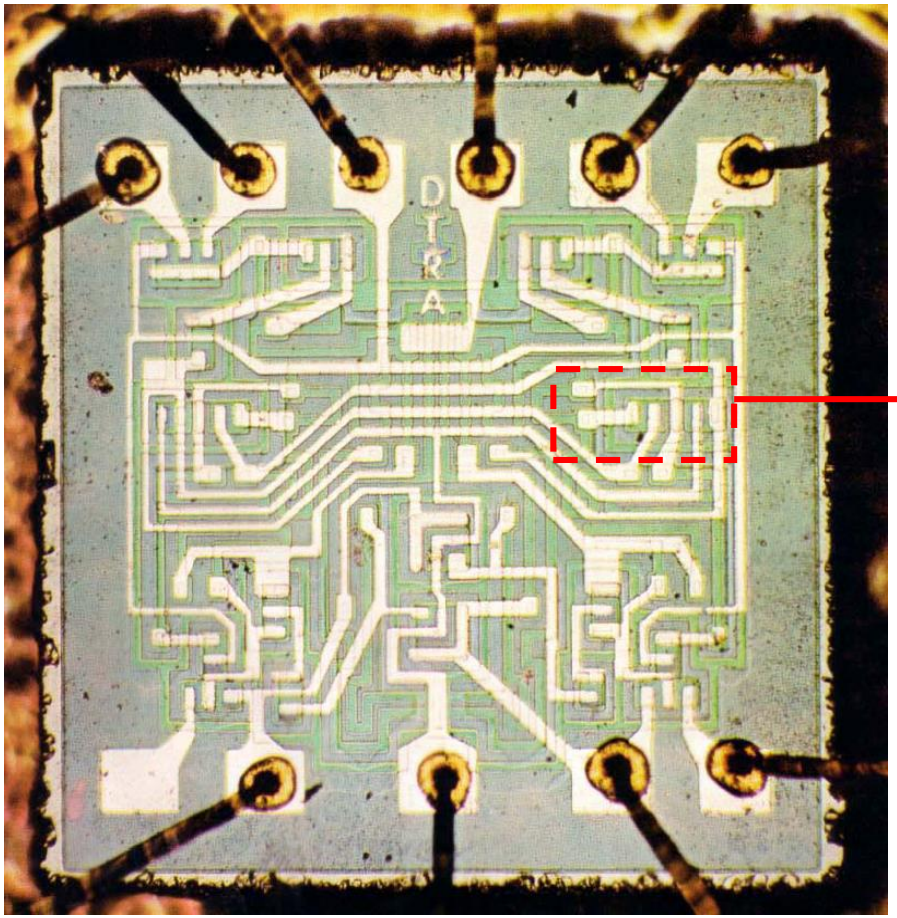
1. **Moores' Law**
2. **Technology Node Definition**
3. **Yield Definition**

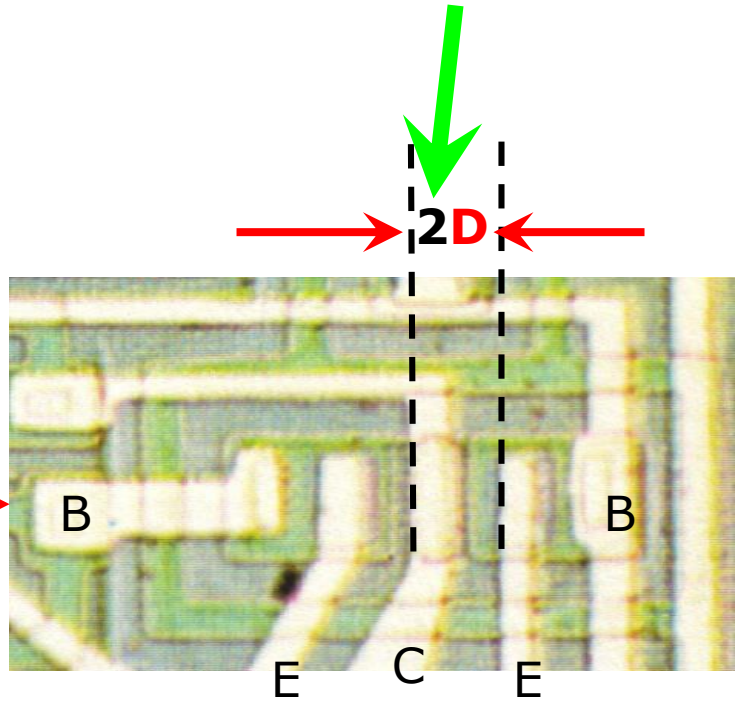
1. Moores' Law:

the number of transistors on a chip doubled every 18 to 24 months.

2. Technology **Node** Definition

- Images courtesy of Fairchild Semiconductor. Used without permission.





"D" represents IC technology level.

The names of "D", nowadays:

"D technology", or

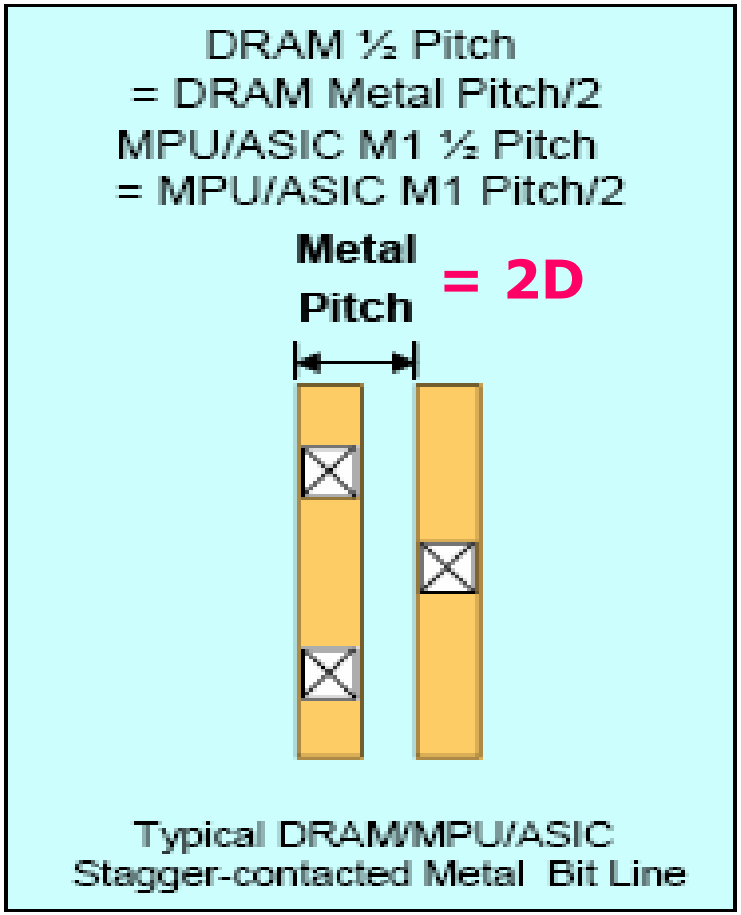
"Generation D", or **"D node"**

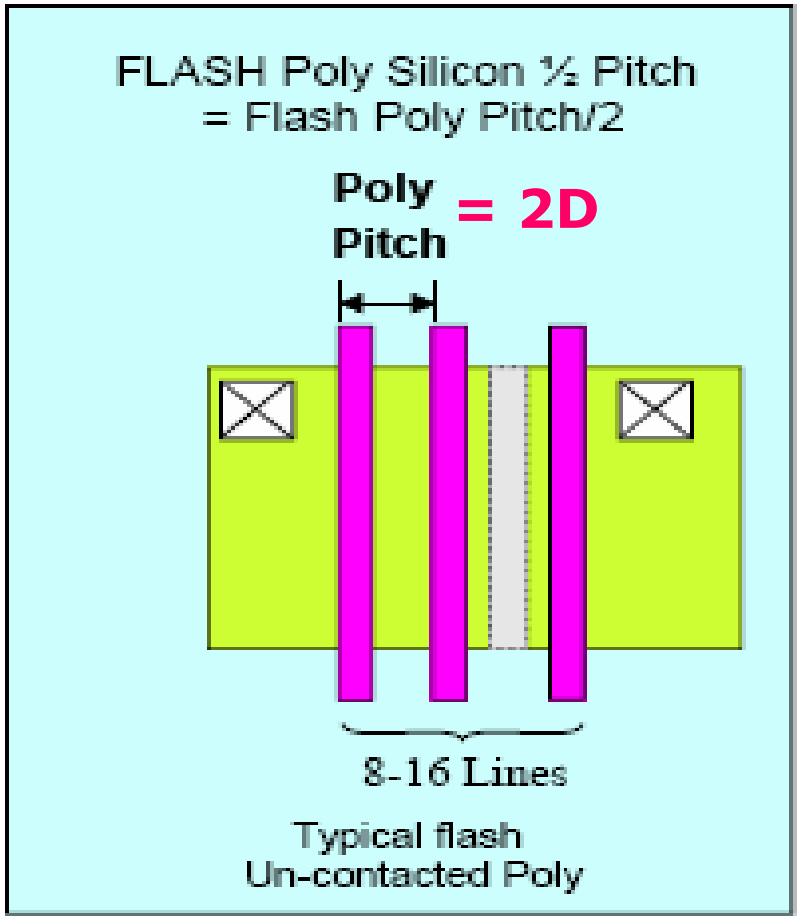
ITRS: http://www.itrs.net/home.html

- The **I**nternational **T**echnology **R**oadmap for **S**emiconductors, known throughout the world as the ITRS, is the fifteen-year assessment of the semiconductor industry's future technology requirements.

ITRS Technology **Node** Definitions

Individual roadmaps are defined for high-performance, low-power, etc.





3. Yield

$$\text{Die yield} = \frac{\text{No. of good chips per wafer}}{\text{Total number of chips per wafer}} \times 100\%$$

$$\text{Die cost} = \frac{\text{Wafer cost}}{\text{Dies per wafer} \times \text{Die yield}}$$

- in Fig.1, the **yield** is 50% and the die cost is £250 (If this wafer costs £500).
- In Fig.2, the **yield** is 87% and the chip cost is £36 (If this wafer costs £500).

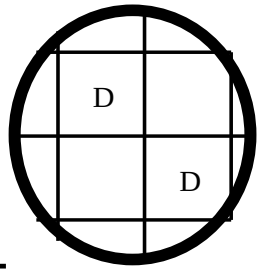


Fig.1

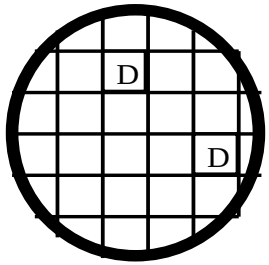


Fig.2

Chapter 2 Outline

Semiconductor Fundamentals-(I)

2.1 Atomic structures
2.2 Crystal structures

Semiconductor Fundamentals-(II)

2.3 Energy bands
2.4 The doping of semiconductors

Semiconductor Fundamentals-(III)

2.5 Boltzmann approximation & E_F, n, p
2.6 Carrier drift and diffusion

Semiconductor Fundamentals – (I)

2.1 Atomic structures 原子结构

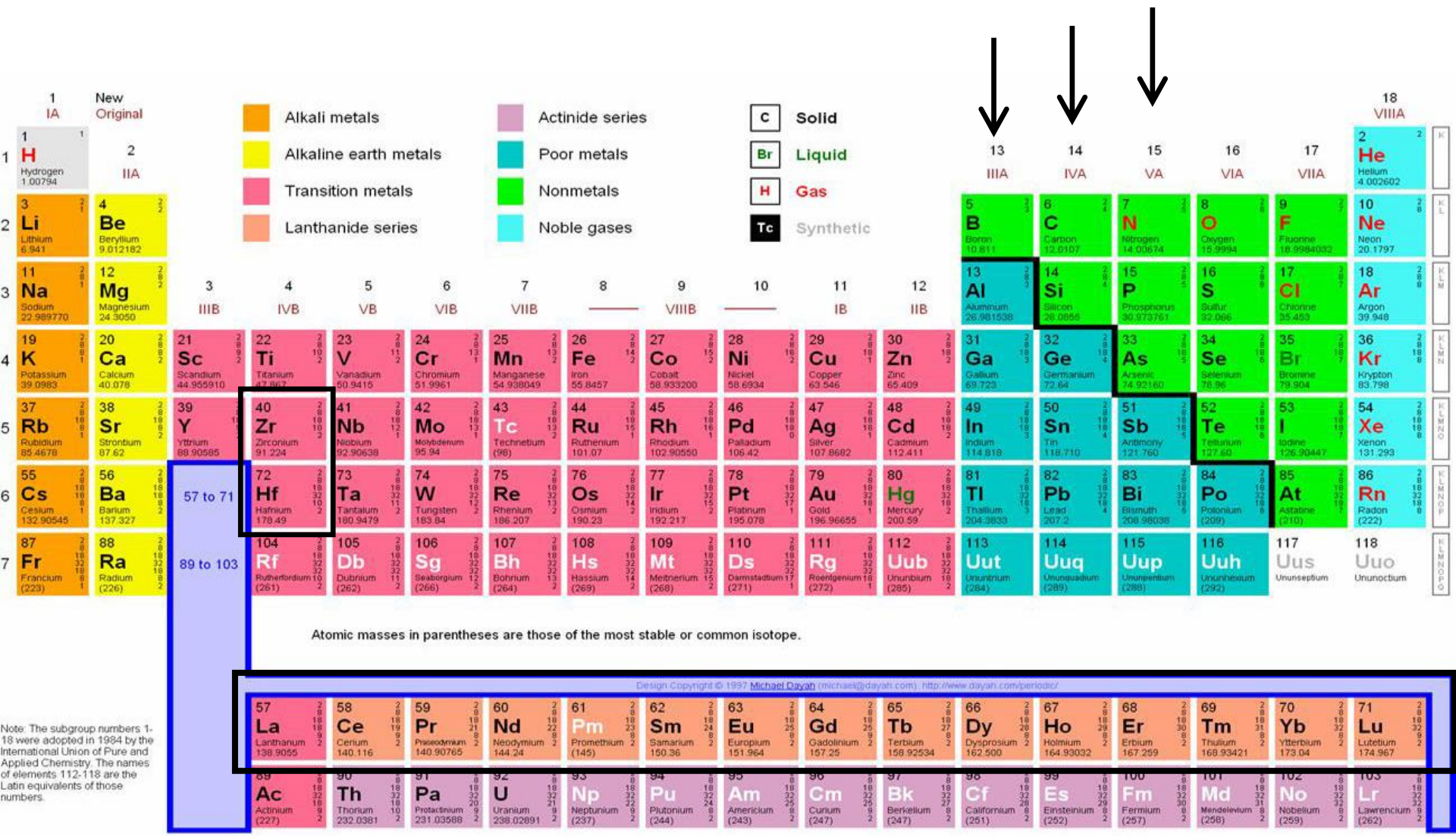
2.2 Crystal structures 晶体结构

2.1 Atomic Structures

- Elements
- Bohr's theory – orbits 轨道
- Distribution of electrons
  - Valence electrons 价电子
- Bonding
  - Ionised bond 离子键
  - Covalent bond 共价键

元素周期表

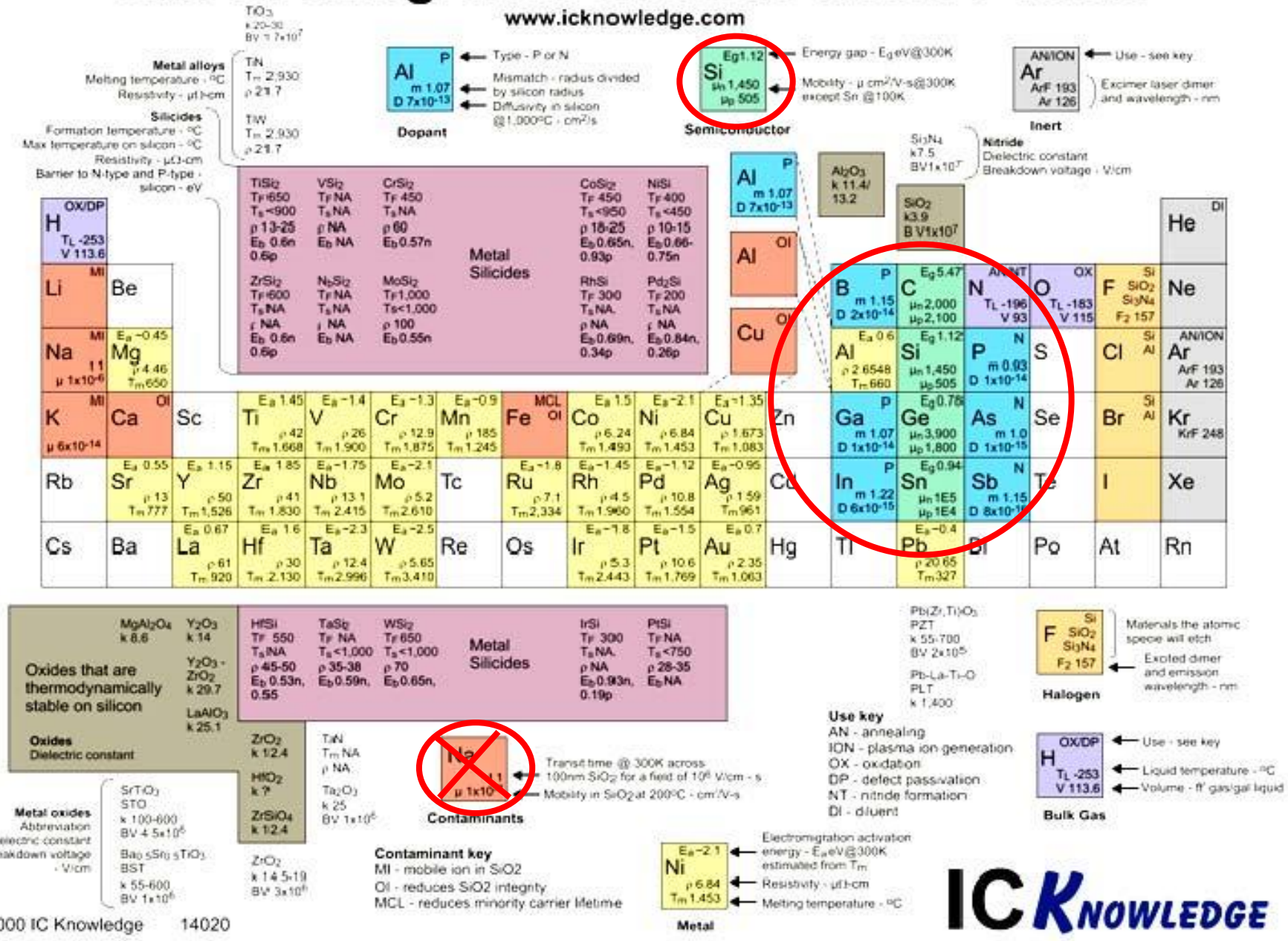
Element periodic table



Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

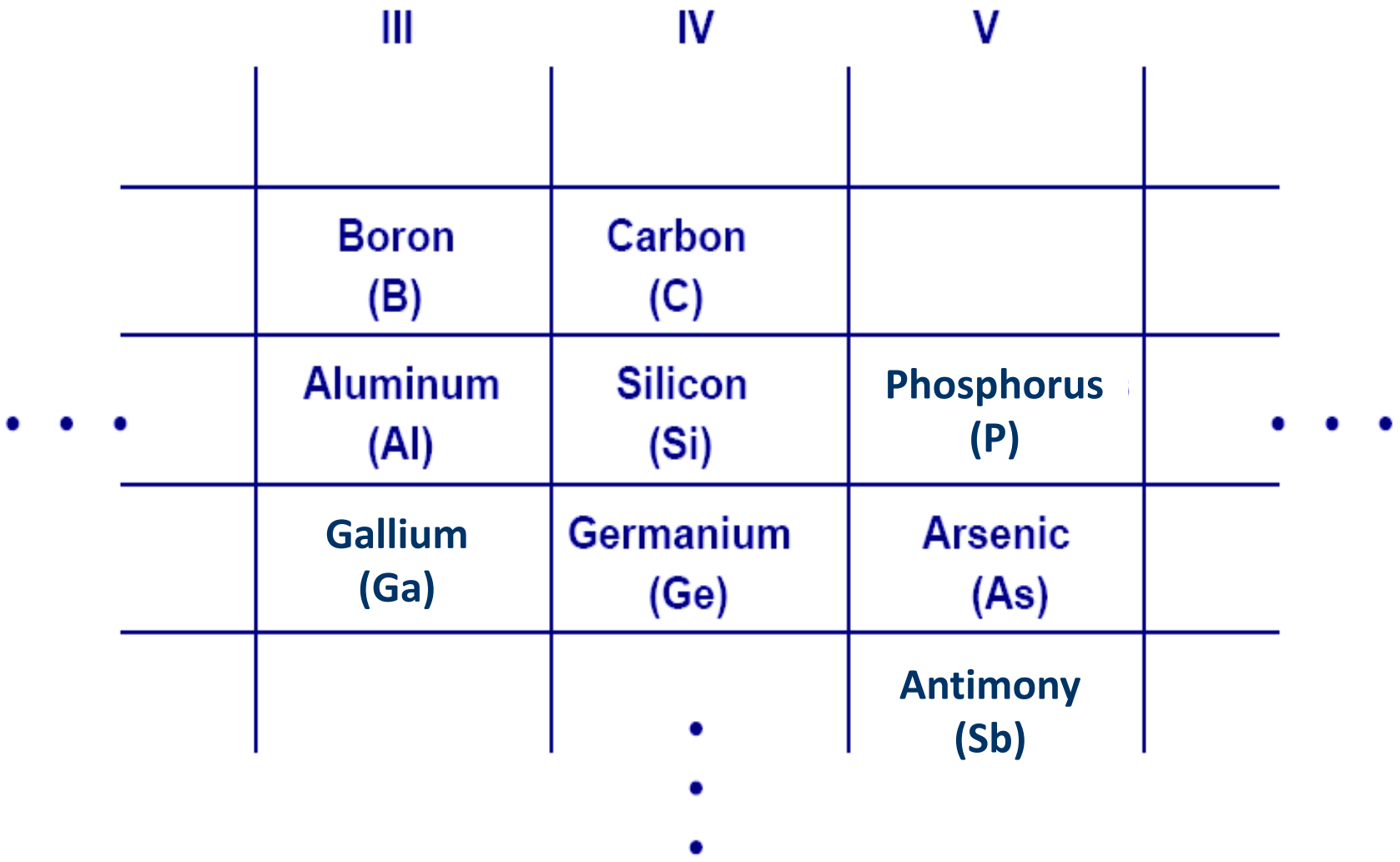
Silicon Integrated Circuit Periodic Table

www.icknowledge.com



IC KNOWLEDGE

Semiconductor Materials



Semiconductor Materials

元素半导体材料

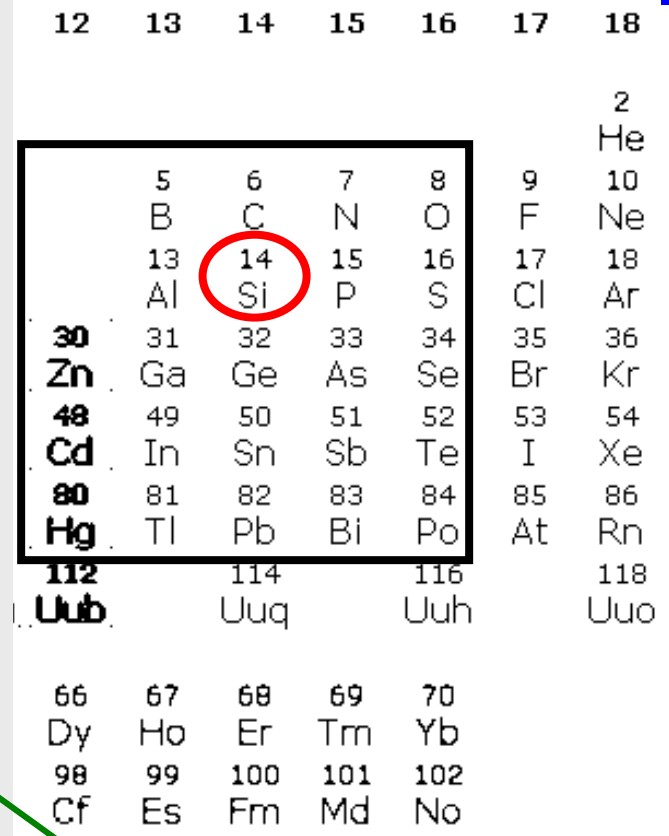
Elemental:

化合物半导体材料

Compound:

合金半导体材料

Alloy:



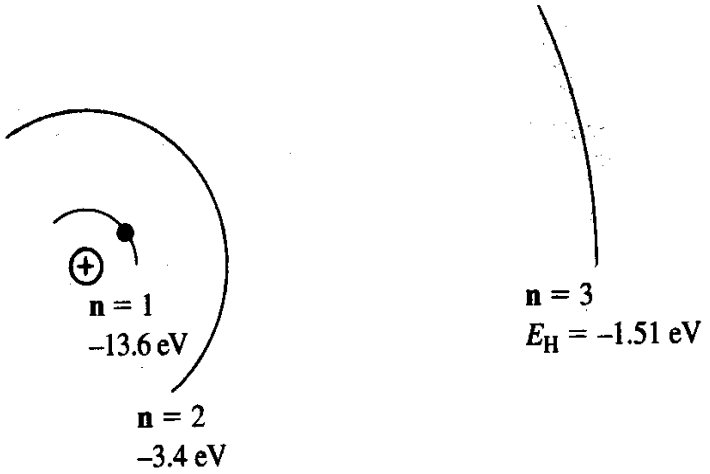
CdTe/CdS

2.1 Atomic Structures

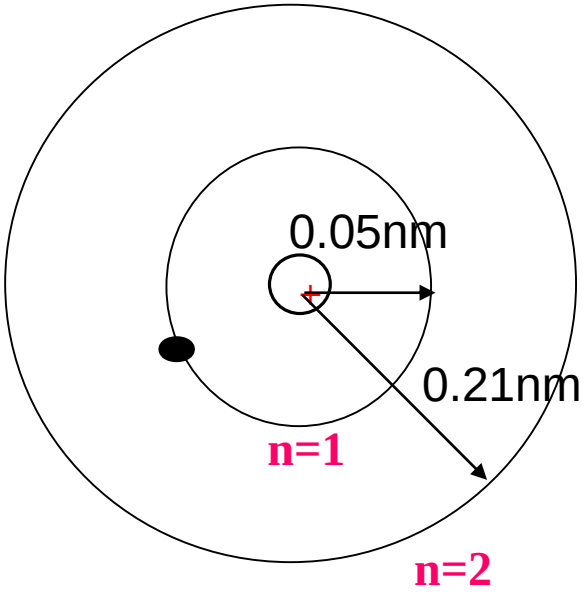
- Elements
- **Bohr's theory – orbits**
- Distribution of electrons
  - Valence electrons
- Bonding
  - Ionised bond
  - Covalent bond

Bohr's Theory - Orbits

- The electrons of an atom can only stay on a number of orbits. **The radius of orbits changes discontinuously.**
- For example, hydrogen atom,



电子伏

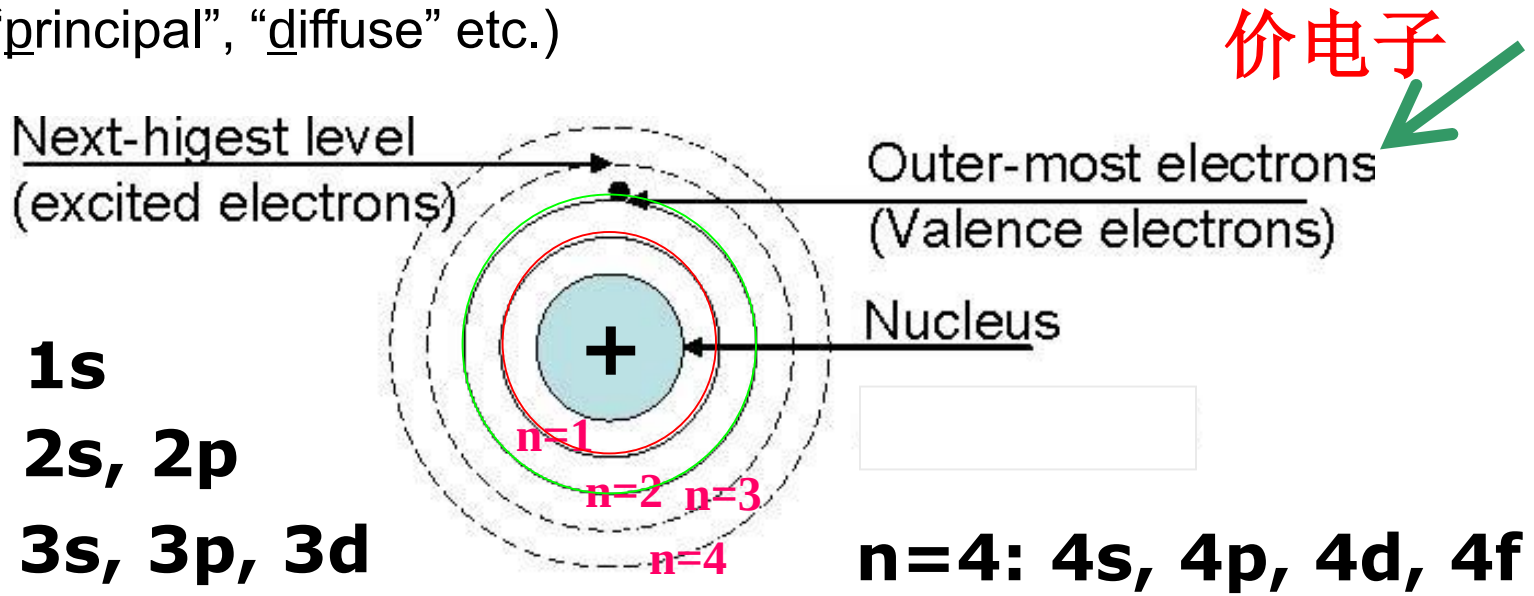


- The orbit with smaller radius has lower energy.

http://winter.group.shef.ac.uk/orbitron/

Orbits

- Electrons reside in stable configurations (orbits, orbitals)
- These orbitals are numbered (in order of increasing energy): 1s 2s 2p 3s 3p 3d 4s 4p 4d 4f …
- Each orbital can have up to two electrons
- "s" levels: **two** electron states
- Each "p" level is 3fold degenerate: **six** electron states
- Historical: "s" was chosen because the optical emission related to transitions for these levels gives "sharp" lines (similarly: "principal", "diffuse" etc.)



n=1: 1s

n=2: 2s, 2p

n=3: 3s, 3p, 3d

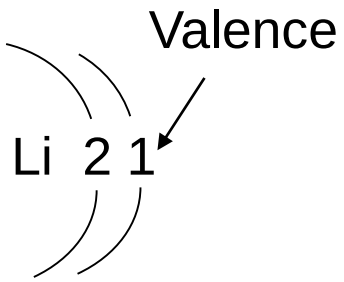
n=4: 4s, 4p, 4d, 4f

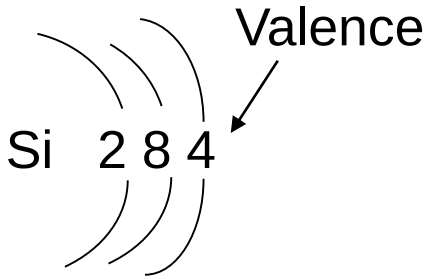
2.1 Atomic Structures

- Elements
- Bohr's theory – orbits
- **Distribution of electrons**
  - Valence electrons
- Bonding
  - Ionised bond
  - Covalent bond

Distribution of electrons in atoms

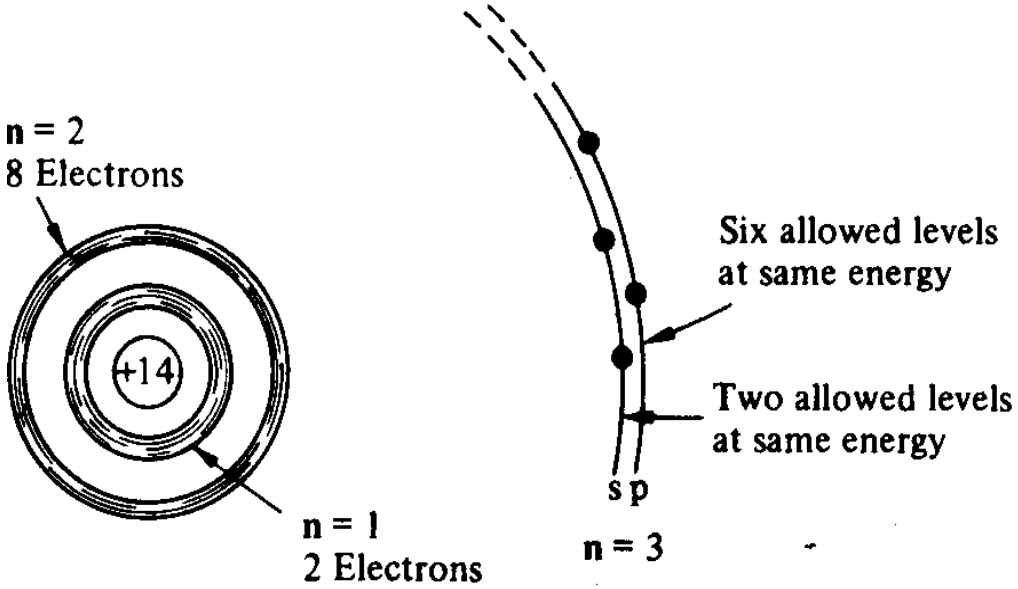
- **<u>Maximum number of electrons in an orbit is fixed</u>**
  - 1st orbit: 2 (1s)
  - 2nd orbit: 8 (2s, 2p) (3rd orbit: 3s, 3p, 3d)
- Orbit with lowest energy is filled first, since the lower energy, the more stable.
- The orbit with smaller radius has lower energy.
- Electrons in **the outmost orbit**: '<u>valence electrons</u>'.
- Property of atoms depends on valence electrons





-13.6eV -3.4eV -1.51eV

From Hydrogen to Silicon

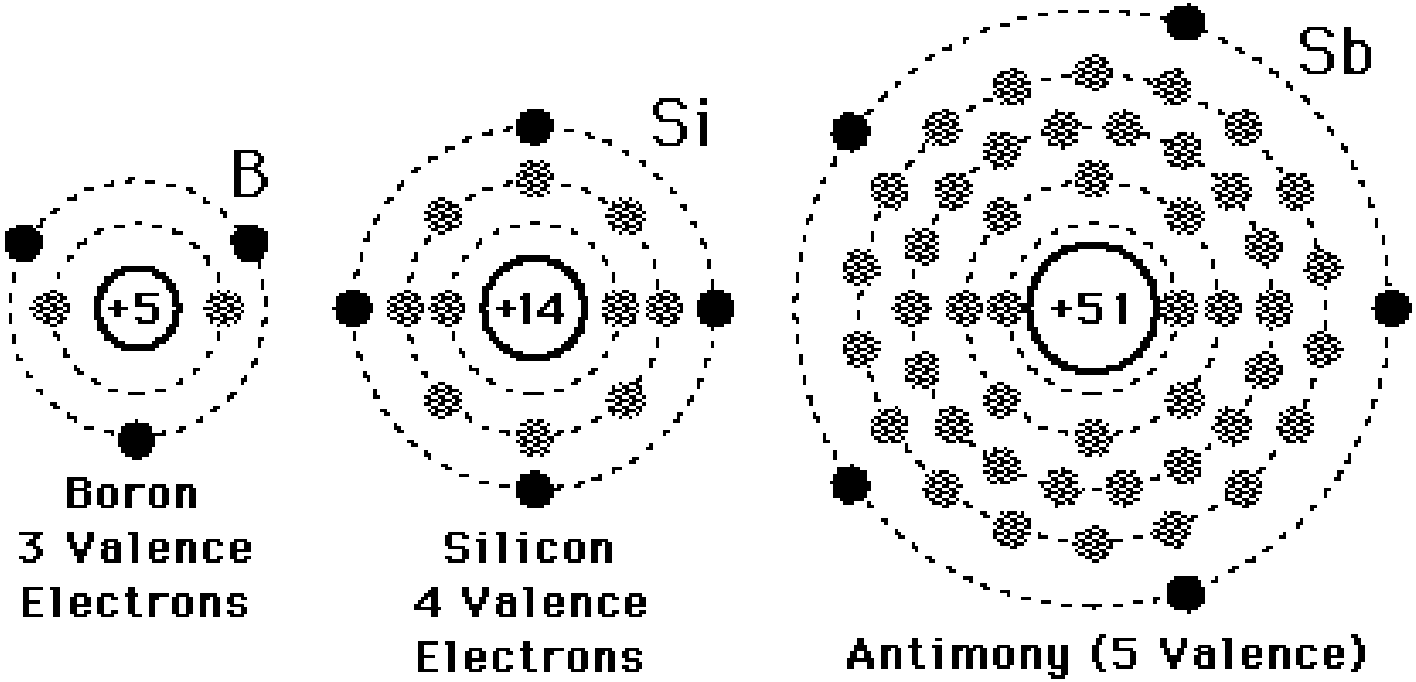


n=3: 3s, 3p, 3d

Z	Name	# of Electrons						Notation
		1	2		3			
		1s	2s	2p	3s	3p	3d	
1	H	1						$1s^1$
2	He	2						$1s^2$
3	Li	2	1					$1s^2\ 2s^1$
4	Be	2	2					$1s^2\ 2s^2$
5	B	2	2	1				$1s^2\ 2s^2\ 2p^1$
6	C	2	2	2				$1s^2\ 2s^2\ 2p^2$
7	N	2	2	3				$1s^2\ 2s^2\ 2p^3$
8	O	2	2	4				$1s^2\ 2s^2\ 2p^4$
9	F	2	2	5				$1s^2\ 2s^2\ 2p^5$
10	Ne	2	2	6				$1s^2\ 2s^2\ 2p^6$
11	Na	2	2	6	1			$1s^2\ 2s^2\ 2p^6\ 3s^1$
12	Mg	2	2	6	2			$1s^2\ 2s^2\ 2p^6\ 3s^2$
13	Al	2	2	6	2	1		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$
14	Si	2	2	6	2	2		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$
15	P	2	2	6	2	3		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^3$
16	S	2	2	6	2	4		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^4$
17	Cl	2	2	6	2	5		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^5$
18	Ar	2	2	6	2	6		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6$

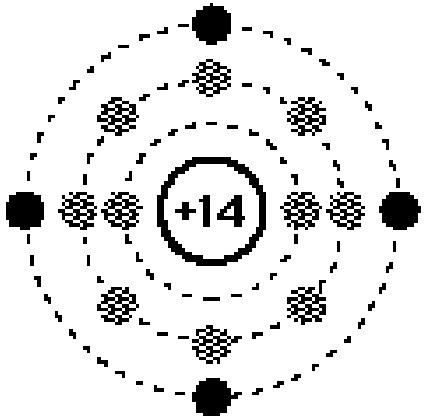
Valence Electrons of B, Si & Sb

- The electrons in the **outermost shell** of an atom are called valence electrons; they dictate the nature of the chemical reactions of the atom and largely determine the electrical nature of solid matter.

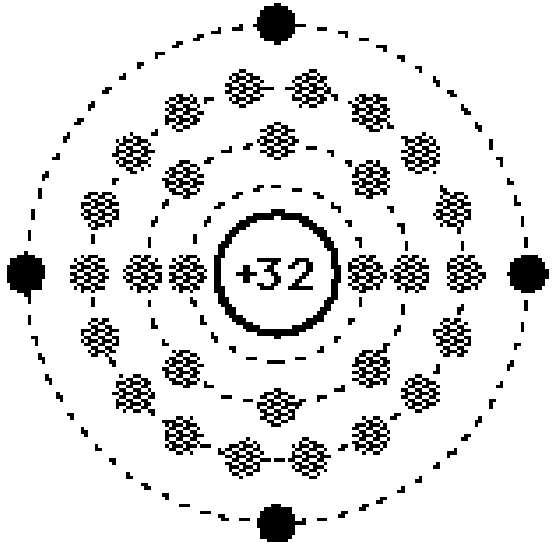


Valence Electrons of Si & Ge

- Solid state electronics arises from the unique properties of silicon and germanium, each of which has four valence electrons and which form crystal lattices.



Silicon



Germanium

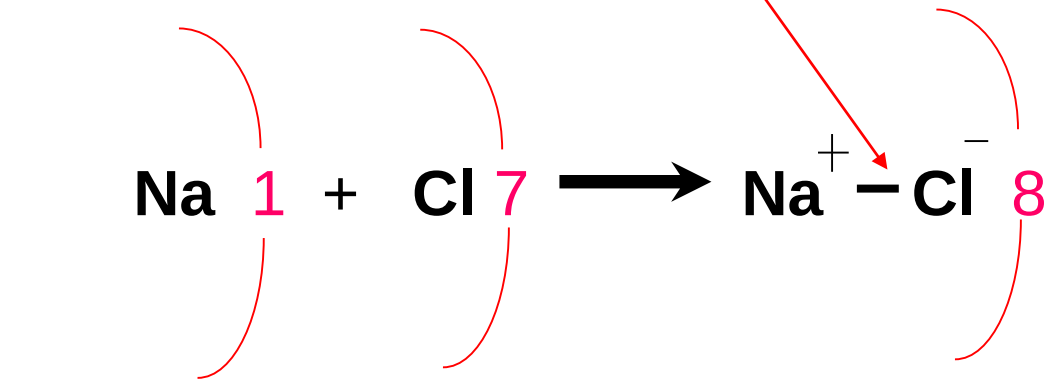
2.1 Atomic Structures

- Elements
- Bohr's theory – orbits
- Distribution of electrons
  - Valence electrons
- **Bonding**
  - Ionised bond
  - Covalent bond

Bonding

- An unstable atom can achieve a quasi-stable structure by bonding with other atoms.
- **Ionized bonds**:

  The atoms are ionized first and then bonded through electrostatic force.

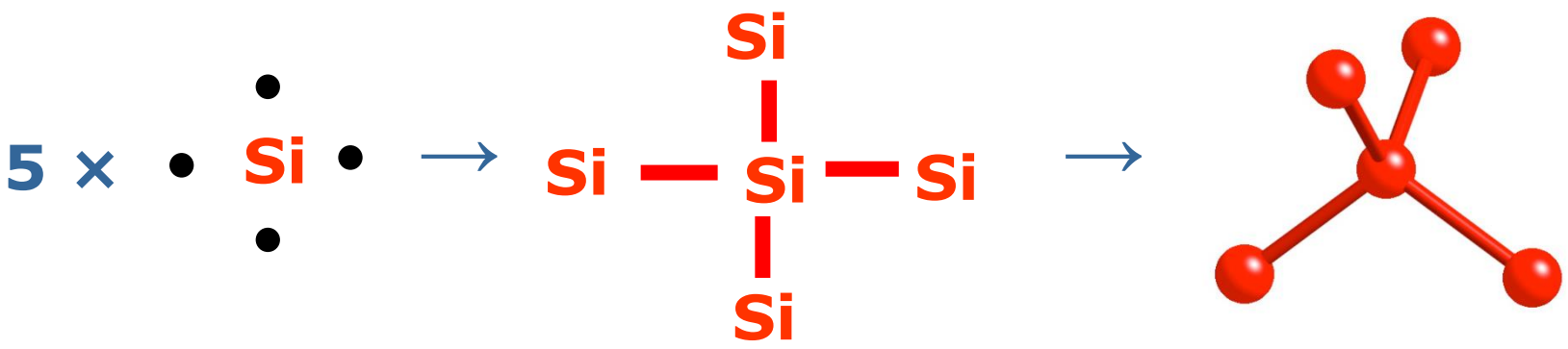


Covalent bonds

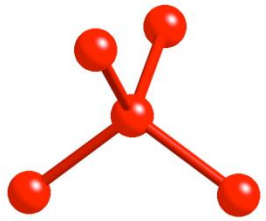
- Valence electrons are **shared**
- Notation of a covalent bond (can't be "seen")

标记法 Si : Si Si — Si Si ⌒ Si

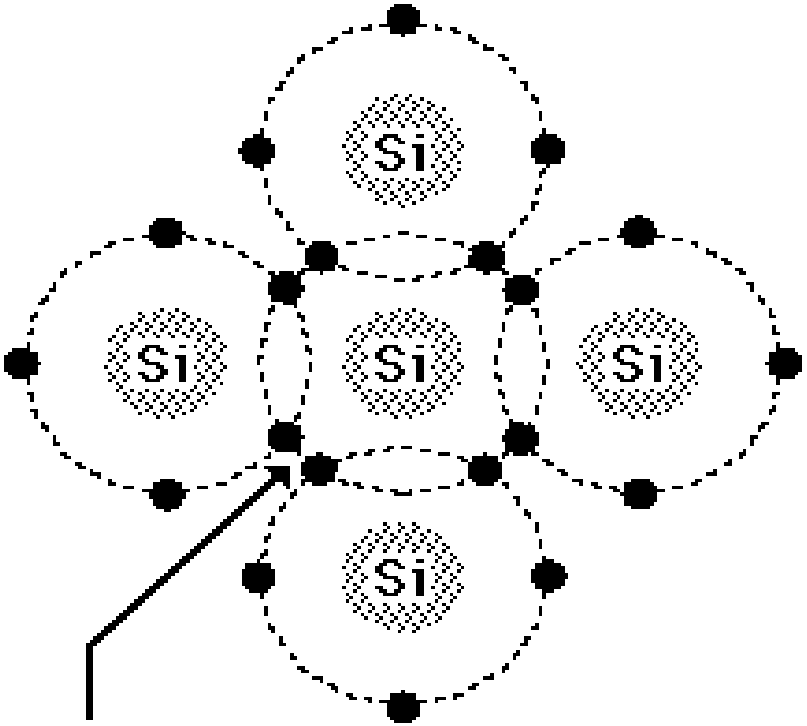
- Si shares its 4 valence electrons with four other Si atoms by forming covalent bonds.

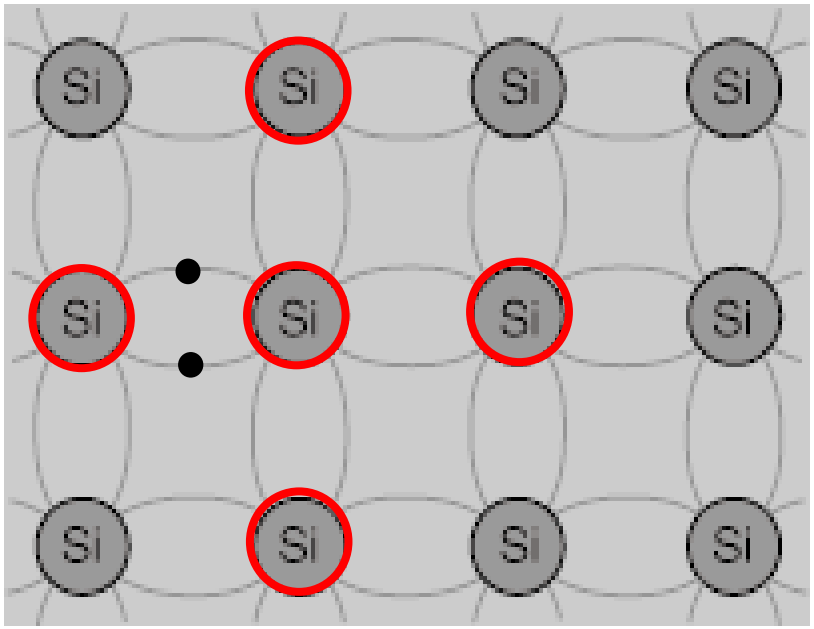


Covalent bonds



- The bonds are of equal length and angular separation to produce a **crystal structure**.



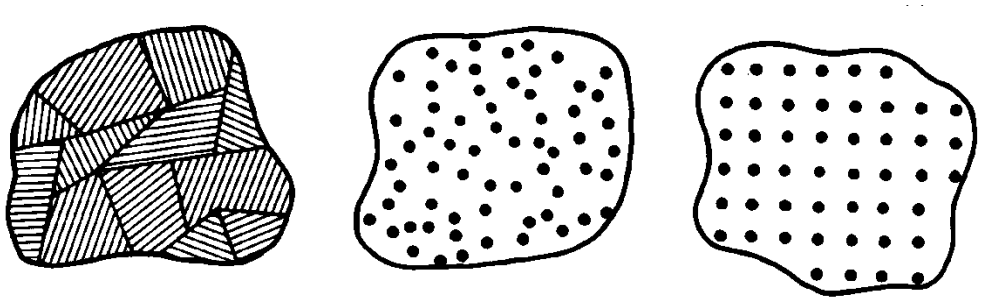


2.2 Crystal Structures

- General material properties
- Crystal structures
- Crystallographic notation
- Bohr’s theory – energy level & band

Material Properties

- generally crystalline in structure for IC devices
  - In recent years, however, non-crystalline semiconductors have become commercially very important



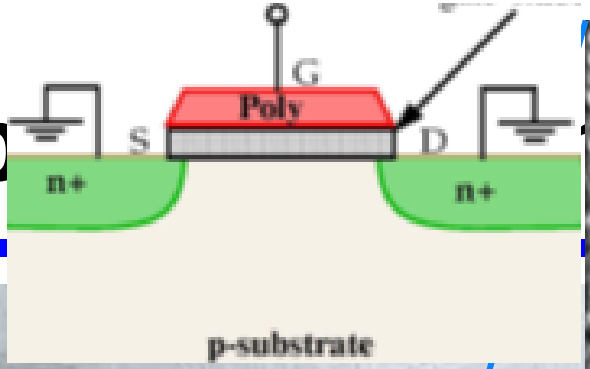
polycrystalline amorphous crystalline

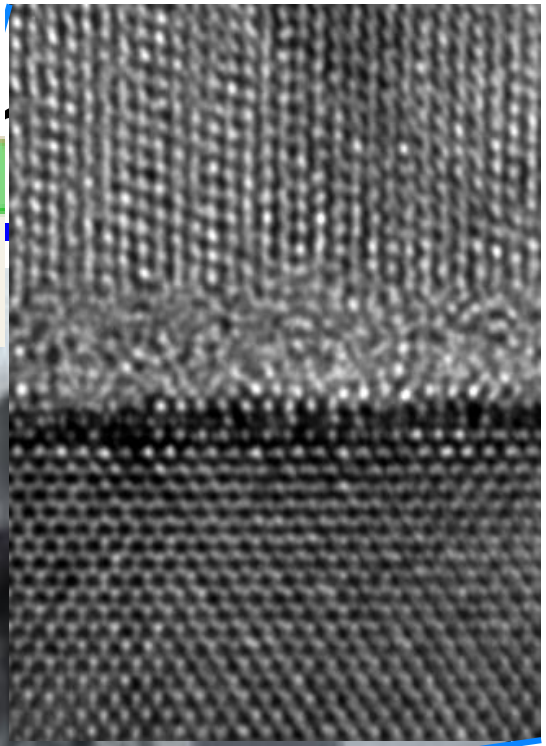
多晶

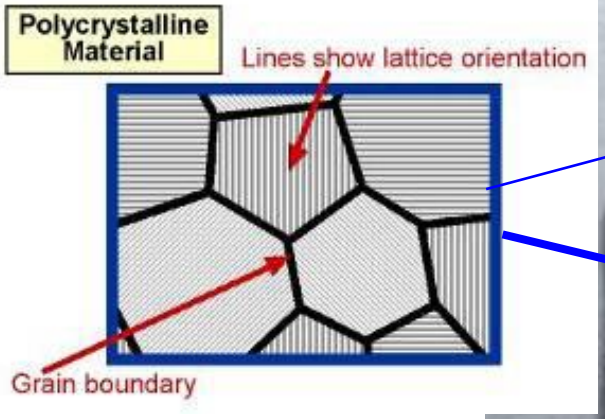
非晶

单晶

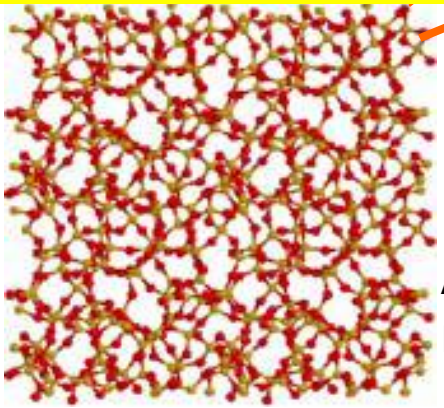
Material Prop



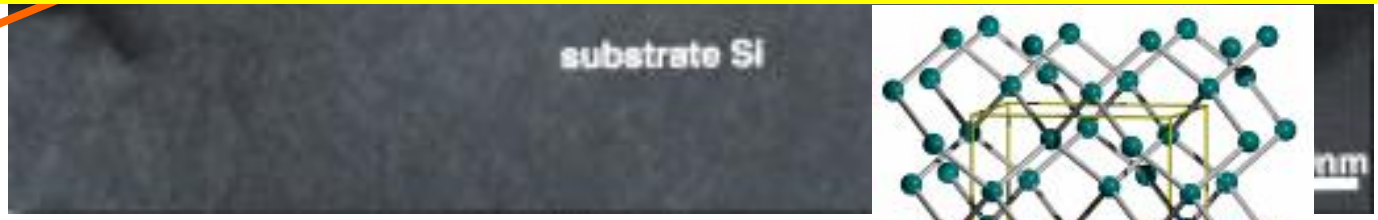




Transmission Electron Microscope透射电子显微镜



Amorphous materials



Single-Crystal Material

2.2 Crystal Structures

- General material properties
- **Crystal structures**
- Crystallographic notation
- Bohr's theory – energy level & band

Silicon Crystallography

晶格

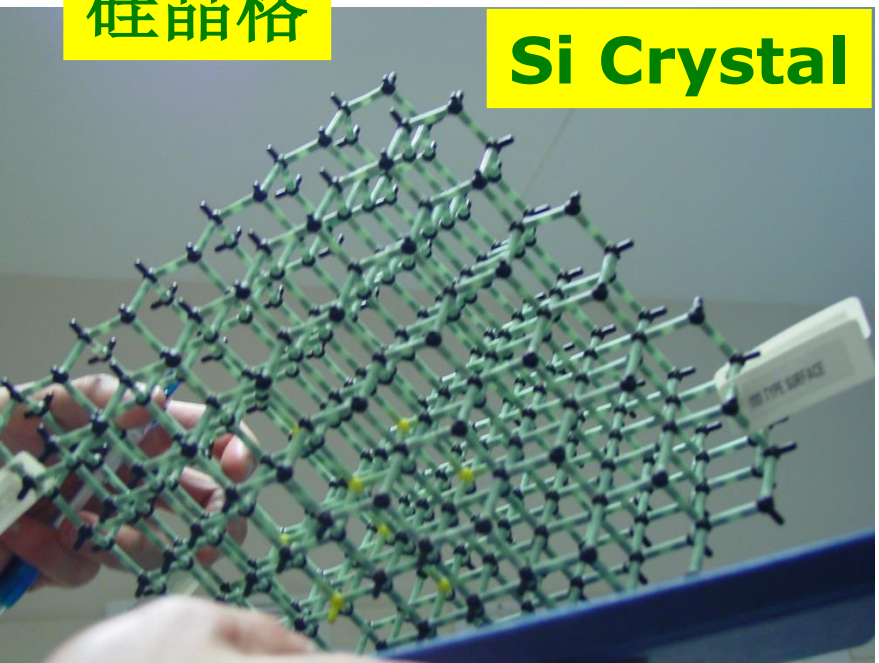
- ***Lattice:*** periodic arrangement of atoms in a crystal
- ***Unit Cell:*** smallest volume segment representative of entire lattice

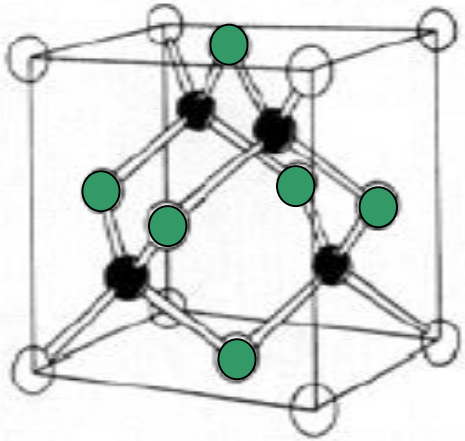
晶胞

Crystal : Atoms + Lattice

- ***Silicon Lattice = Diamond Lattice:*** atoms with four covalent bonds, cubic lattice

硅晶格





Lattice and Crystal

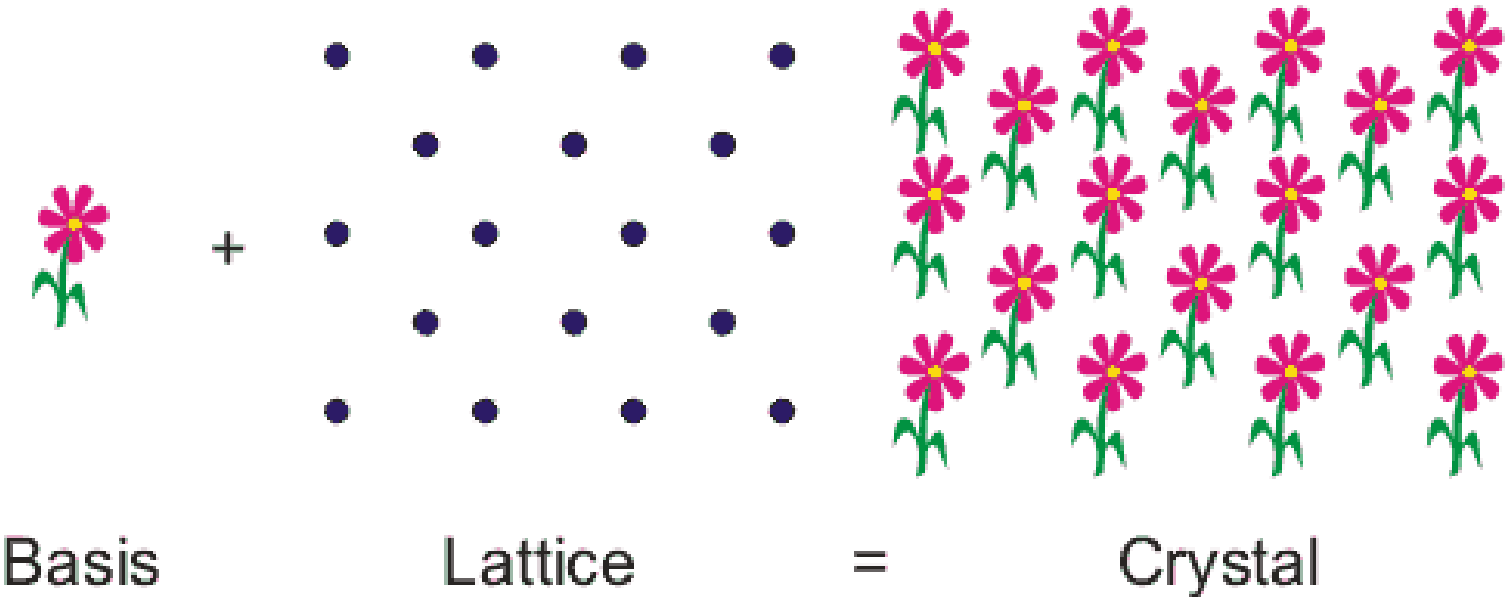
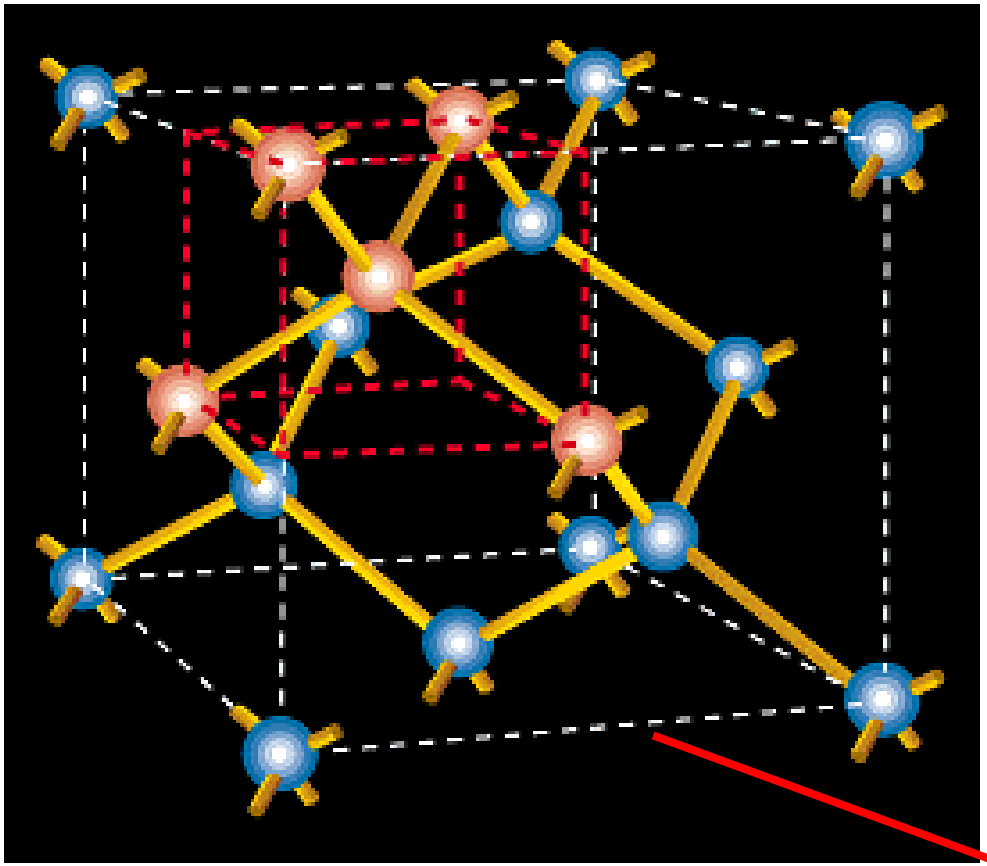
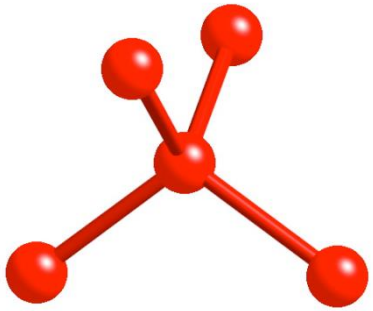


Figure 1. A crystal can be thought of as being like wallpaper. The motif is analogous to the basis and the arrangement of the motif over the surface is like the lattice.

The Si Crystal: Unit Cell



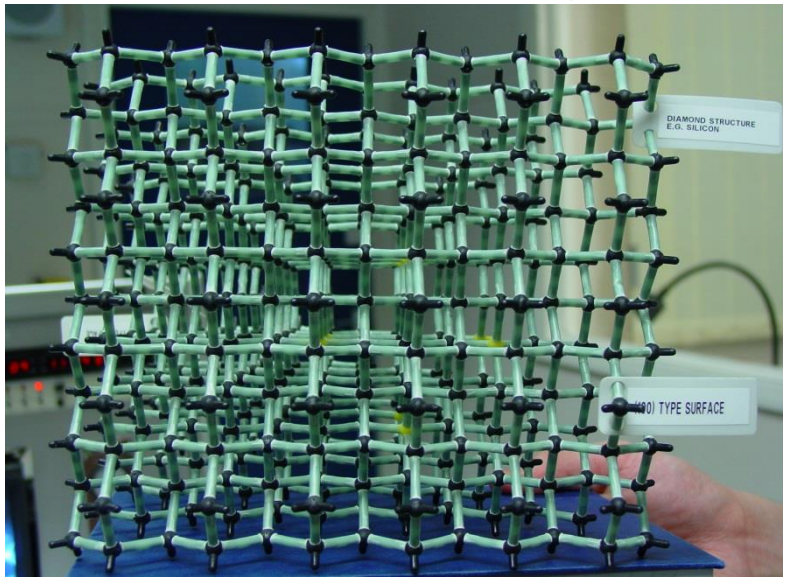


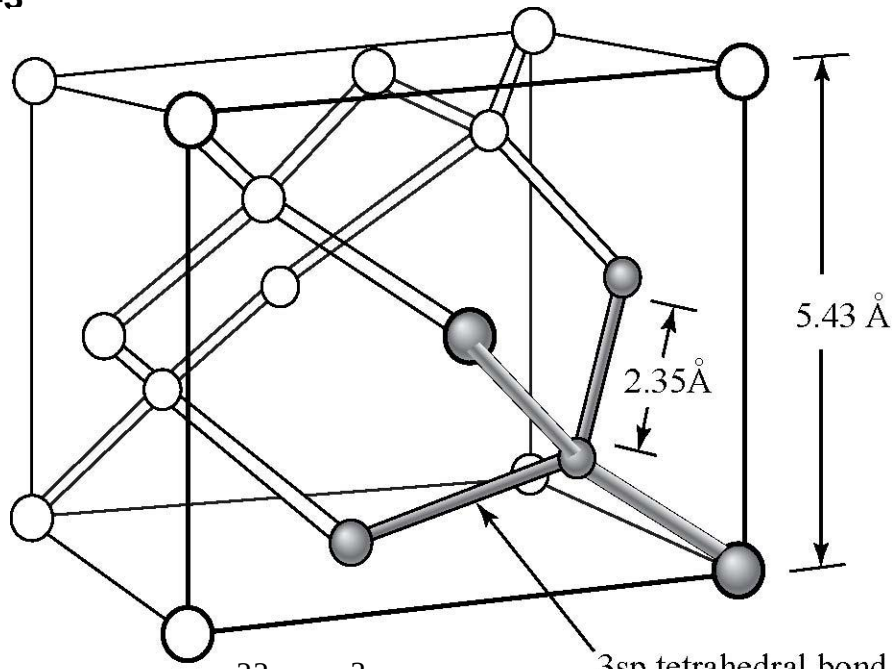
- Each Si atom has 4 nearest neighbors
- lattice constant = 5.431Å

“diamond cubic” lattice

Silicon crystal structure

- Silicon is a crystalline material: – long range atomic arrangement
- Diamond lattice: – atoms tetrahedrally bonded by sharing valence electrons (covalent bonding)
- Each atom shares 8 electrons: – low energy and stable situation
- **Si atomic density: 5 ×10^{22} cm^{-3}**



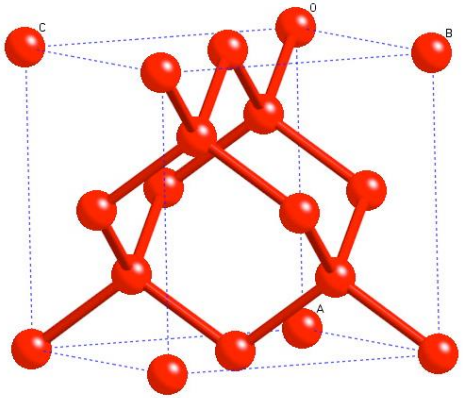


$$\frac{\#\,Atoms}{Volume} = \frac{8\times 1/8 + 6\times 1/2 + 4}{a_0^3} = \frac{8}{(5.43\times 10^{-8} cm)^3} = 5\times 10^{22} cm^{-3}$$

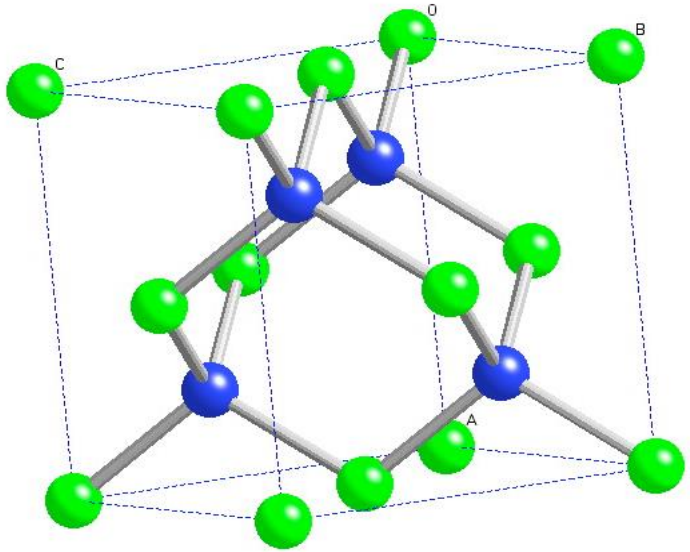
HW-1

Silicon crystal structure: summary

- Silicon atoms form covalent bonds and can crystallize into a regular lattice.
- The main point here is that a silicon atom has four electrons which it can share in covalent bonds with its neighbors.
- Silicon crystallizes in the same pattern as diamond.
- The bold lines between silicon atoms in the lattice illustration indicate nearest-neighbor bonds.



Compound Semiconductors



闪锌矿

- “zinc blende” structure

  Simply the diamond structure in which the species of atoms alternate

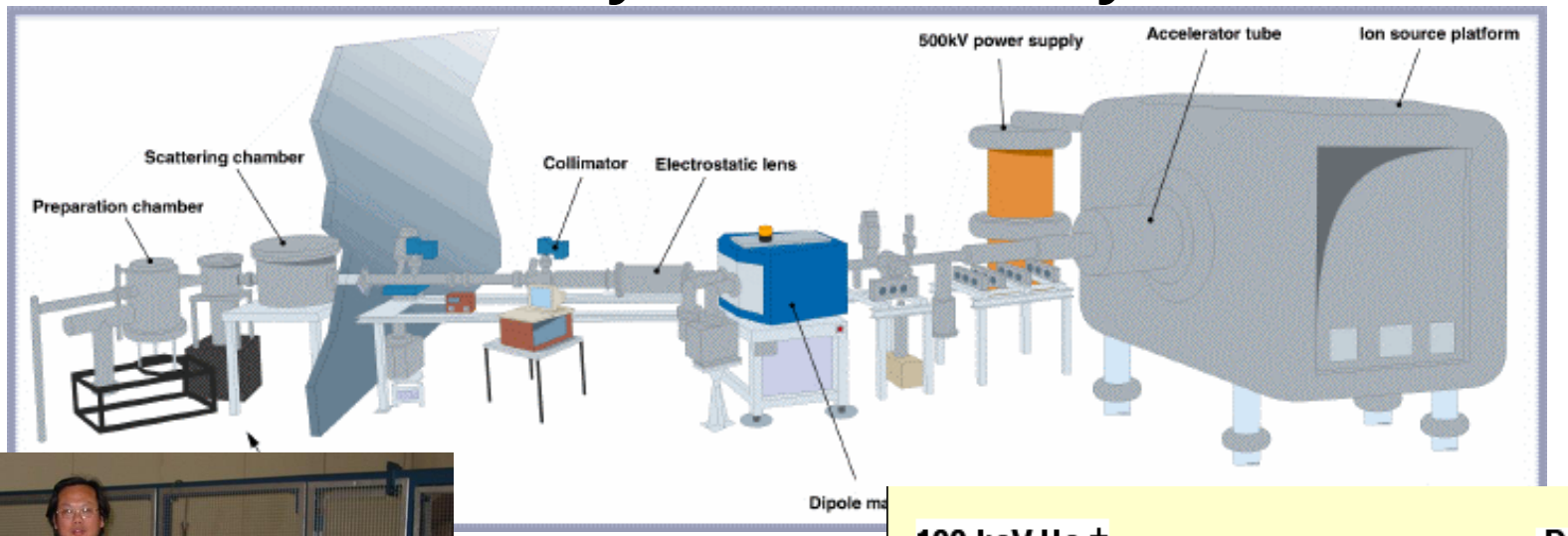
- III-V compound semiconductors: GaAs, GaP, GaN, *etc.*

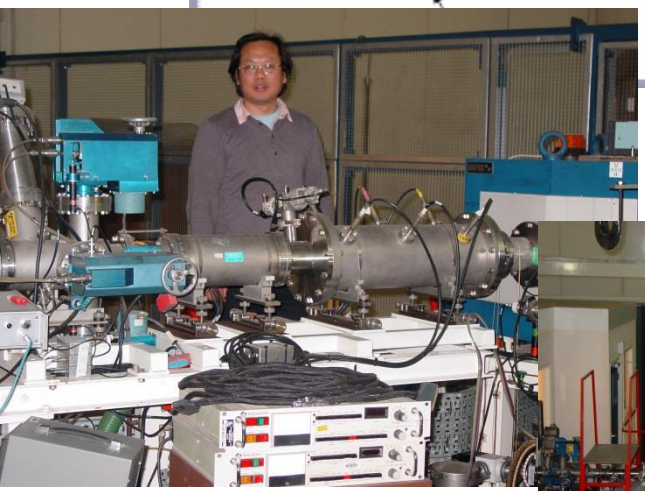
  ✓ important for optoelectronics and high-speed ICs

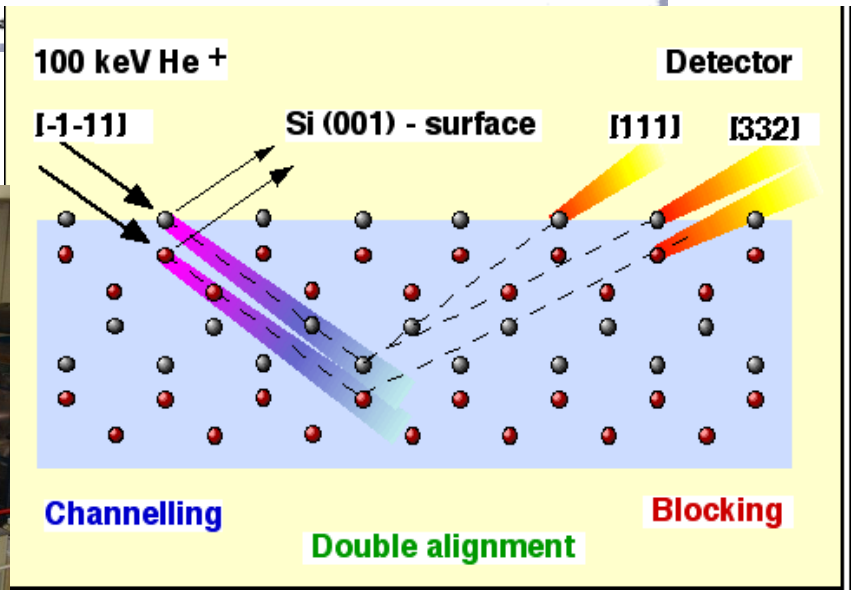
中等能量离子散射谱

How do we know crystal structures?

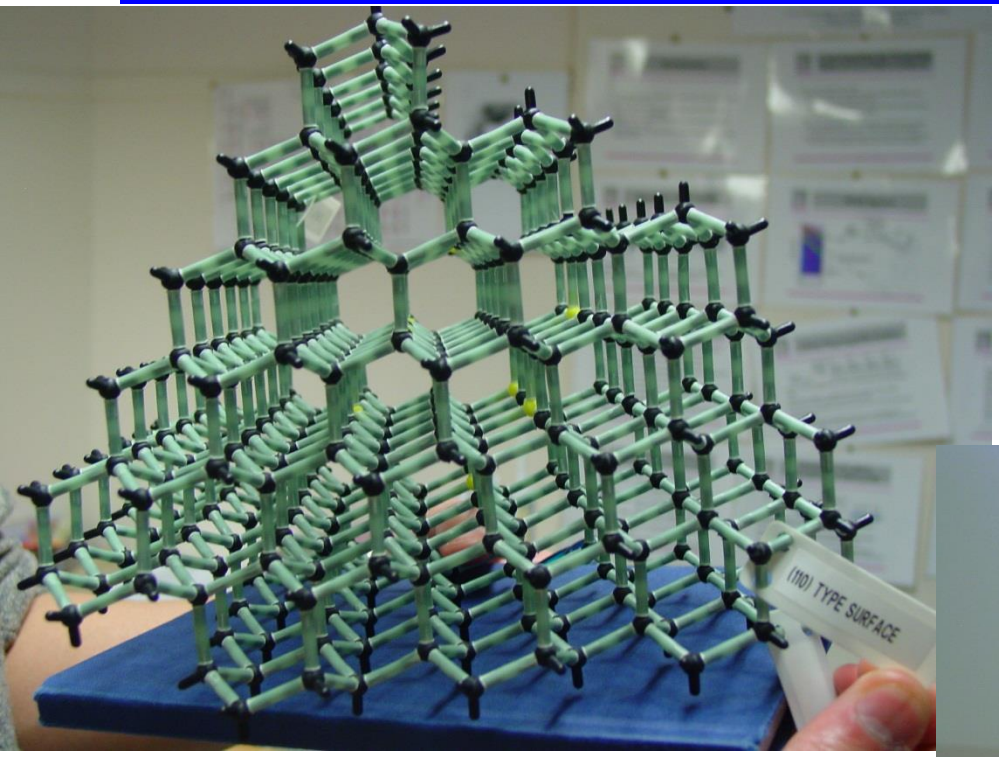
- the Daresbury MEIS facility, UK

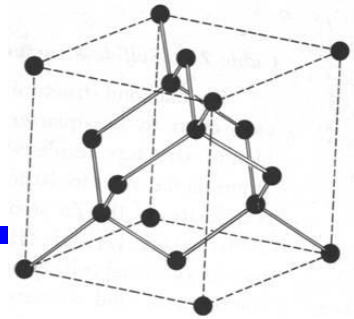


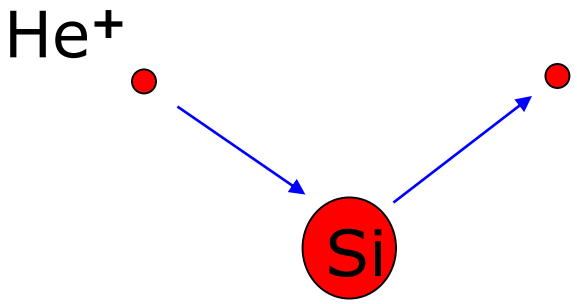


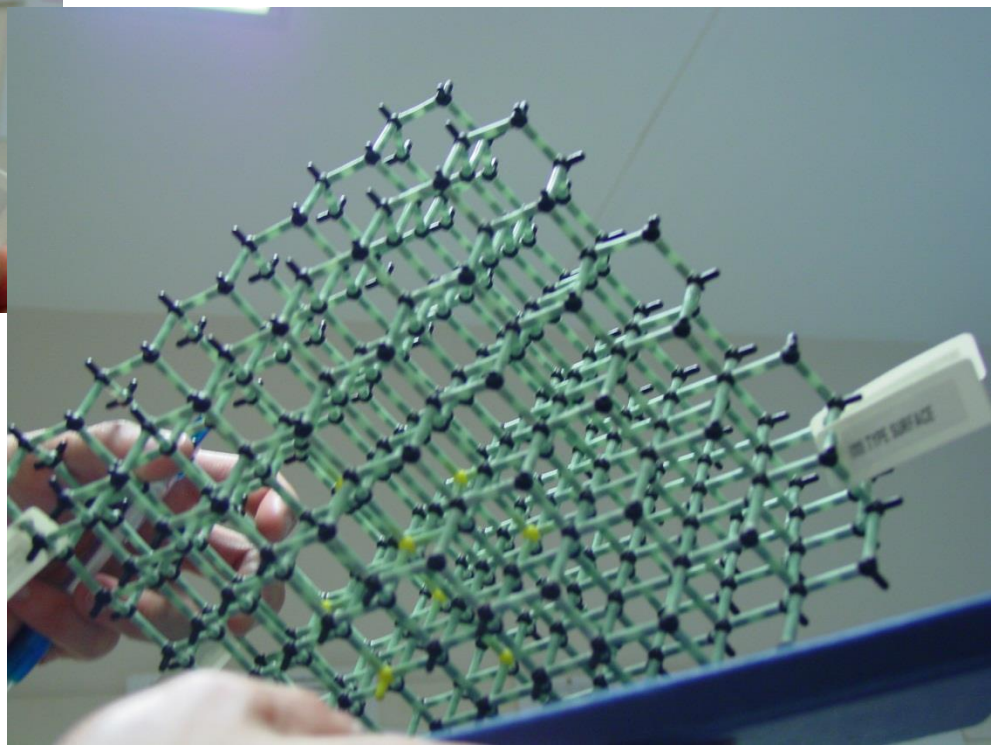


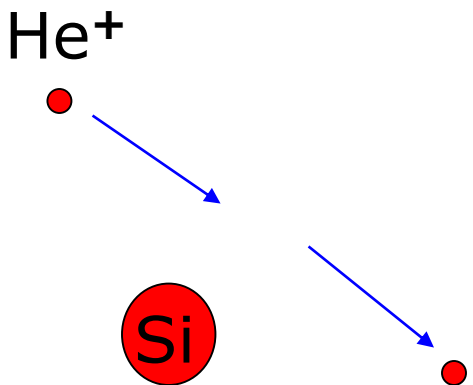
Elastic scattering









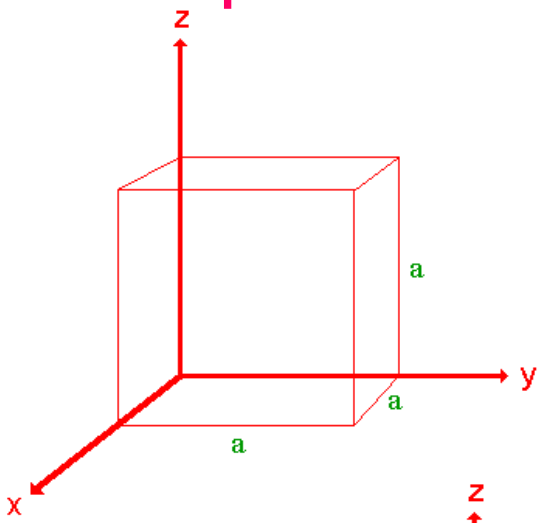


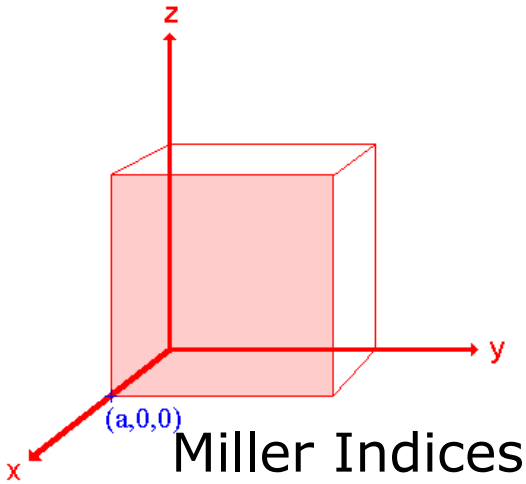
2.2 Crystal Structures

- General material properties
- Crystal structures
- **Crystallographic notation**
  晶面表示法
- Bohr's theory – energy level & band

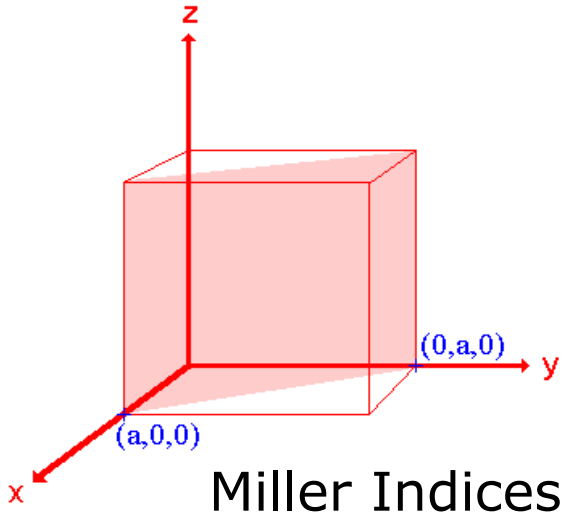
Crystallographic Notation

- **Miller indices** are a notation system in crystallography for **planes** and directions in crystal lattices.

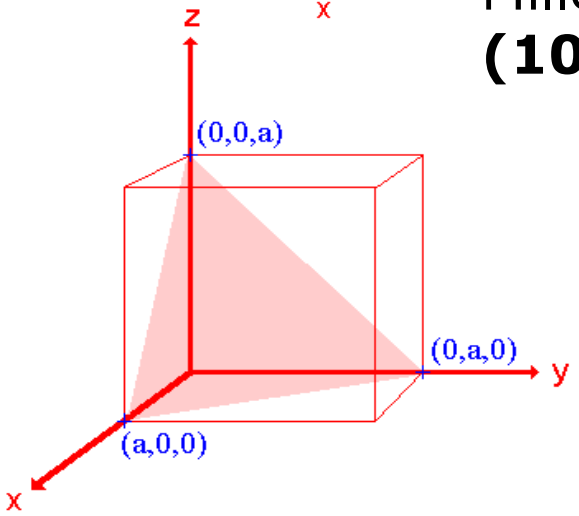




Miller Indices: **(100)**



Miller Indices: **(110)**



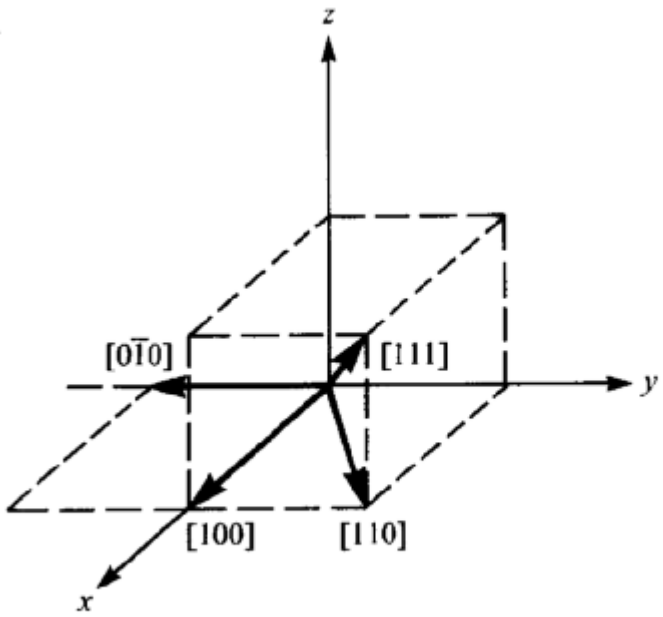
Miller Indices: **(111)**

密勒指数

Crystallographic Notation: directions

Miller Indices:

Notation	Interpretation
[*h k l*]	crystal direction
< *h k l* >	equivalent directions

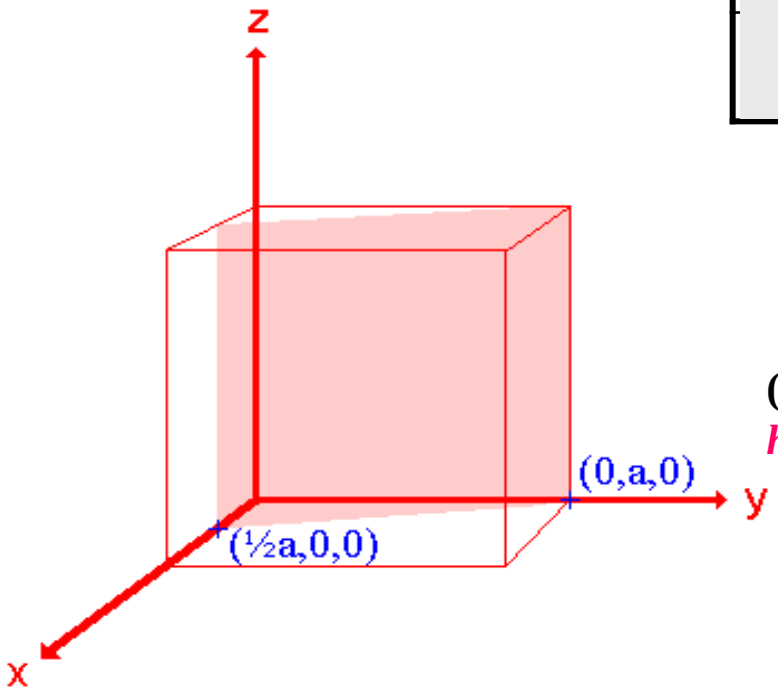


Sample direction vectors and their corresponding Miller indices.

Crystallographic Notation: planes

Miller Indices:

Assignment:
Intercepts: ½ a , a , ∞
Fractional intercepts: ½ ,1,∞
Miller Indices: (210)



Notation	Interpretation
(*h k l*)	crystal plane
{ *h k l* }	equivalent planes
	截距

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

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

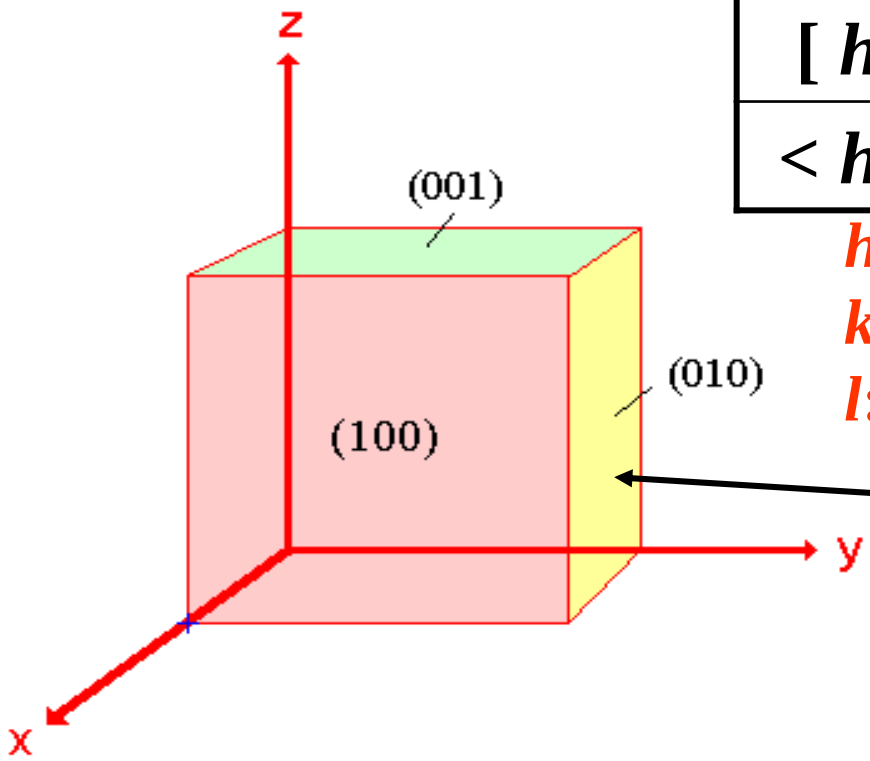
截距的倒数

截距的倒数的整数

Crystallographic Notation: planes

HW-2

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



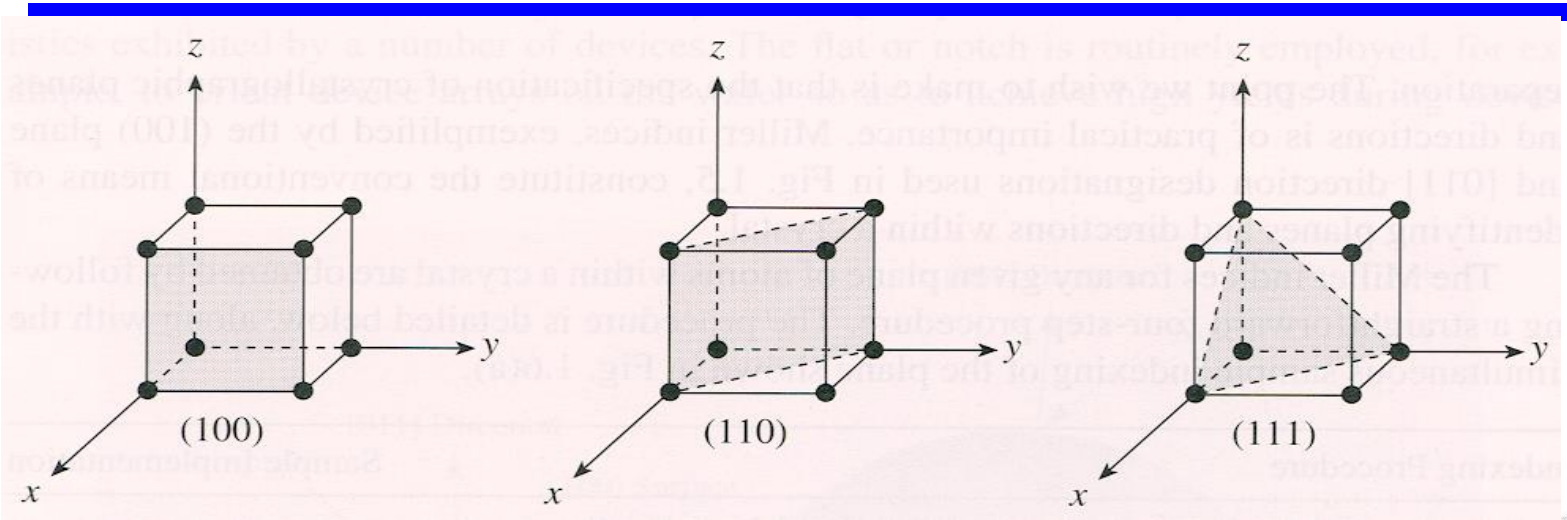
***h*: inverse *x*-intercept of plane**

***k*: inverse *y*-intercept of plane**

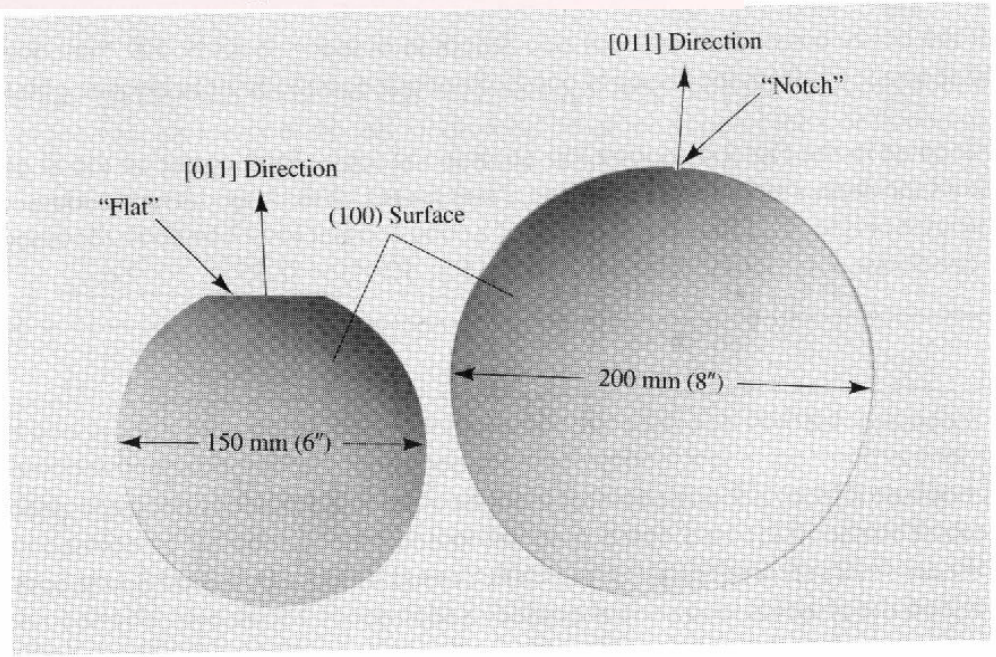
***l*: inverse *z*-intercept of plane**

Why the Miller indices of this plane is (010)?

Crystallographic Planes and Si Wafers



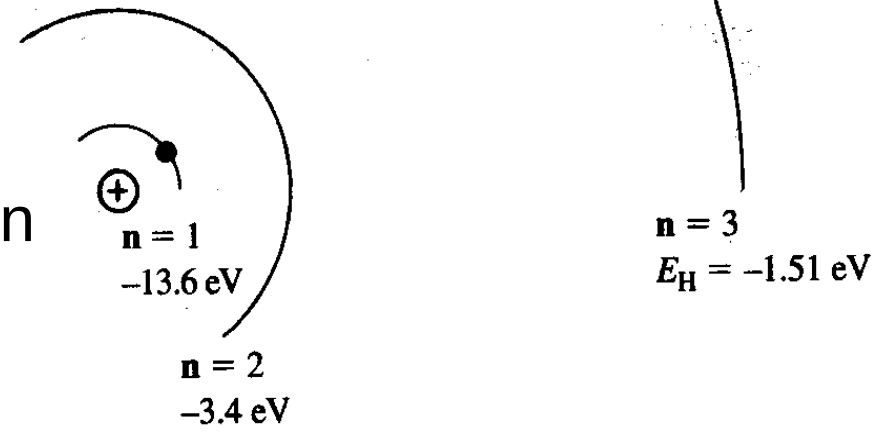
Silicon wafers are usually cut along a {100} plane with a flat or notch to orient the wafer during IC fabrication:



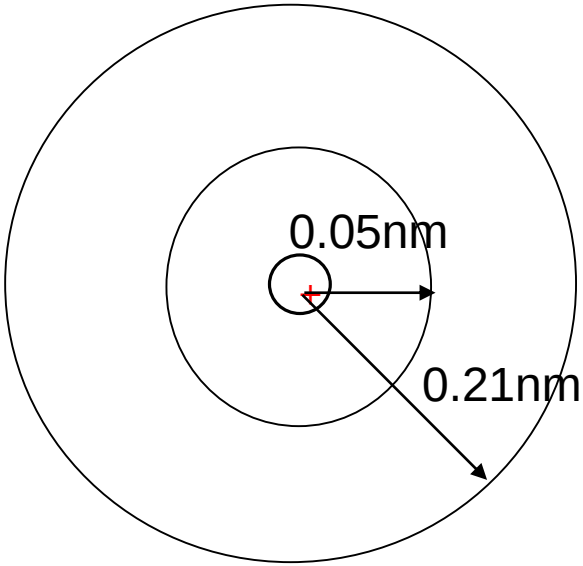
2.2 Crystal Structures

- General material properties
- Crystal structures
- Crystallographic notation
- Bohr's theory – energy level (能级) & band (能带)

Bohr's Theory

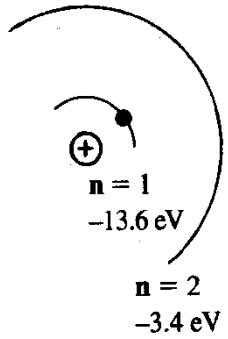


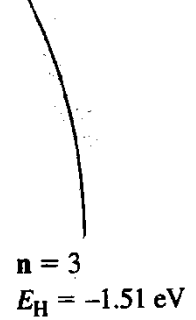
- The electrons of an atom can only stay on a number of orbits. The radius of orbits changes **discontinuously**.
- For example, hydrogen atom,

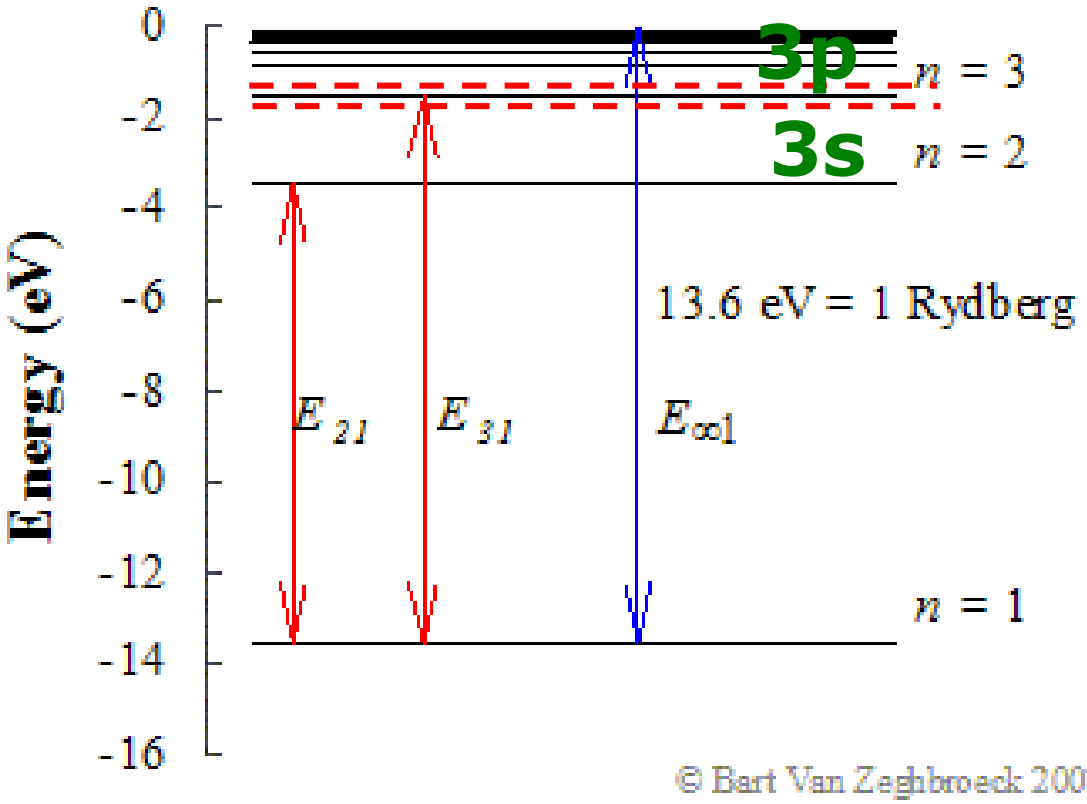


PL

The Bohr model





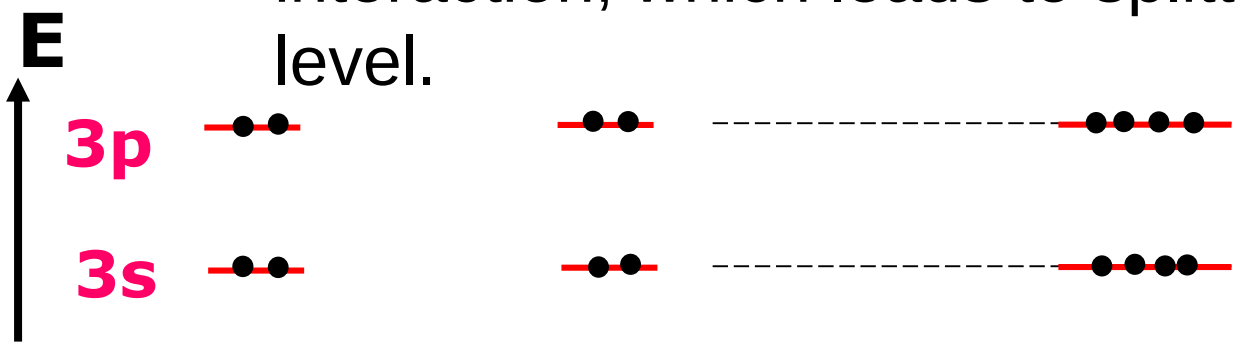


Outmost orbit

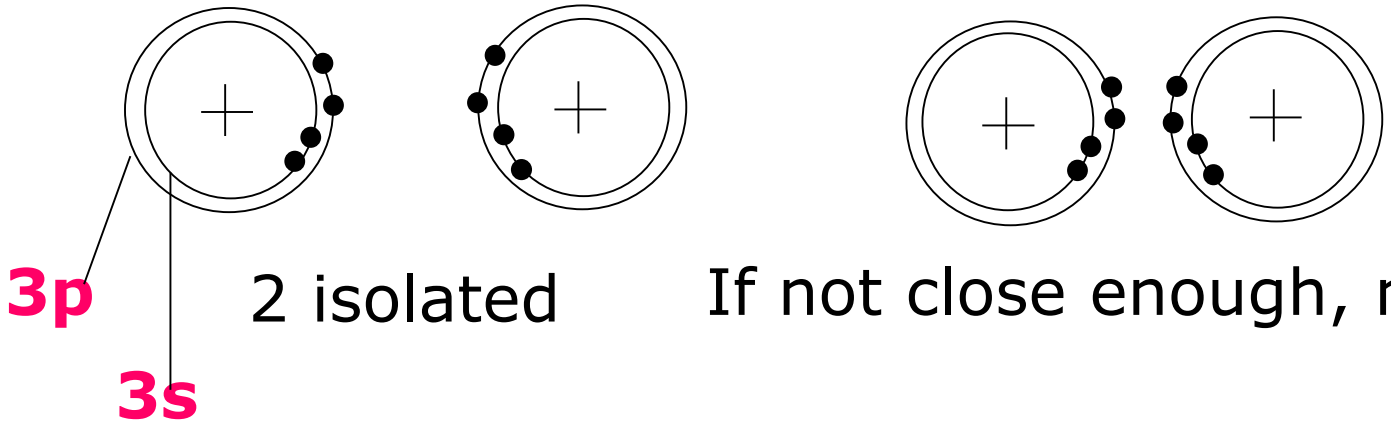
Energy levels and possible electronic transitions in a hydrogen atom. Shown are the first six energy levels, as well as three possible transitions involving the lowest energy level (n = 1)

Energy Bands

- Energy level of an isolated atom
- In solids, atoms interact with each other
- The orbits of electrons will be altered by interaction, which leads to splitting in energy level.



No splitting

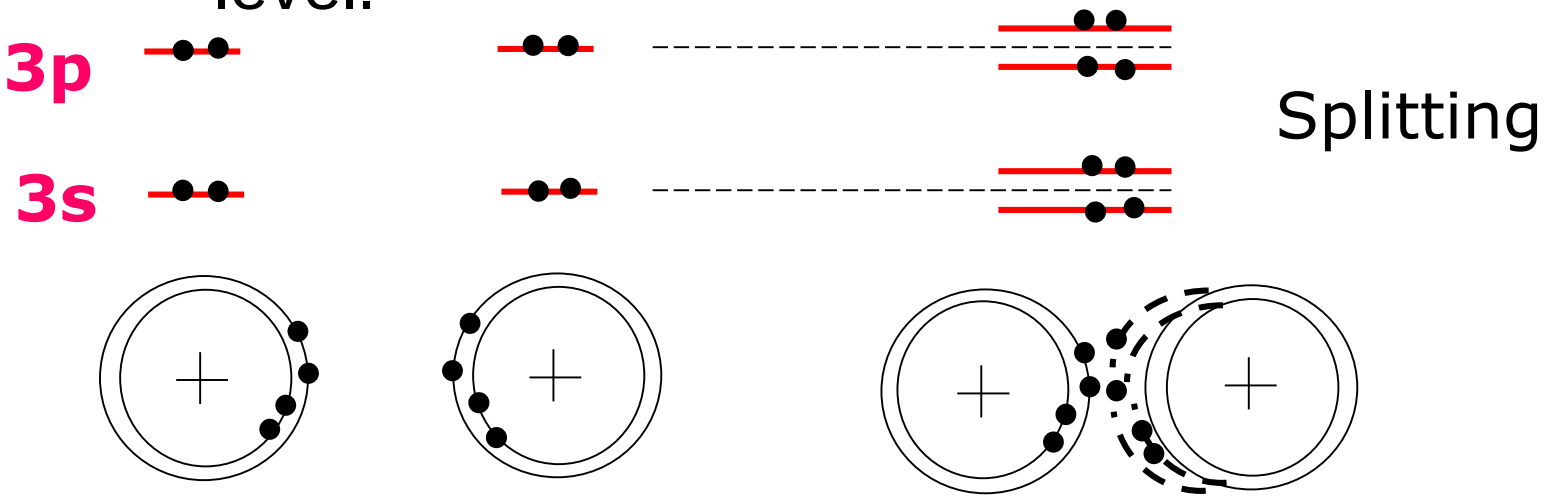


2 isolated

If not close enough, no interacting

Energy Bands

- Energy level of an isolated atom
- In solids, atoms interact with each other
- The orbits of electrons will be altered by interaction, which leads to splitting in energy level.



Energy Bands

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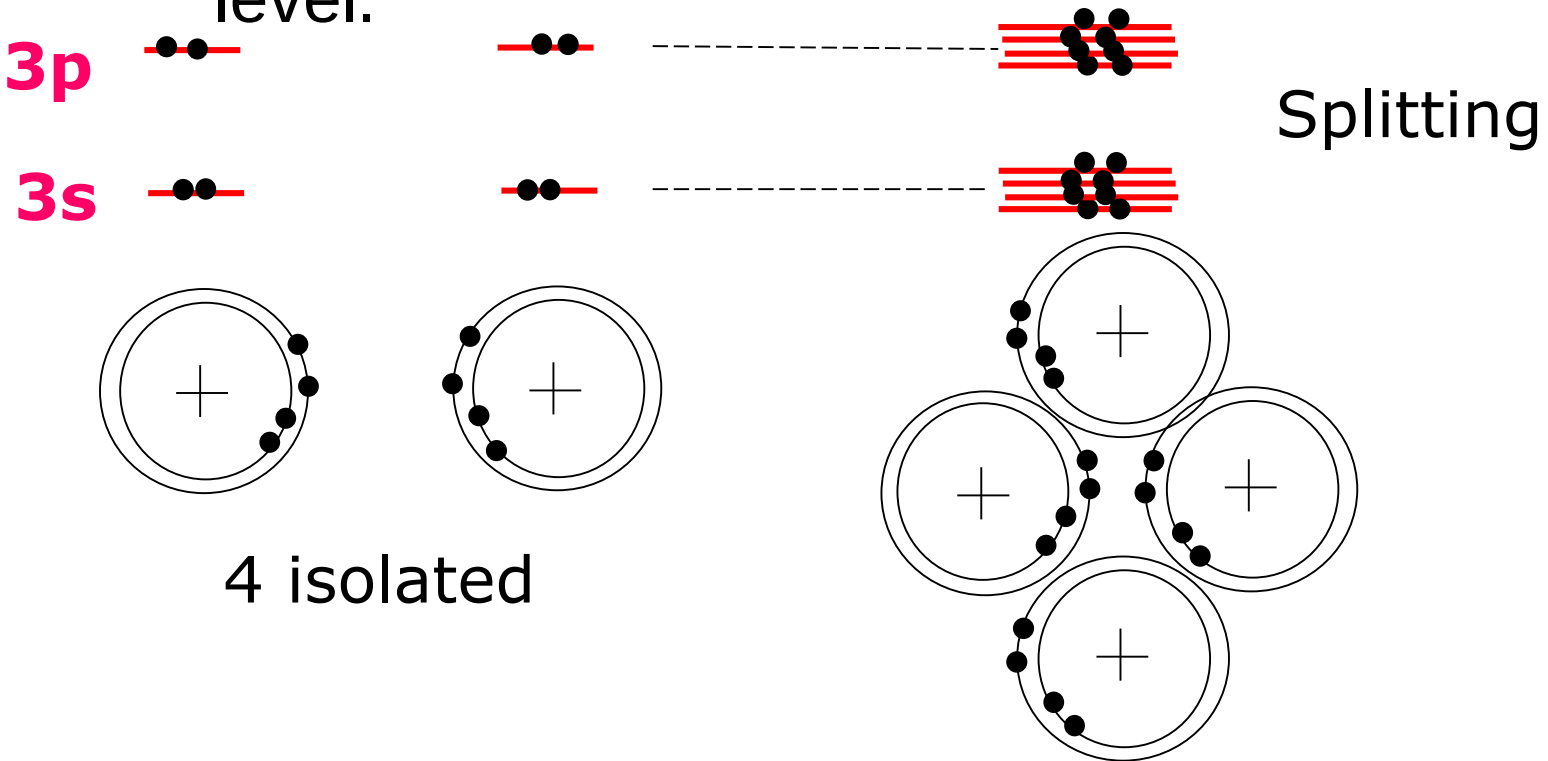
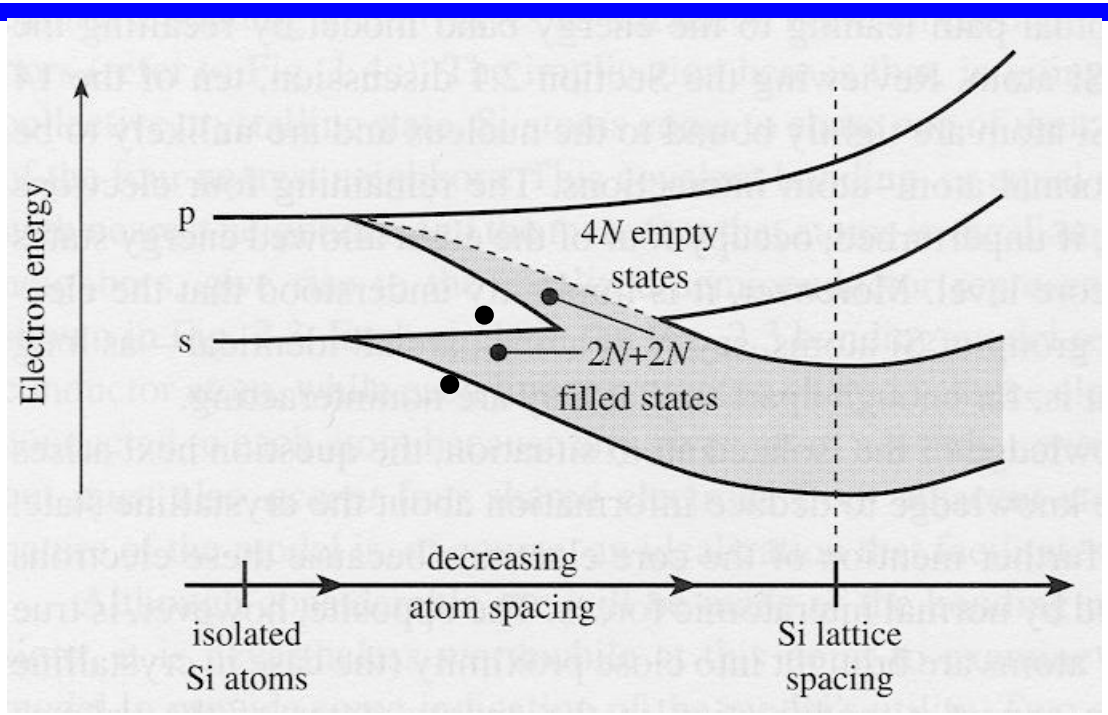
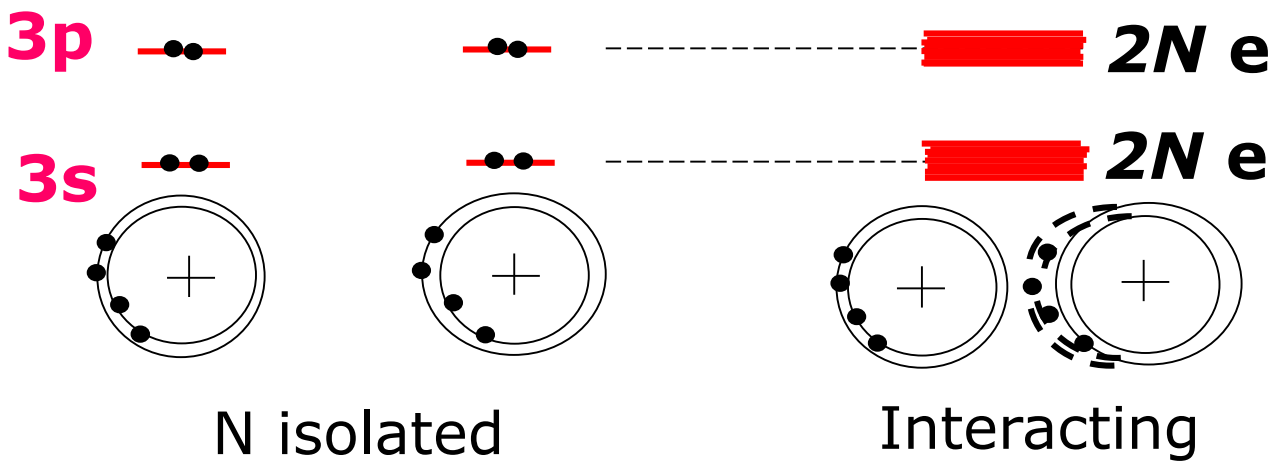
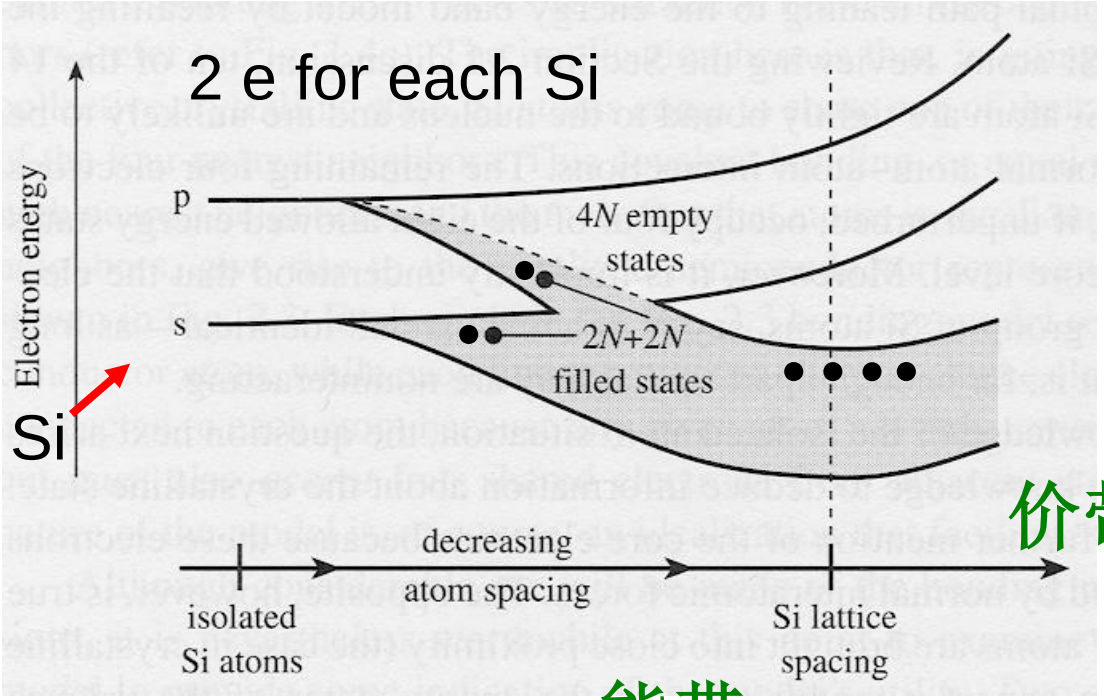


Si: From Atom to Crystal





Si: From Atom to Crystal



导带

no e

2 e for each Si

4N e

价带

能级

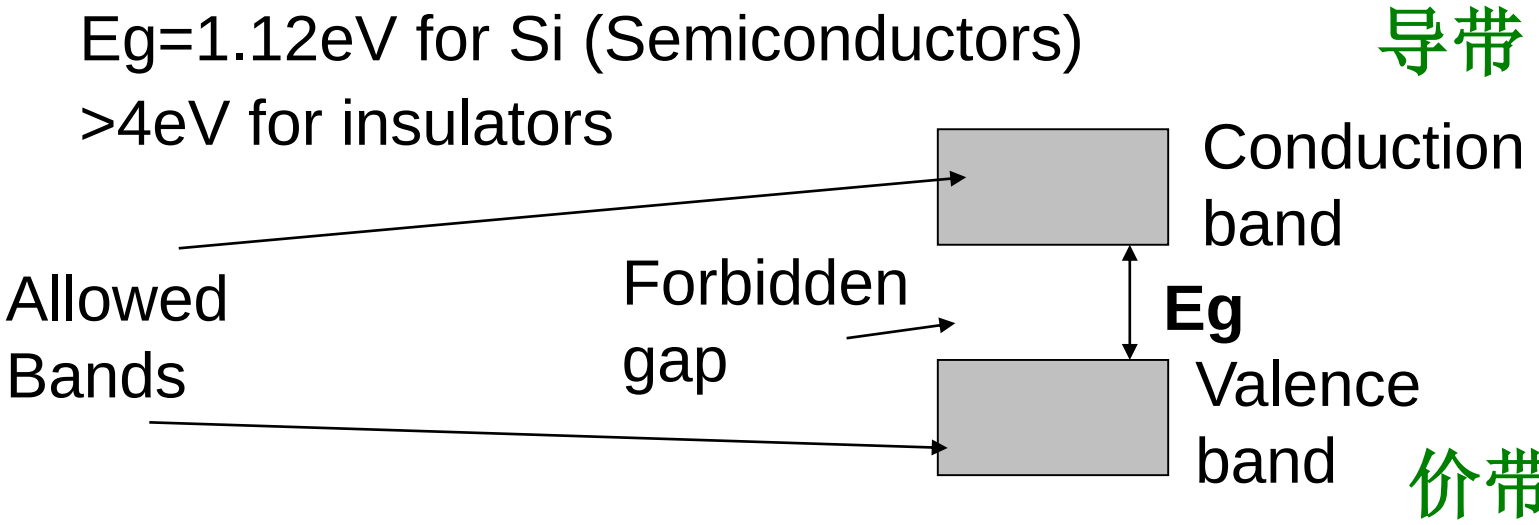
能带

Energy levels in Si atom → energy bands in Si crystal

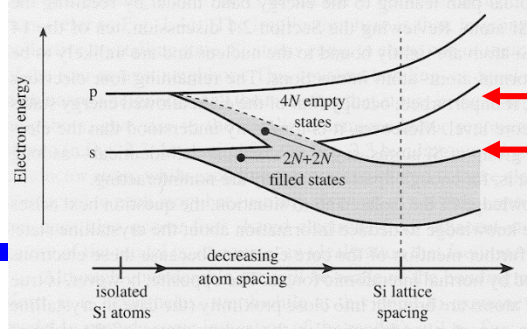
- The highest nearly-filled band is the ***valence band***
- The lowest nearly-empty band is the ***conduction band***

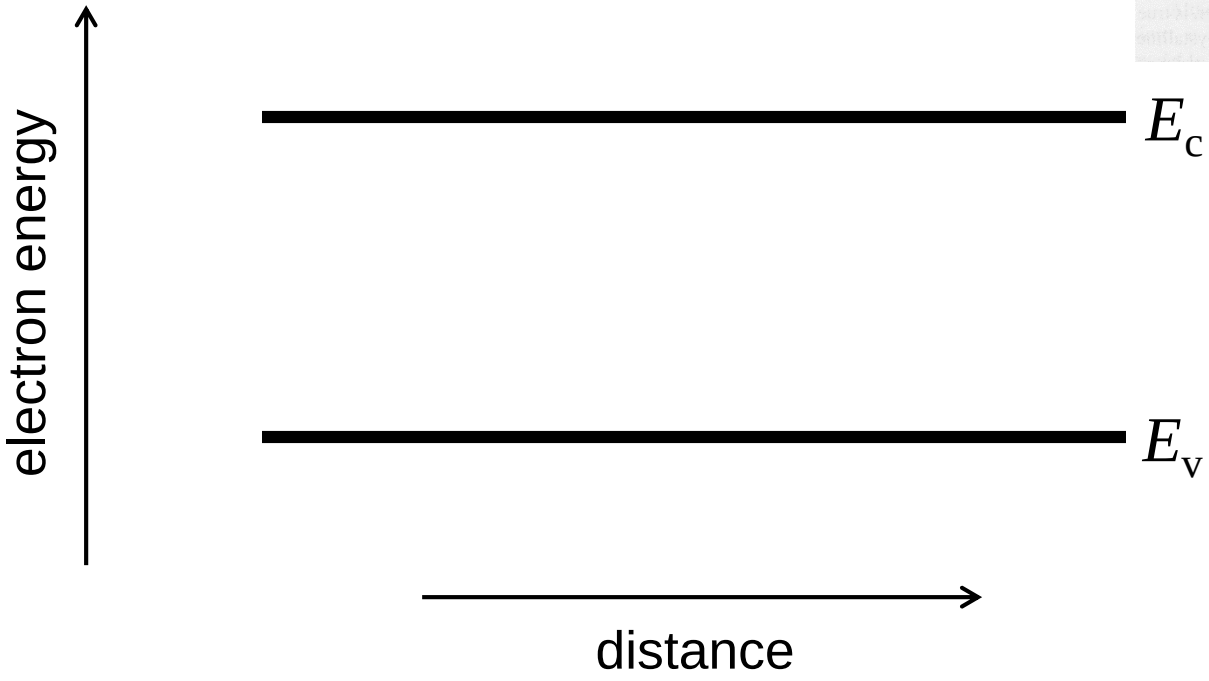
Formation of Energy Bands

- Many atom interactions form energy bands.
- Valence band: where valence electrons stay
- Conduction band: where free electrons stay
- Eg: The minimum energy required to free an electron from an atom.
  - Eg≈0 for metals (conductors)
  - Eg=1.12eV for Si (Semiconductors)
  - >4eV for insulators



Energy Band Diagram





Simplified version of energy band model, indicating

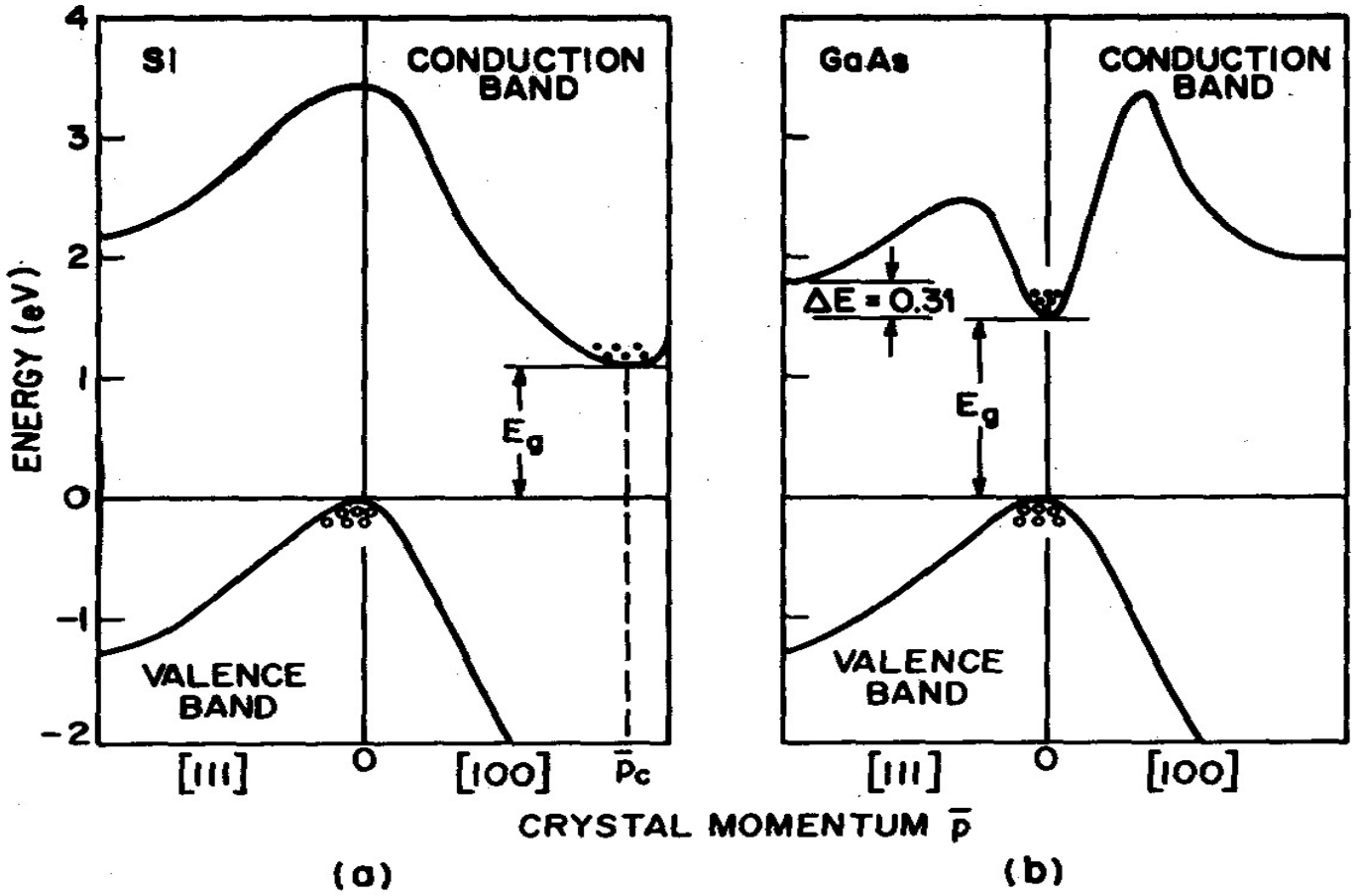
- bottom edge of the conduction band (E_c)
- top edge of the valence band (E_v)

➢ E_c and E_v are separated by the **band gap energy E_g**

Real band structures

NS

- The highest nearly-filled band is the ***valence band***
- The lowest nearly-empty band is the ***conduction band***



Summary of Section 2.1 & 2.2

- Crystalline Si:
  - 4 valence electrons per atom
  - diamond lattice
    - each atom has 4 nearest neighbors
  - 5×10^{22} atoms/cm^3
- Crystallographic notation
  - Miller indices are used to designate planes and directions within a crystalline lattice
- Ec, Ev and Eg

Outline

Semiconductor Fundamentals-(I)

2.1 Atomic structures
2.2 Crystal structures

Semiconductor Fundamentals-(II)

2.3 Energy bands
2.4 The doping of semiconductors

Semiconductor Fundamentals-(III)

2.5 Boltzmann approximation & E_F, n, p
2.6 Carrier drift and diffusion