Semiconductor Fundamentals

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Feb 2024

https://www.xjtlu.edu.cn/en/departments/academic-departments/electrical-and-electronic-engineering/staff/chun-zhao

Last Lecture: 3 key points

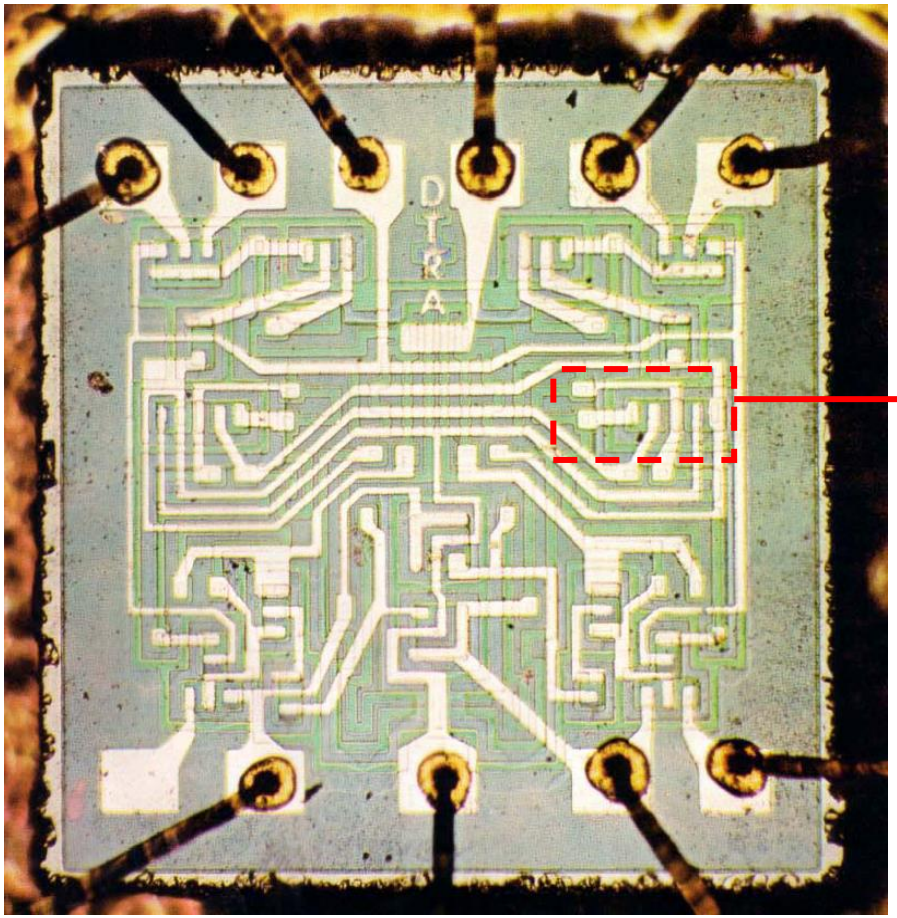
1. **Moores' Law**
2. **Technology Node Definition**
3. **Yield Definition**

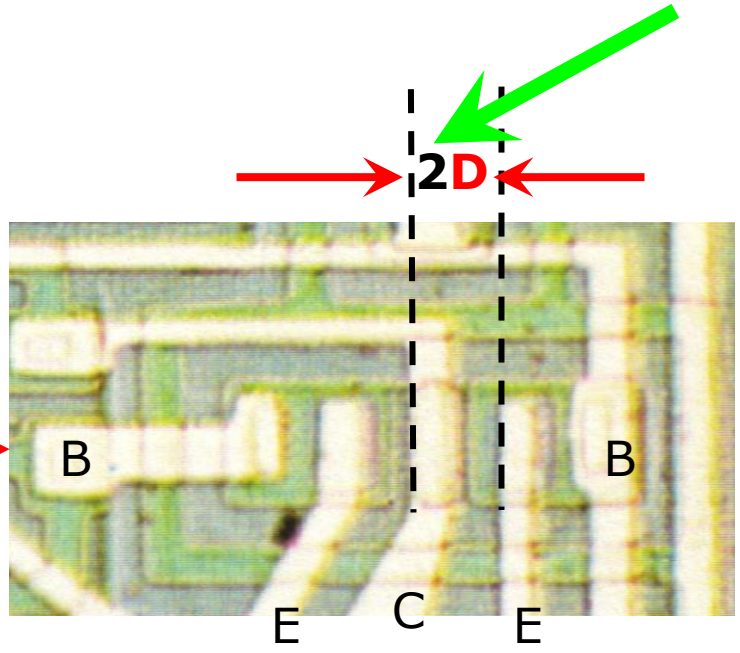
1. Moores' Law:

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

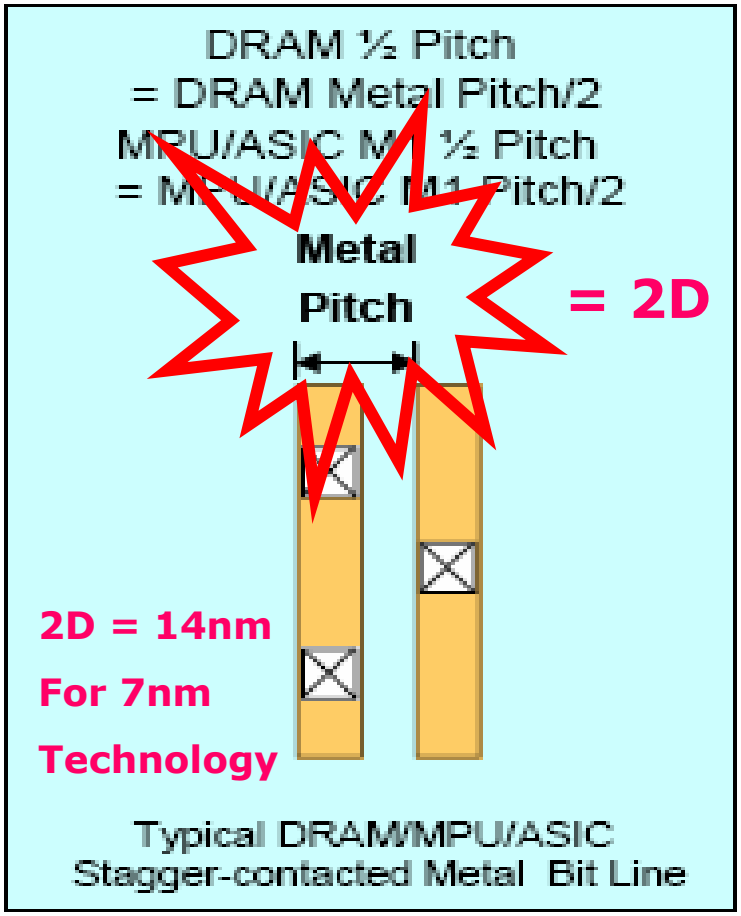
"Generation D", or **"D node"**

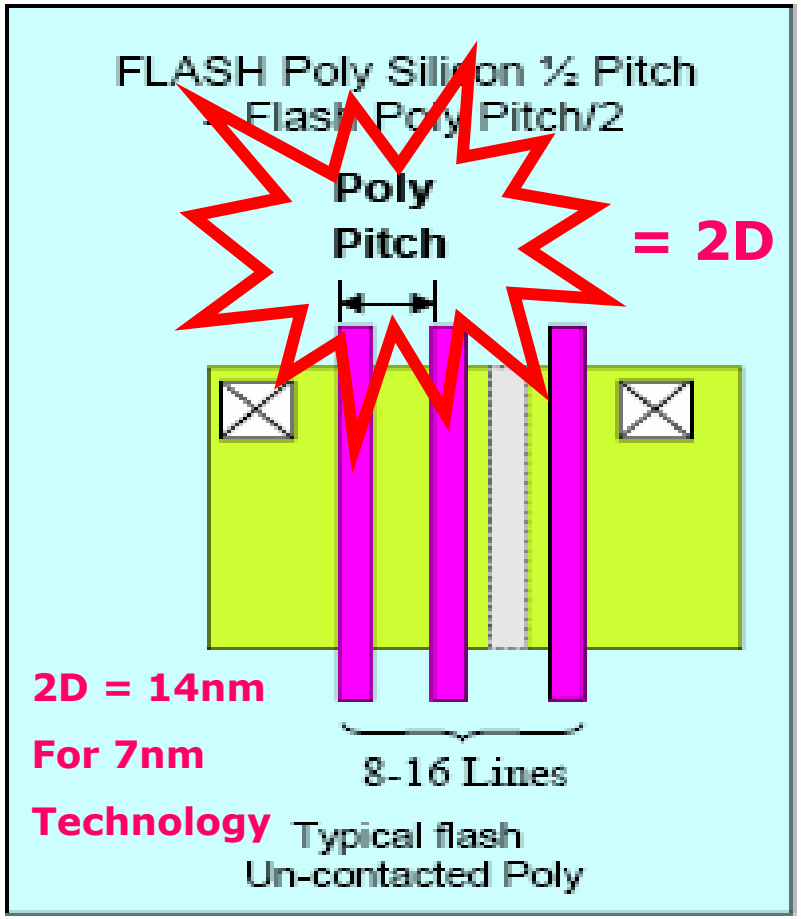
ITRS: *http://www.itrs.net/home.html*

- 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

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

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

Die = Chip

- 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).

Technology node ⇩

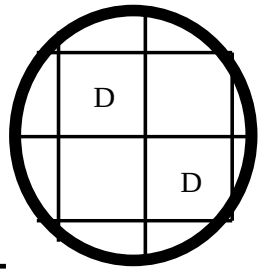


Fig.1

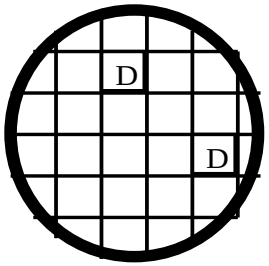
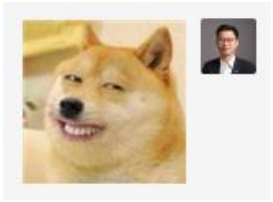


Fig.2

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

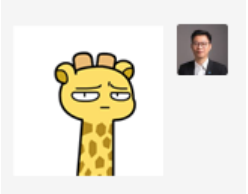
Semiconductor Fundamentals – (I)

2.1 Atomic structures

2.2 Crystal structures

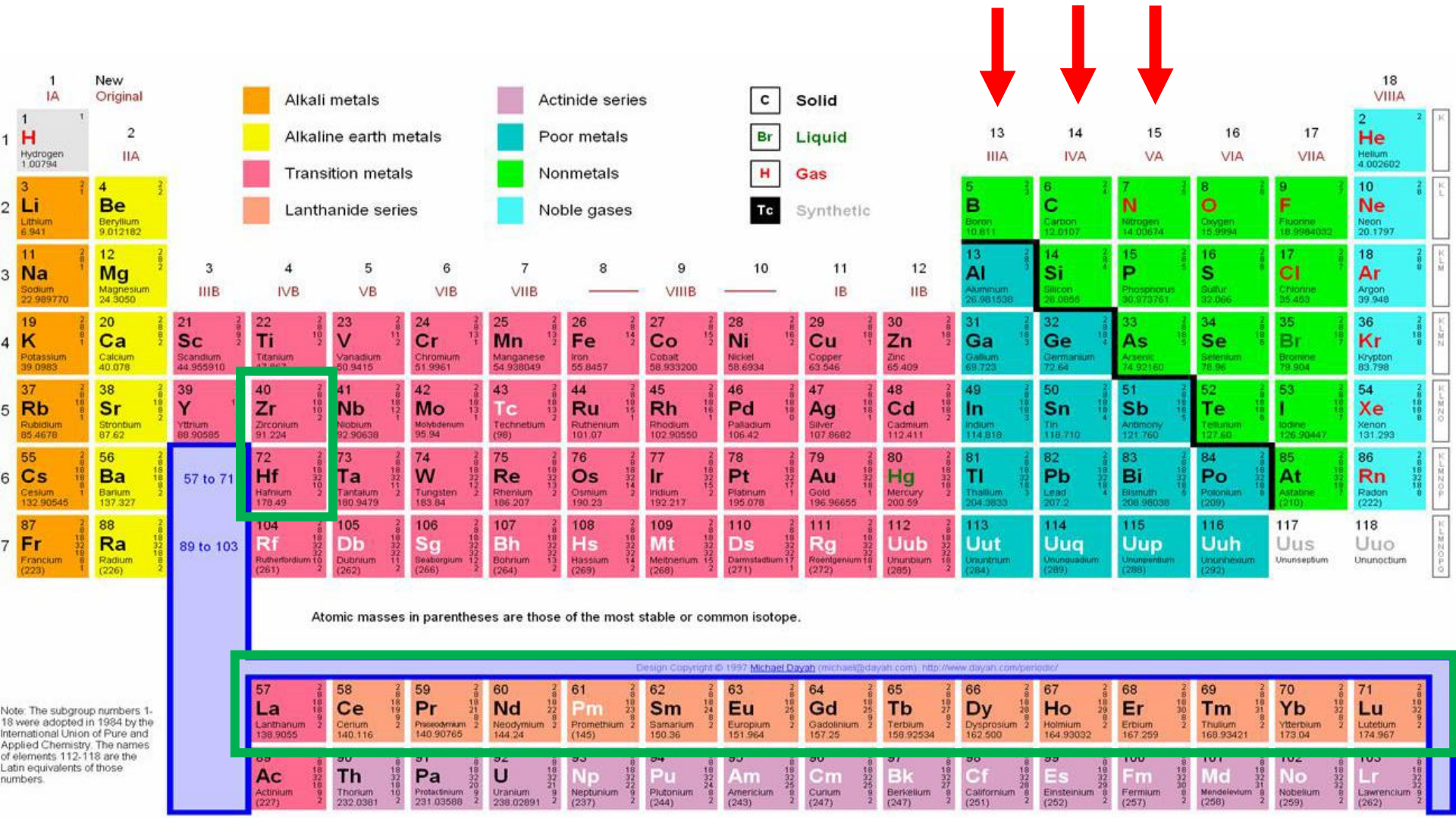
2.1 Atomic Structures

- **Elements**



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

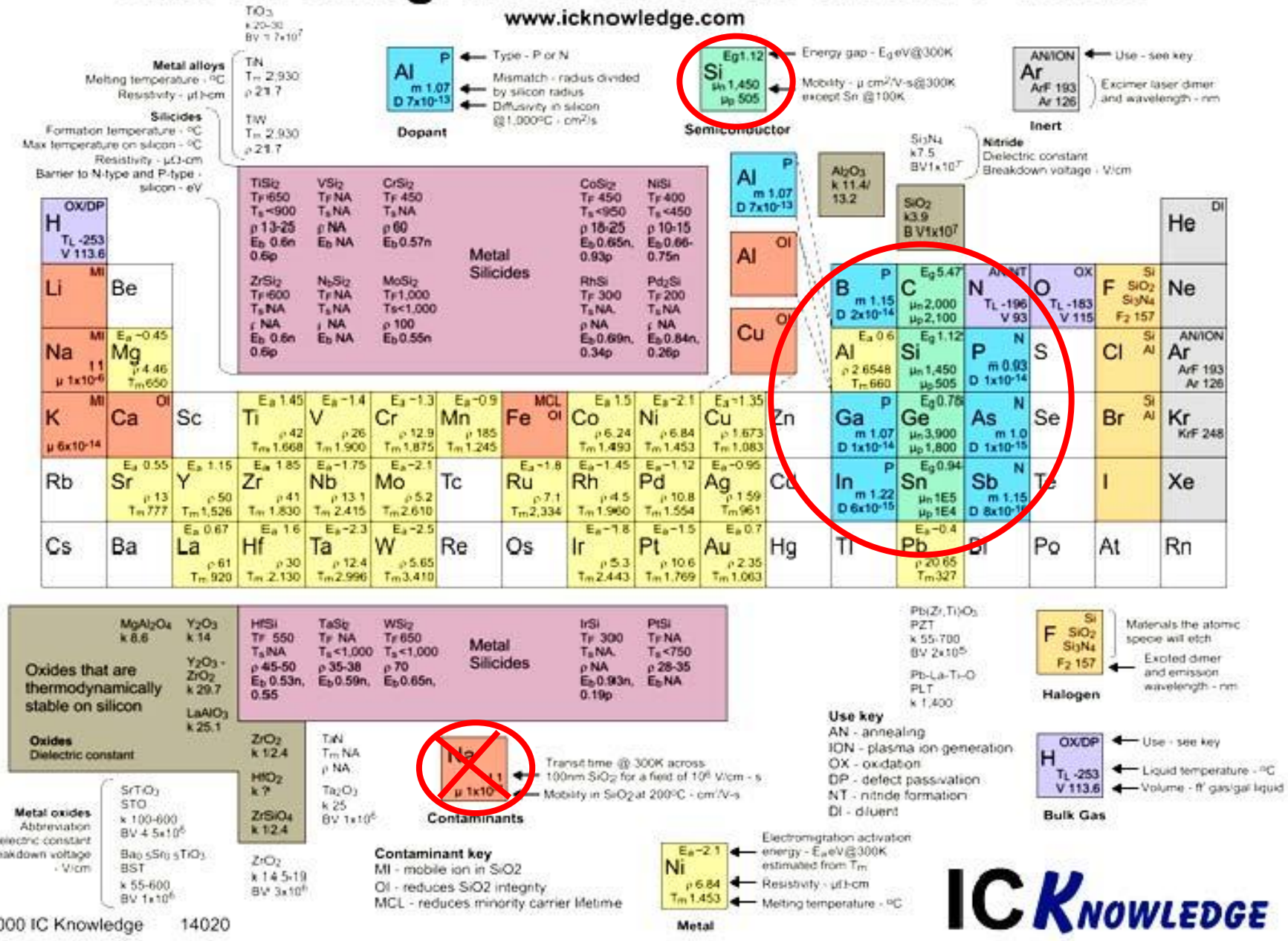
Element Periodic Table



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.

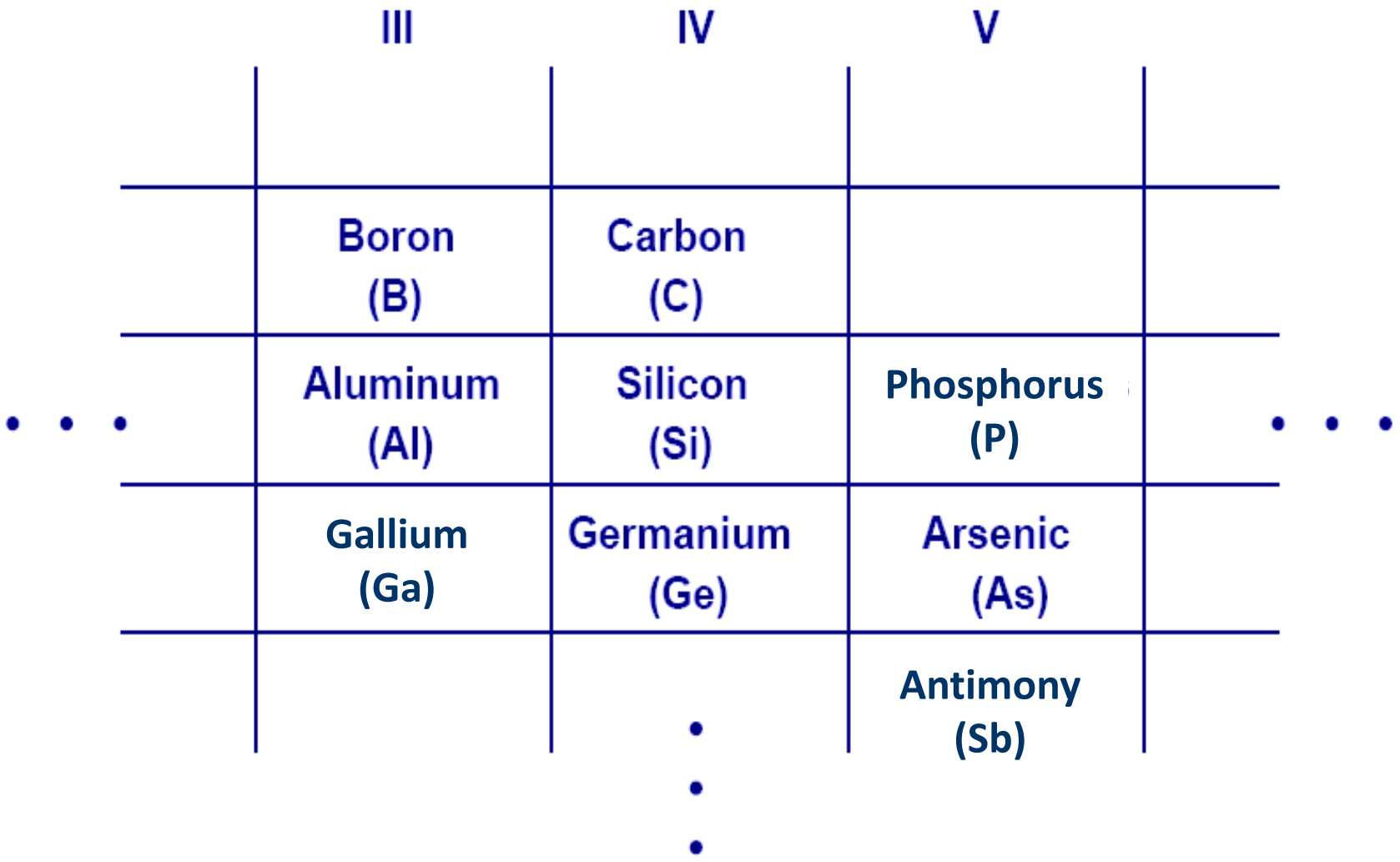
Silicon Integrated Circuit Periodic Table

www.icknowledge.com



IC KNOWLEDGE

Semiconductor Materials



Semiconductor Materials

Elemental: Si, Ge, C

Compound: IV-IV : SiC

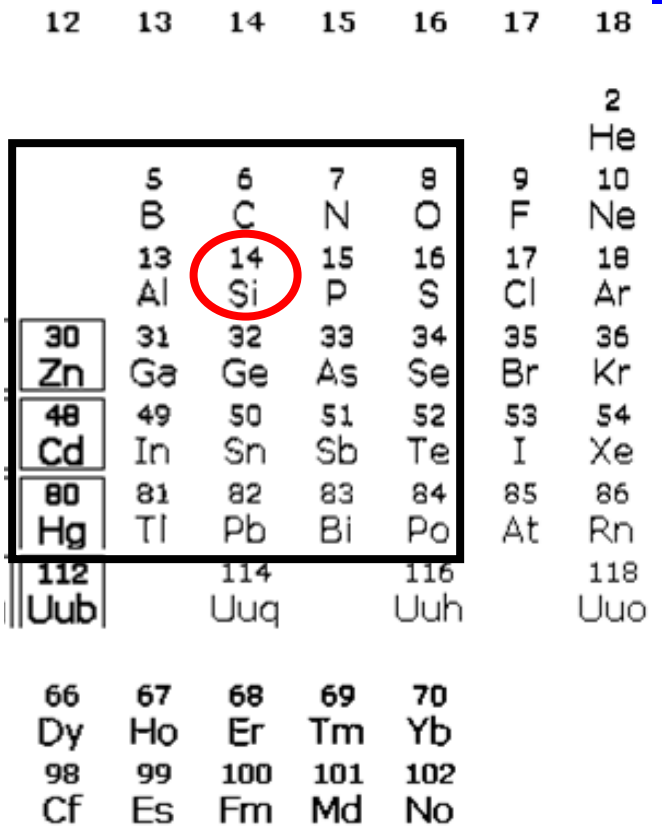
III-V : GaAs

GaN

II-VI : CdSe

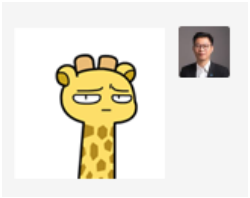
Alloy: $Si_{1-x}Ge_x$

$Al_xGa_{1-x}As$



2.1 Atomic Structures

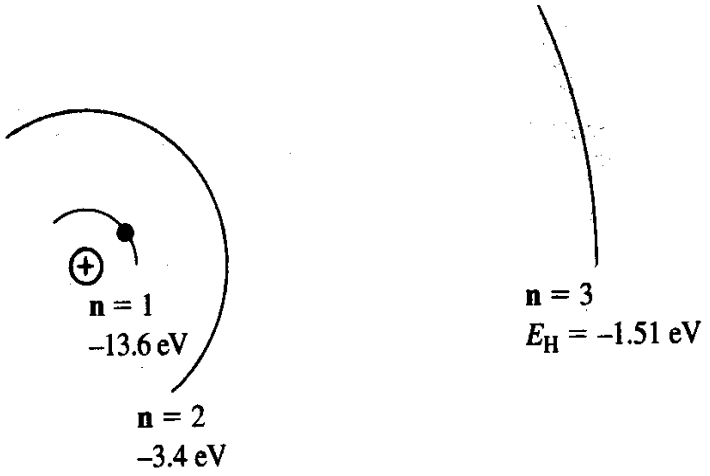
- Elements
- **Bohr's theory – orbits**

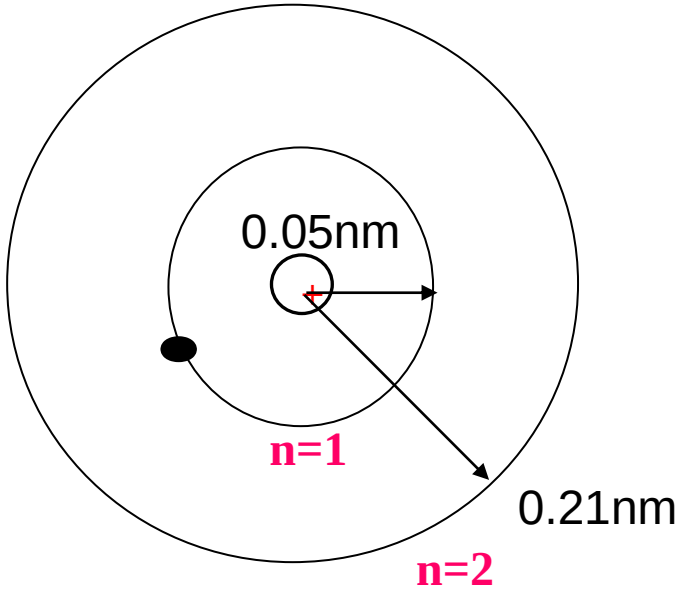


- Distribution of electrons
  - Valence electrons
- Bonding
  - Ionised bond
  - Covalent bond

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**,

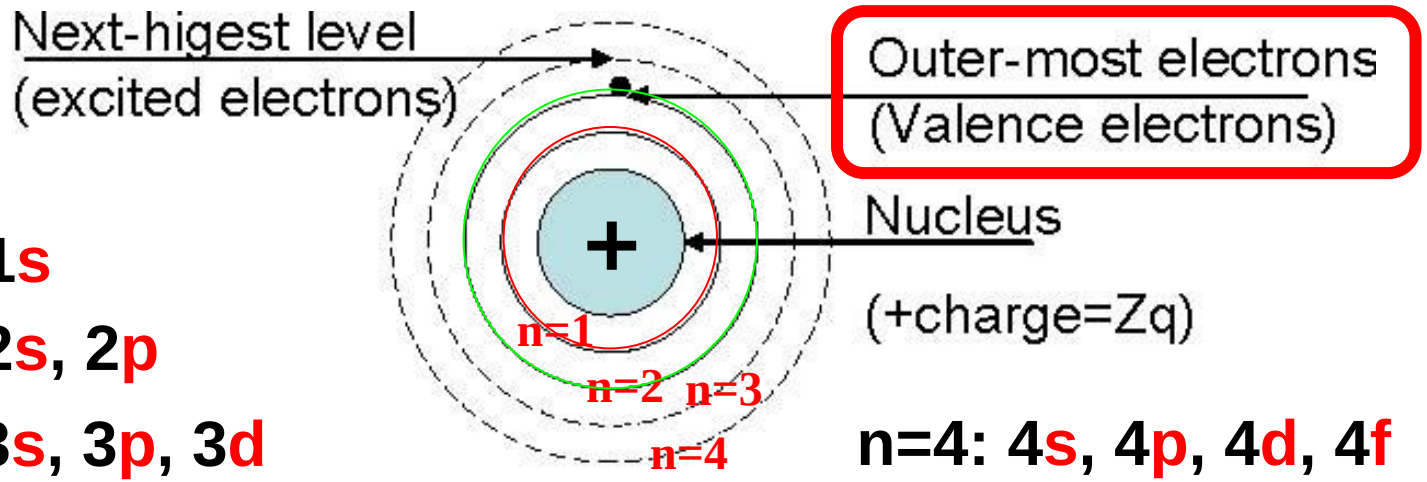




- The orbit with **smaller radius** has **lower energy**.

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

- 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 …
- "s" levels: **two** electron states
- Each "p" level is 3 fold degenerate: **six** electron states
- Historical: "s" was chosen because the optical emission related to transitions for these levels gives "**s**harp" lines (similarly: "principal", "diffuse" etc.)



n=1: 1s

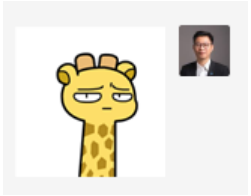
n=2: 2s, 2p

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

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

2.1 Atomic Structures

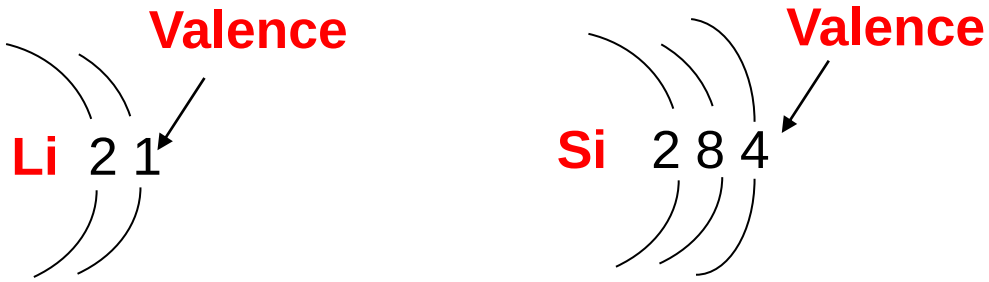
- Elements
- Bohr's theory – orbits
- **Distribution of electrons**
  - Valence electrons



- Bonding
  - Ionised bond
  - Covalent bond

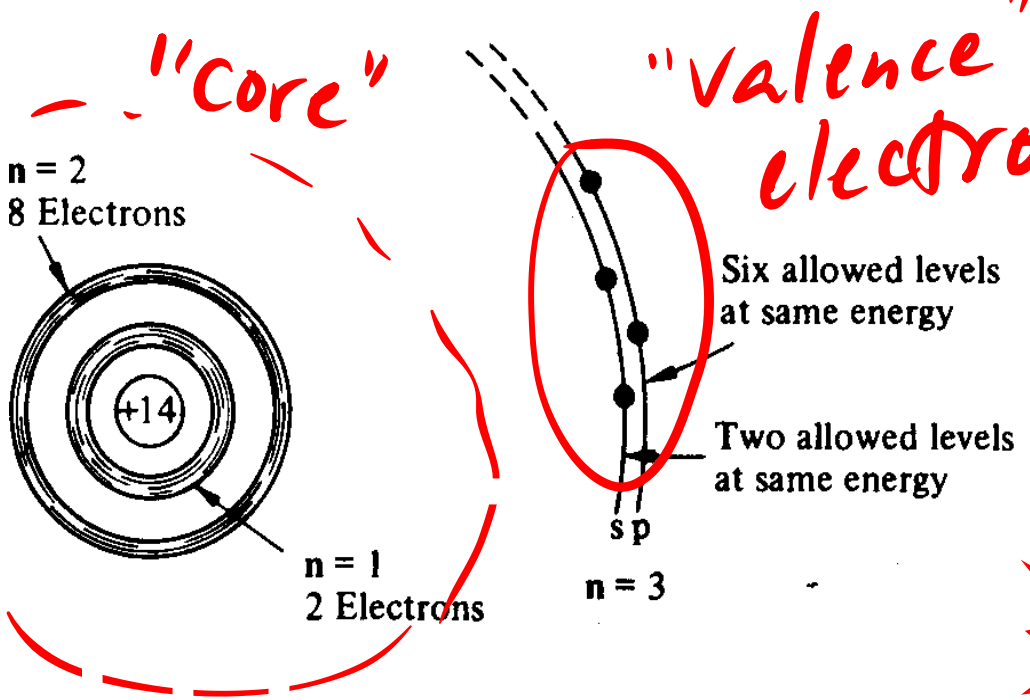
Distribution of electrons in atoms

- **<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**

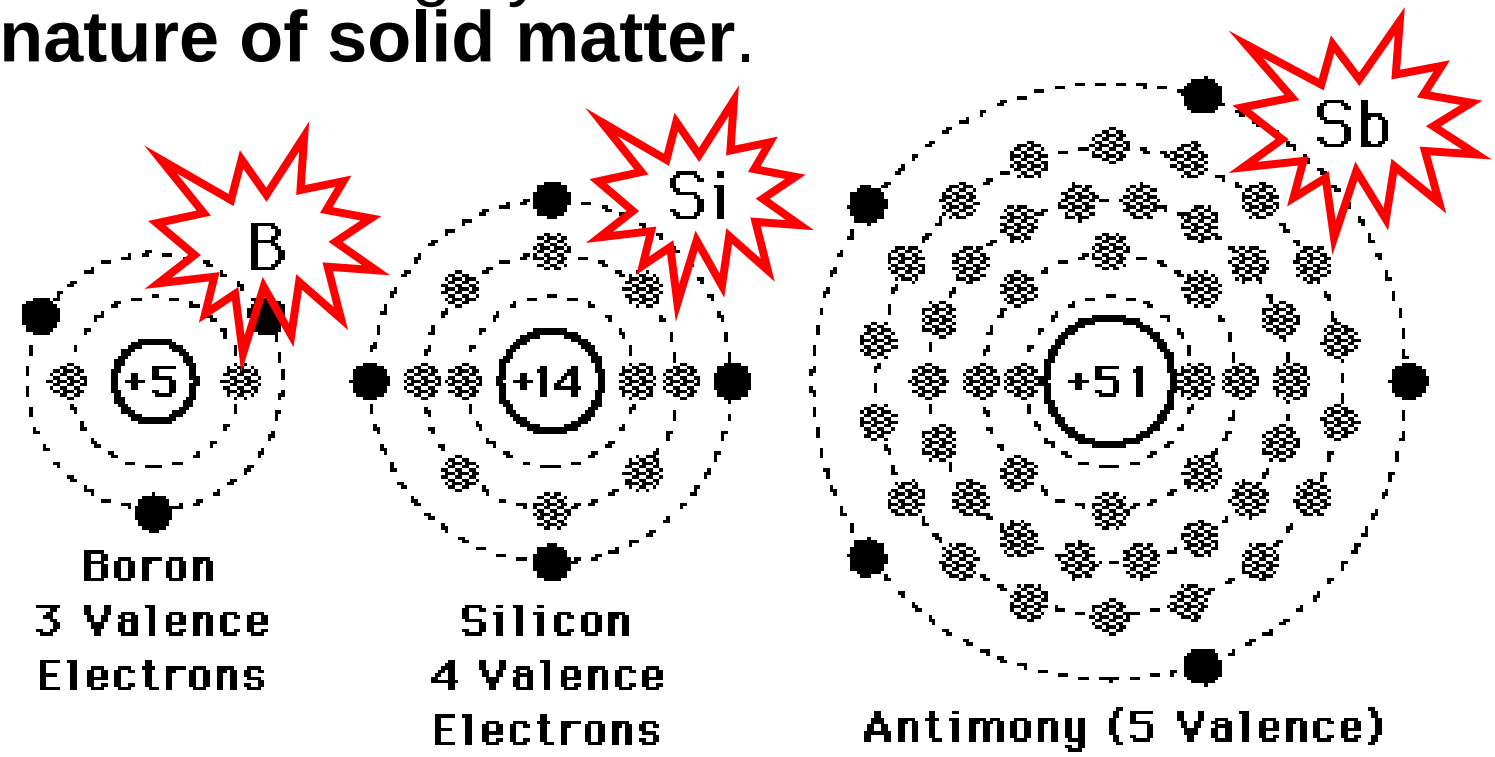


n=3: 3s, 3p, 3d

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		$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6$

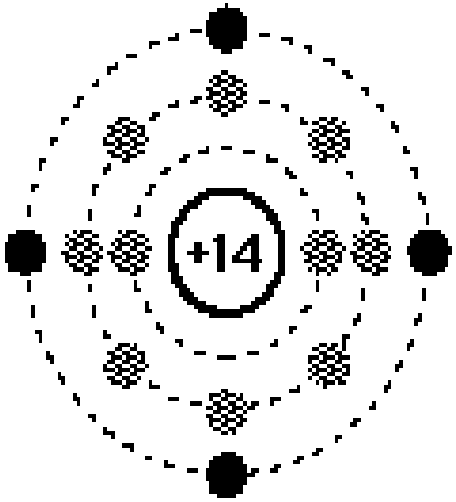
Valence Electrons of **B**, **Si** & **Sb**

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

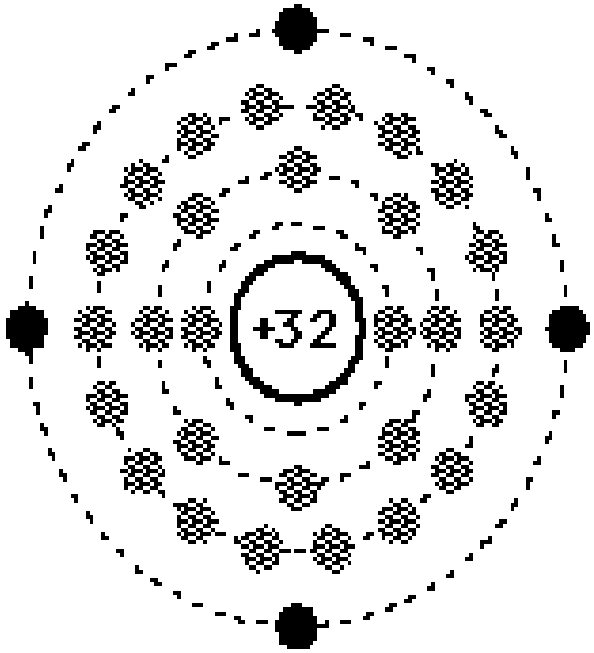


Valence Electrons of **Si** & **Ge**

- **Solid state electronics** arises from the **unique properties** of **silicon** and **germanium**, each of which has **4 valence electrons** and which form crystal lattices.



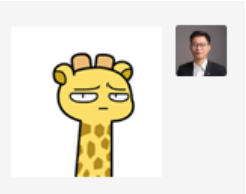
Silicon



Germanium

2.1 Atomic Structures

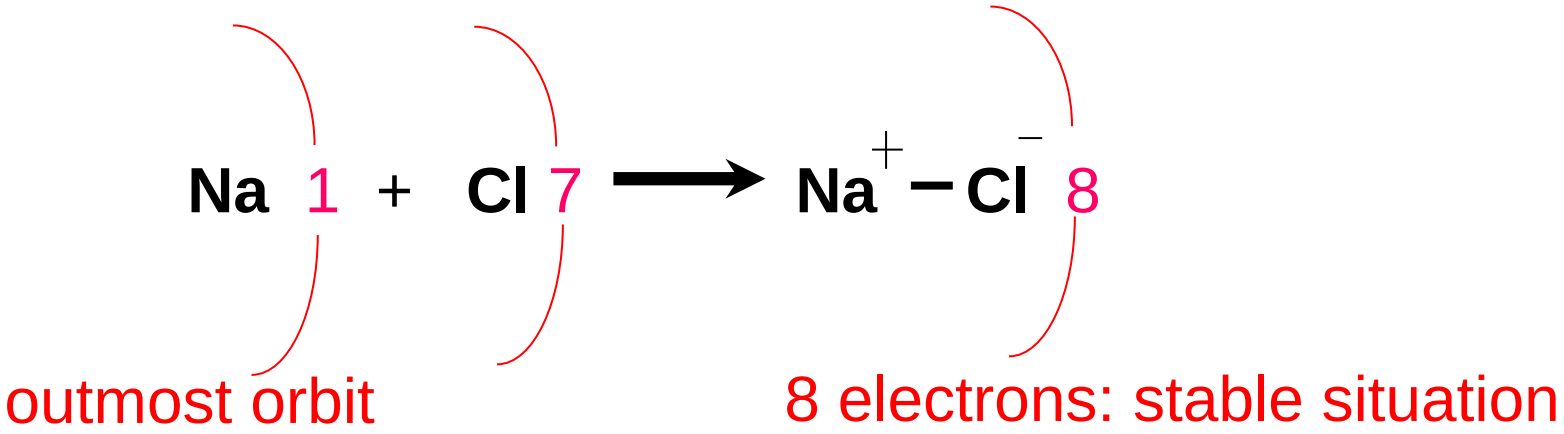
- Elements
- Bohr's theory – orbits
- Distribution of electrons
  - Valence electrons
- **Bonding**
  - Ionised bond
  - Covalent bond



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.

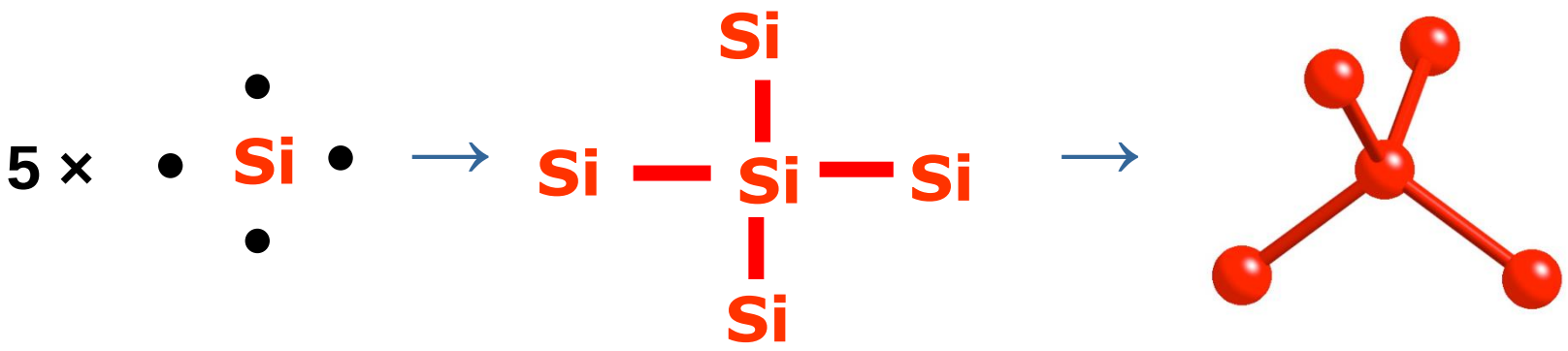


Covalent bonds

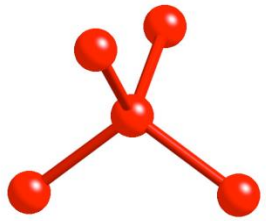
- Valence electrons are **shared**
- Notation of a covalent bond (can't be "seen")

Si : Si Si — Si Si ⌒ Si

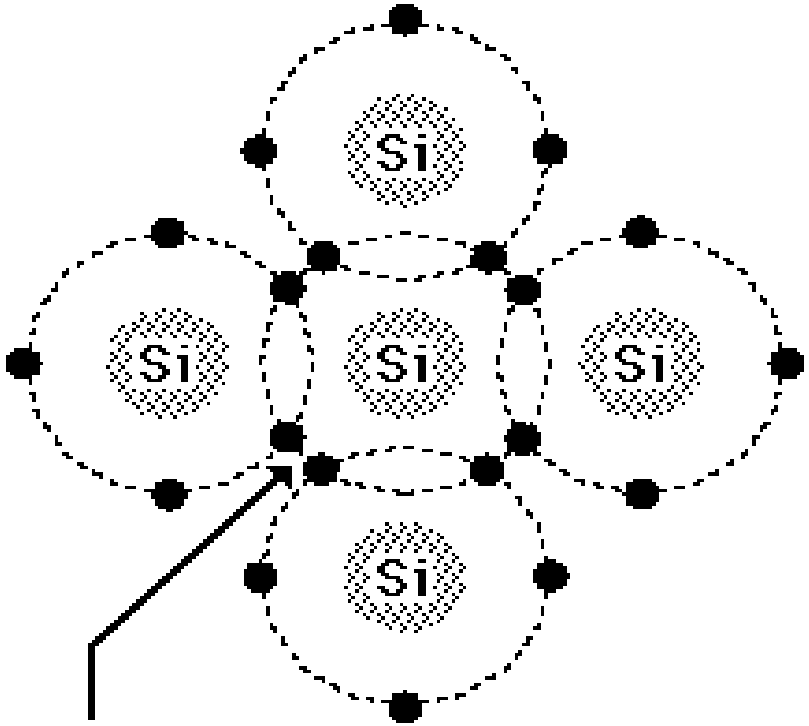
- Si shares its **4** valence electrons with **4** other Si atoms by forming covalent bonds.

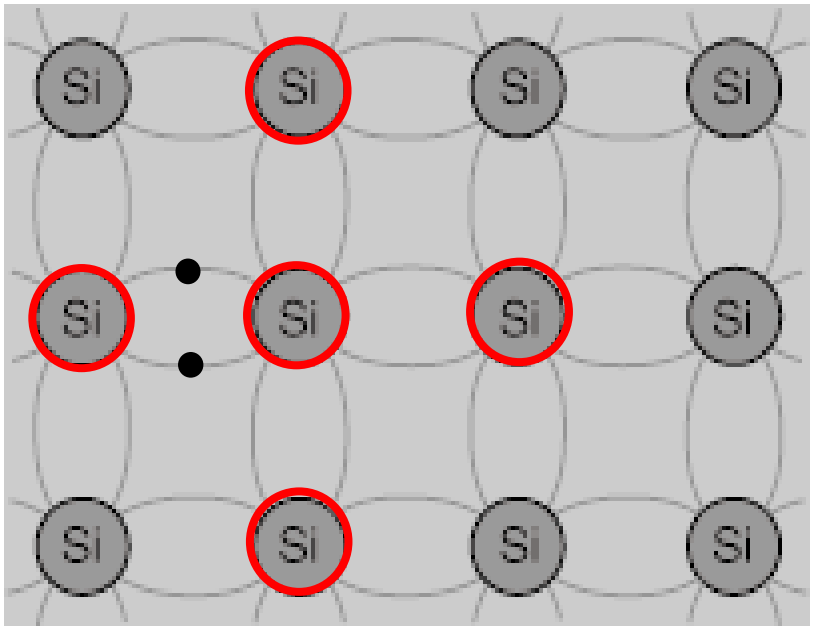


Covalent bonds



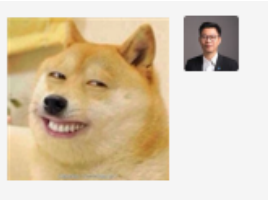
- The bonds are of equal length and angular separation to produce a **crystal structure**.





2.2 Crystal Structures

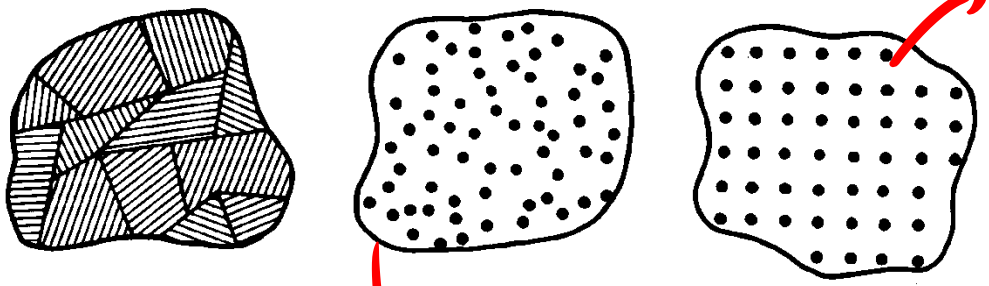
- **General material properties**



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

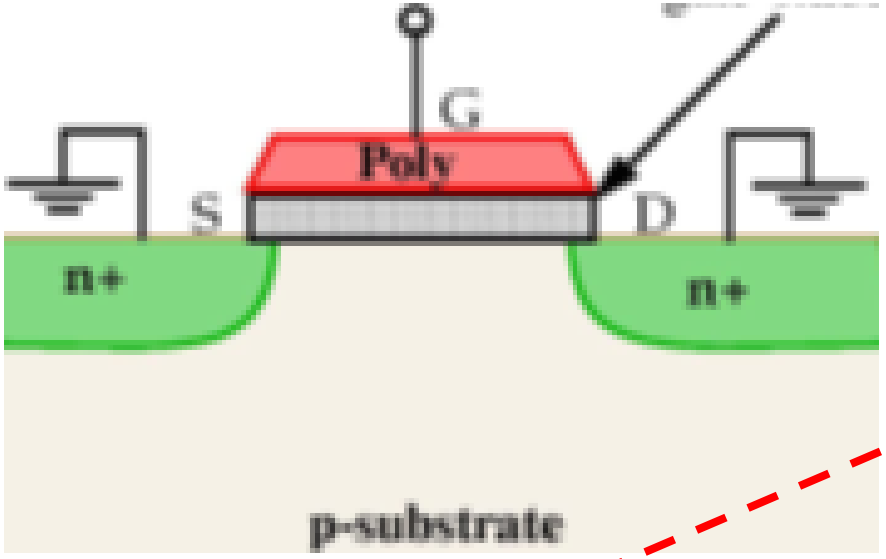
Material Properties

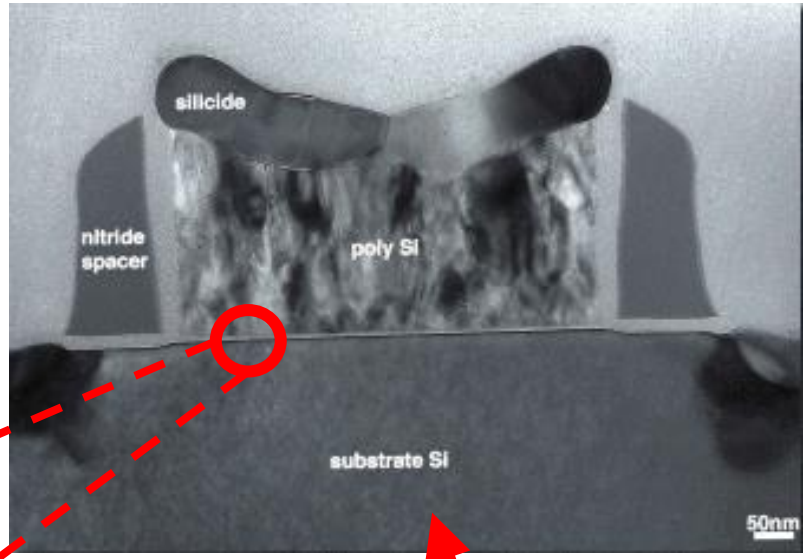
- Generally **crystalline** in structure for IC devices
  - In recent years, however, **non-crystalline** semiconductors have become commercially very important

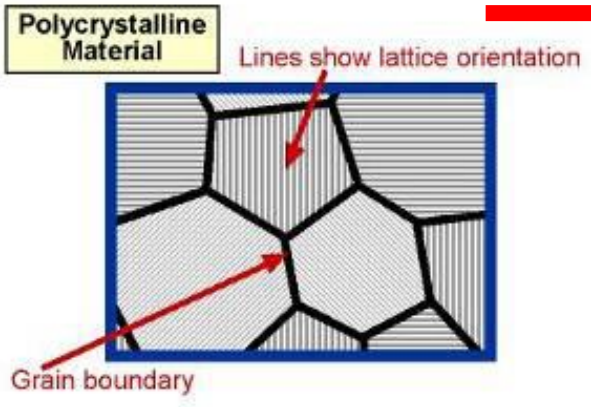


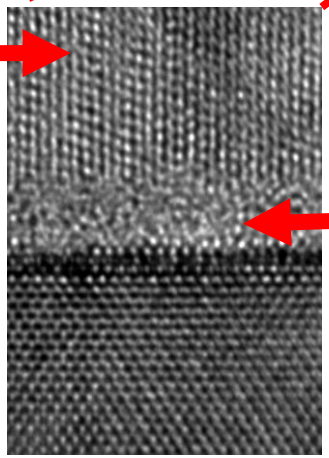
Material Properties: Example

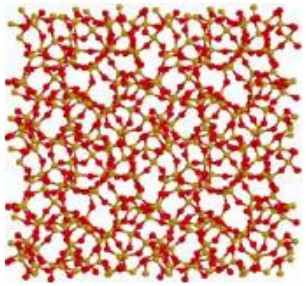
Transmission Electron Microscope



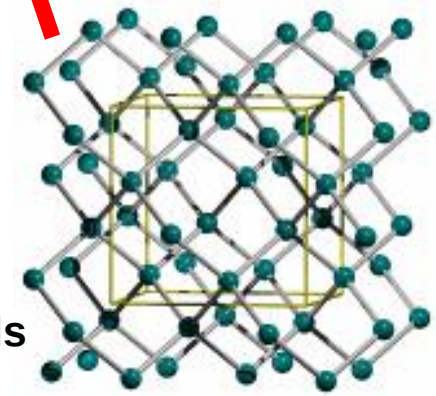








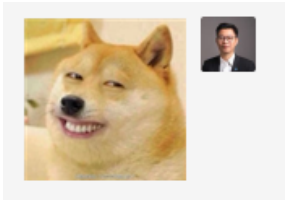
Amorphous Materials



Single-Crystal Material

2.2 Crystal Structures

- General material properties
- **Crystal structures**



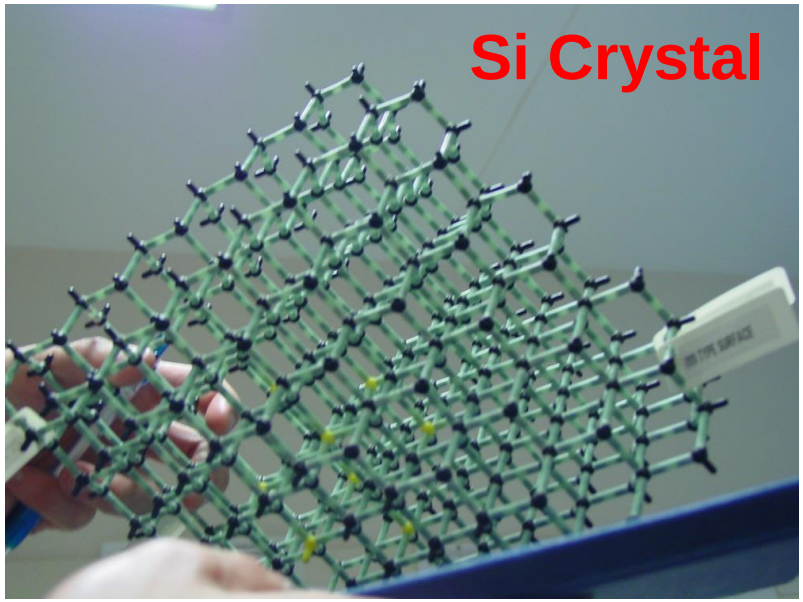
- Crystallographic notation
- Bohr’s theory – energy level & band

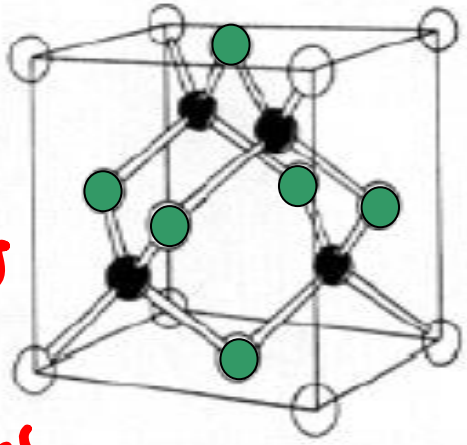
Silicon Crystallography

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

Crystal : Atoms + Lattice

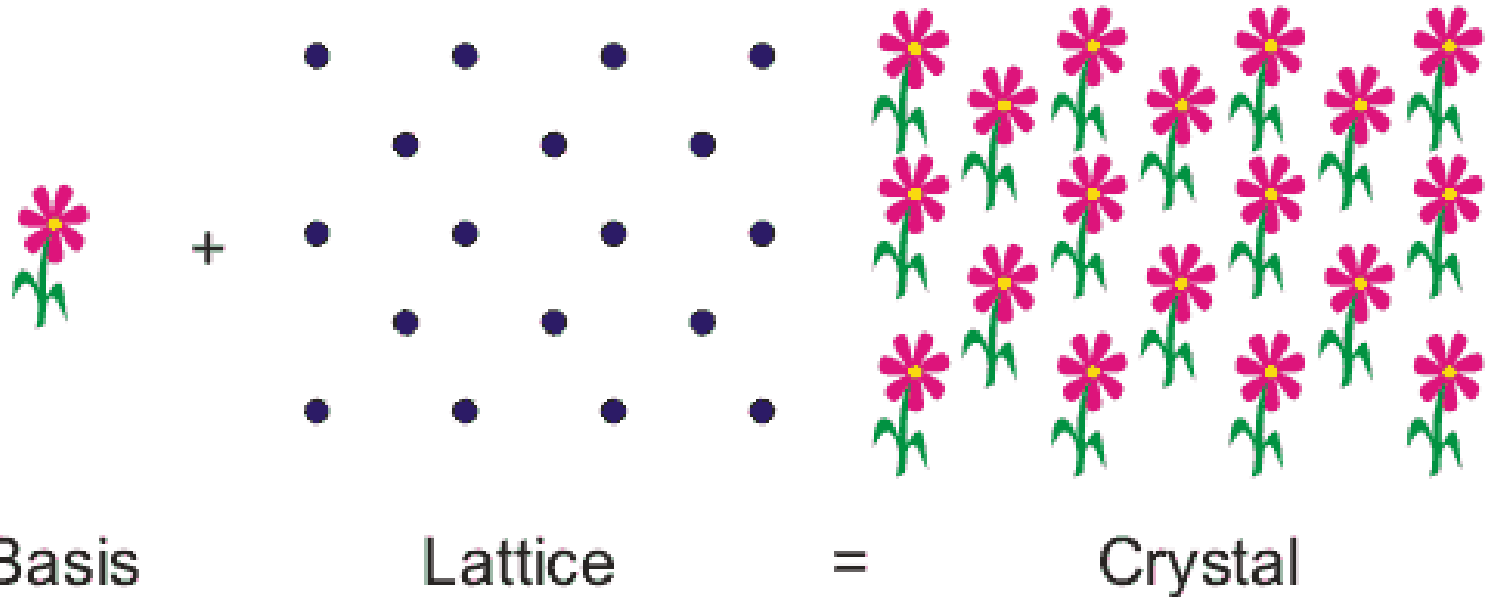
- ***Silicon Lattice = Diamond Lattice:*** atoms with four covalent bonds, cubic lattice





8 corner atoms
6 face atoms
4 interior atoms

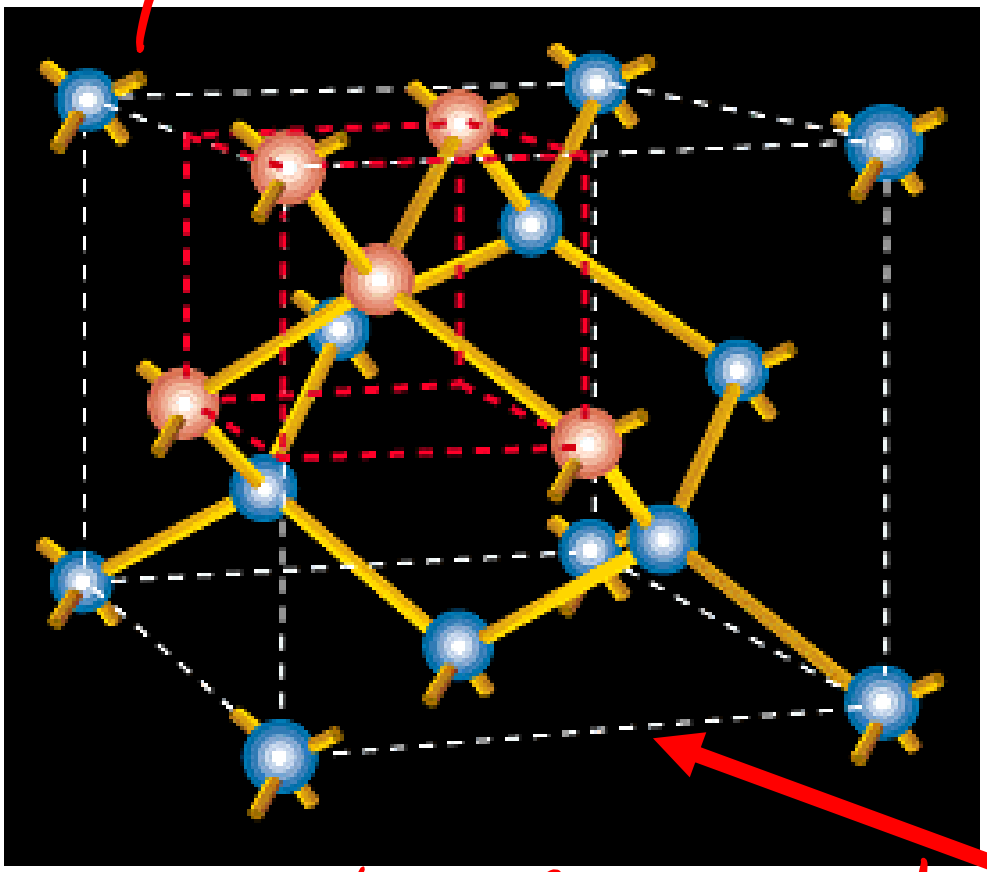
Lattice and **Crystal**

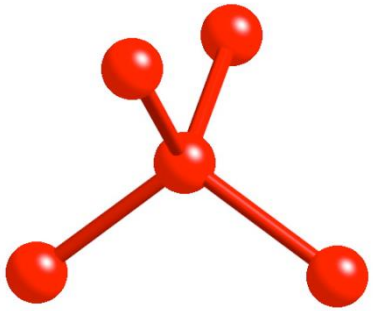


A **crystal** can be thought of as being like wallpaper. The motif is analogous to the basis and the arrangement of the motif over the surface is like the **lattice**.

The Si Crystal: **Unit Cell**

unit cell (building block)





- Each Si atom has **4** nearest neighbors
- **Lattice Constant**, a
  = 5.431 Å
  = 0.5431 nm

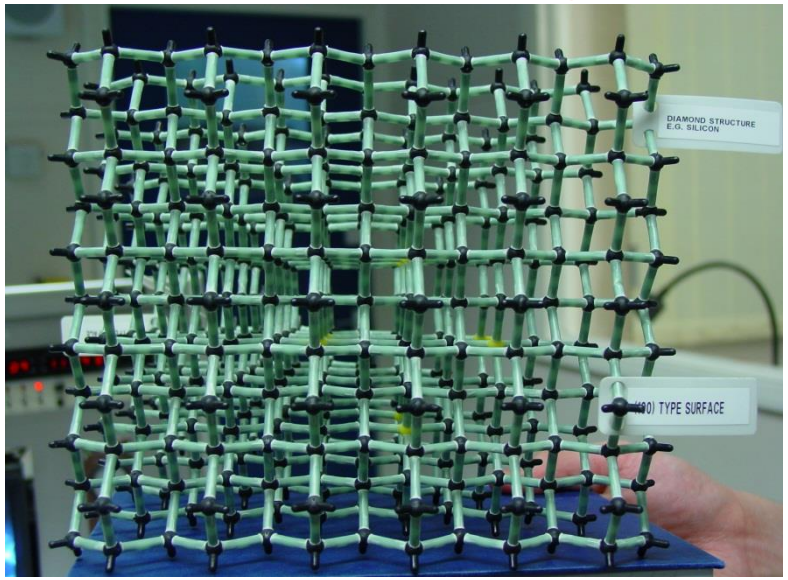
a

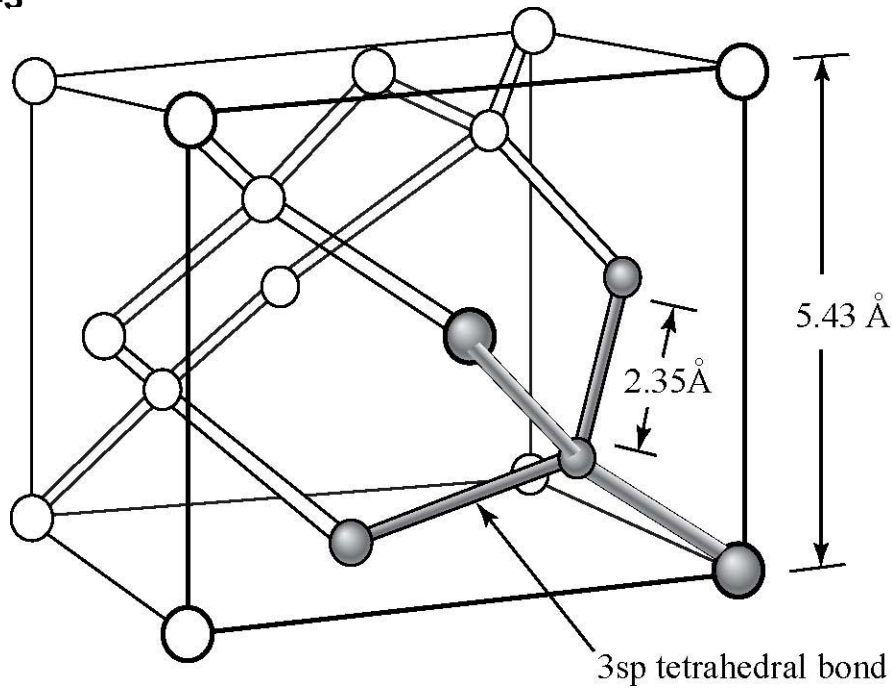
"diamond cubic" lattice

"diamond 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}**



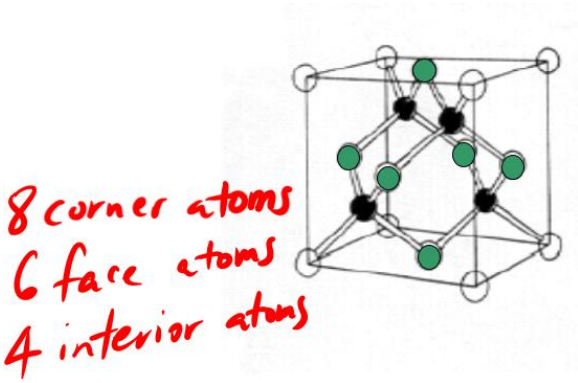


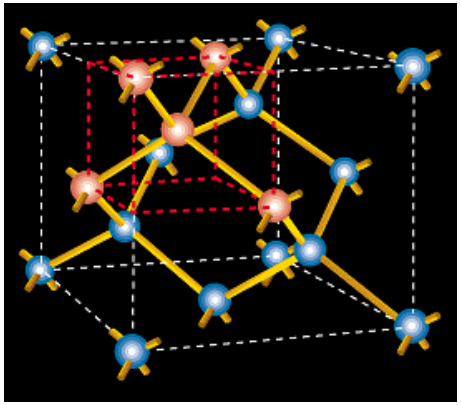
$$\frac{\#\,Atoms}{Volume} = \frac{8\times 1/8 + 6\times 1/2 + 4}{a_0^3} = \frac{8}{(5.43\times 10^{-8}\,cm)^3} = 5\times 10^{22}\,cm^{-3}$$

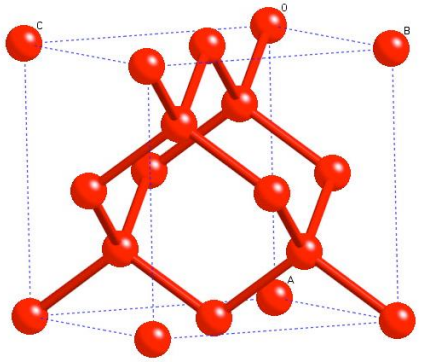
HW-1

Silicon crystal structure: **Summary**

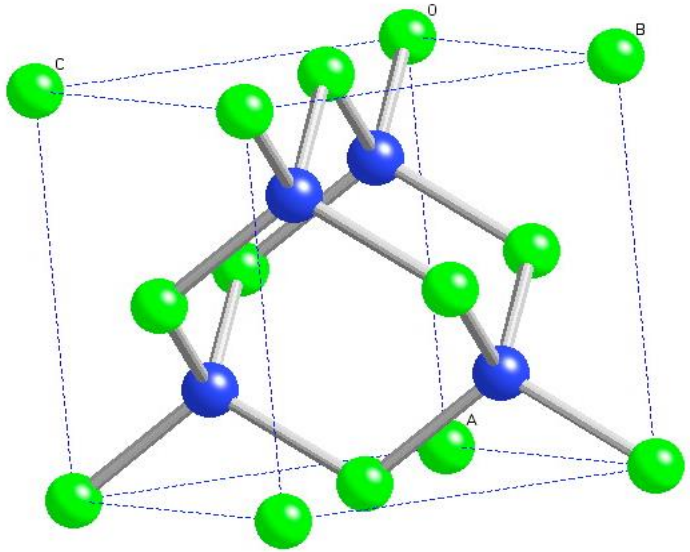
- **Silicon atoms** form covalent bonds and can crystallize into a regular lattice.
- **Silicon atom** has 4 electrons which it can share in covalent bonds with its neighbors.
- **Silicon crystallizes** in the same pattern as **diamond**.
- Bold lines between silicon atoms in the lattice illustration indicate nearest-neighbor bonds.







Compound Semiconductors



- "**Zinc Blende**" structure

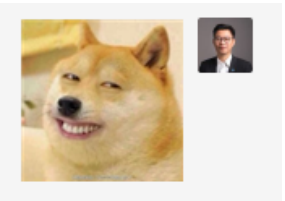
  Simply the diamond structure in which the species of atoms alternate

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

  ✓ important for optoelectronics and high-speed ICs

2.2 Crystal Structures

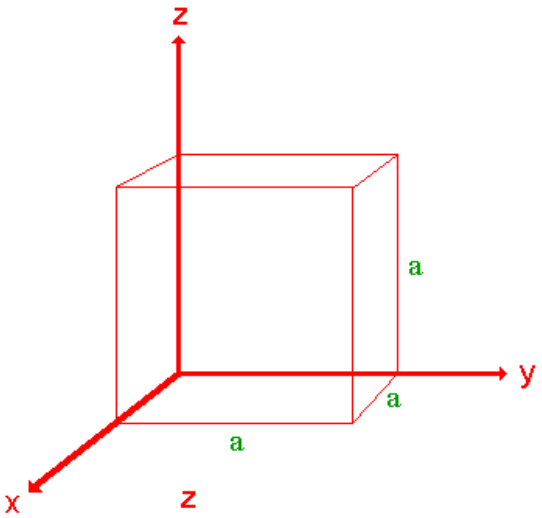
- General material properties
- Crystal structures
- **Crystallographic notation**

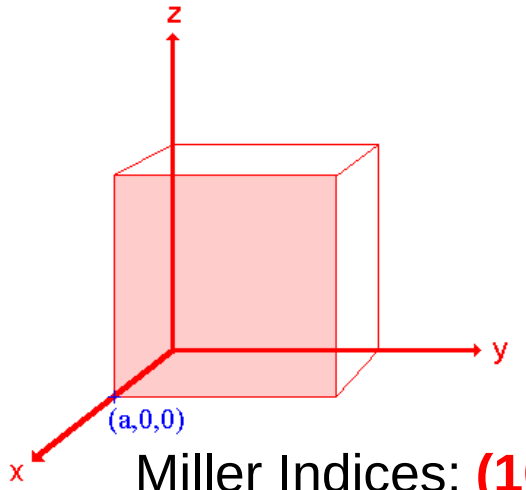


- Bohr's theory – energy level & band

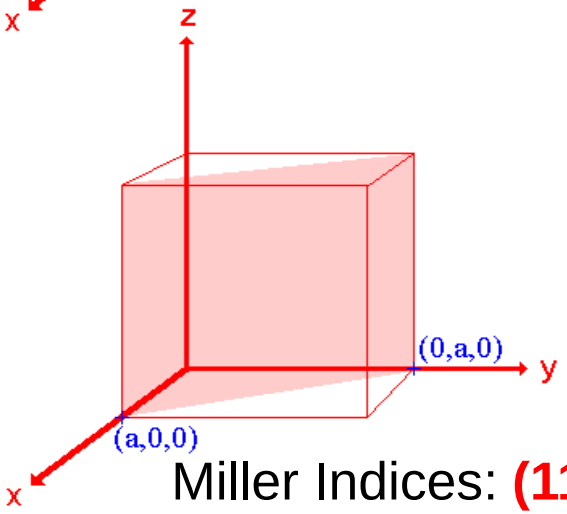
Crystallographic Notation

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

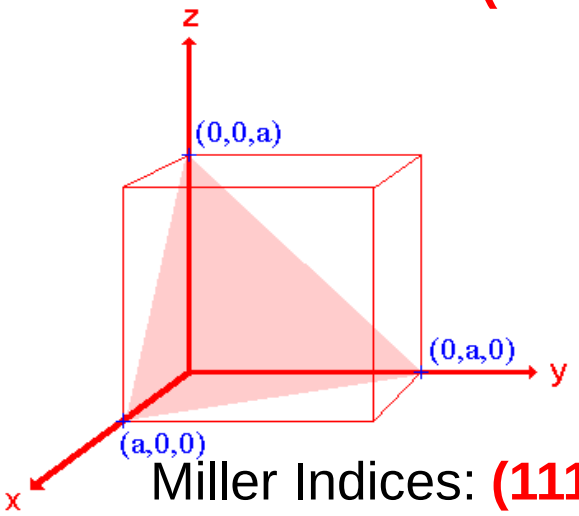




Miller Indices: **(100)**



Miller Indices: **(110)**

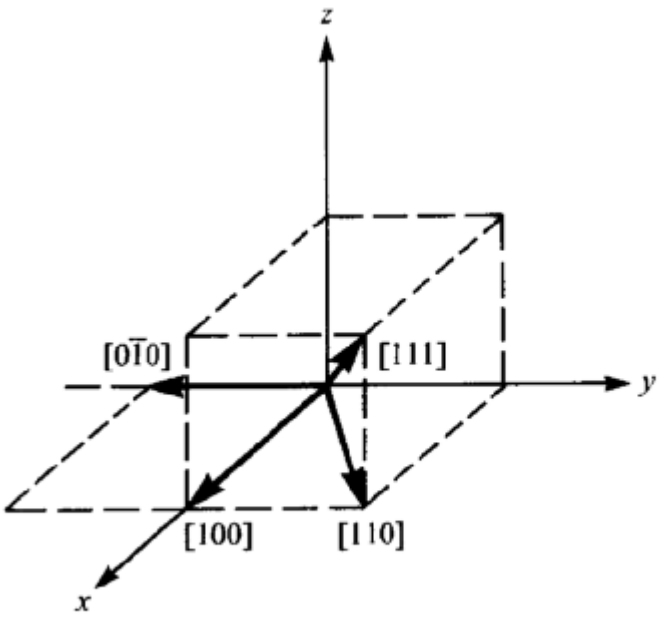


Miller Indices: **(111)**

Crystallographic Notation: **Directions**

Miller Indices:

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



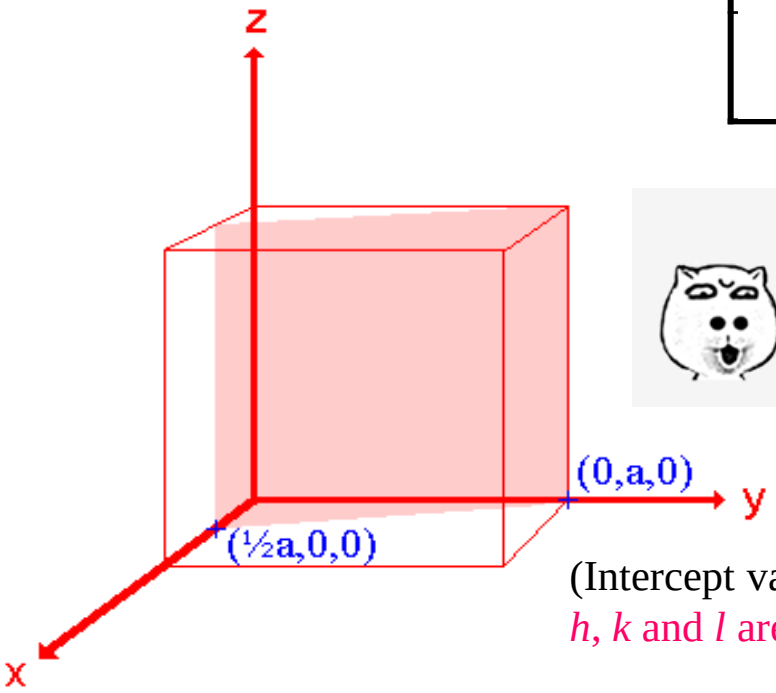
Sample direction vectors and their corresponding Miller indices.

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**



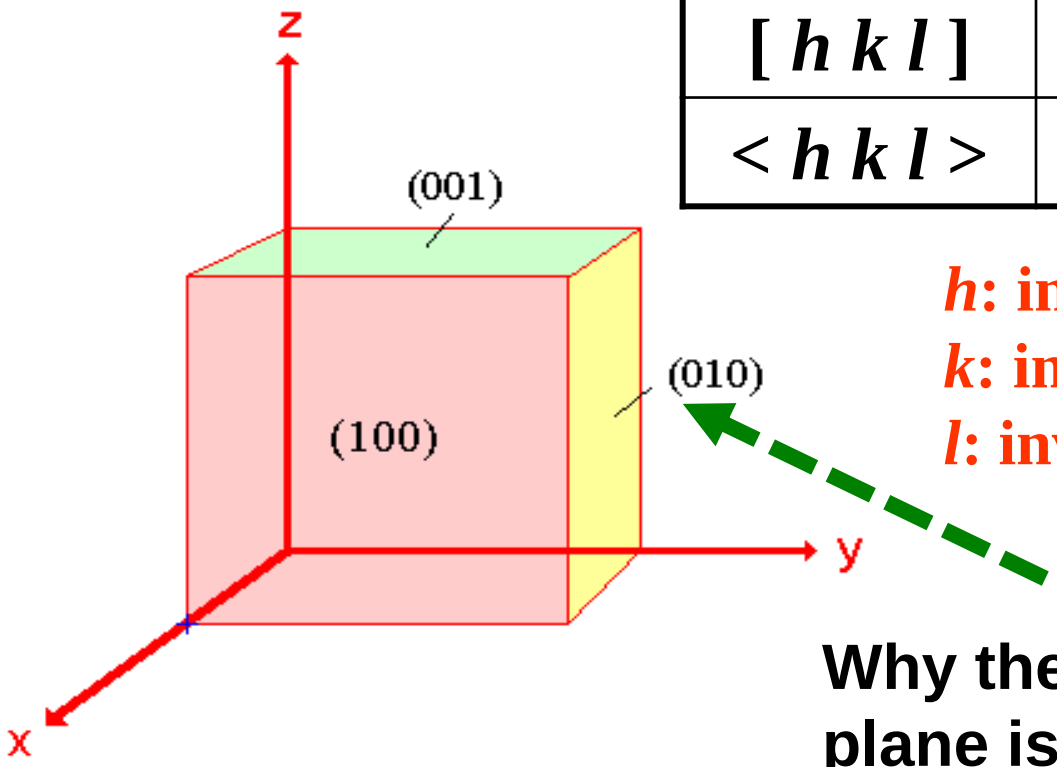
***h*: inverse *x*-intercept of plane**
***k*: inverse *y*-intercept of plane**
***l*: inverse *z*-intercept of plane**

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

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**

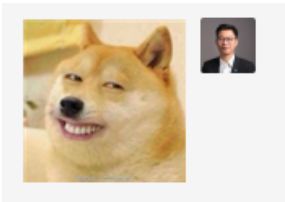


***h*: inverse *x*-intercept of plane**
***k*: inverse *y*-intercept of plane**
***l*: inverse *z*-intercept of plane**

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

2.2 Crystal Structures

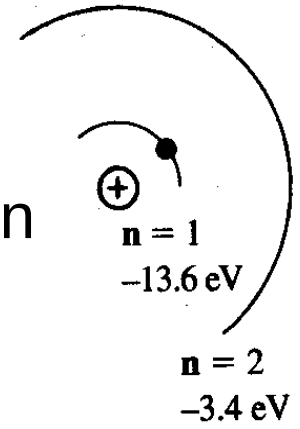
- General material properties
- Crystal structures
- Crystallographic notation

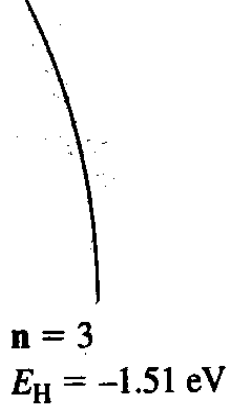


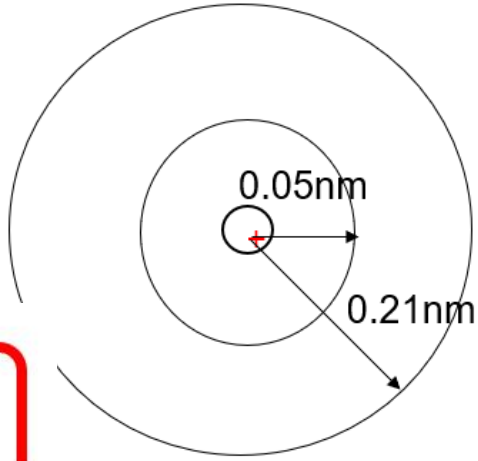
- **Bohr’s theory – energy level & band**

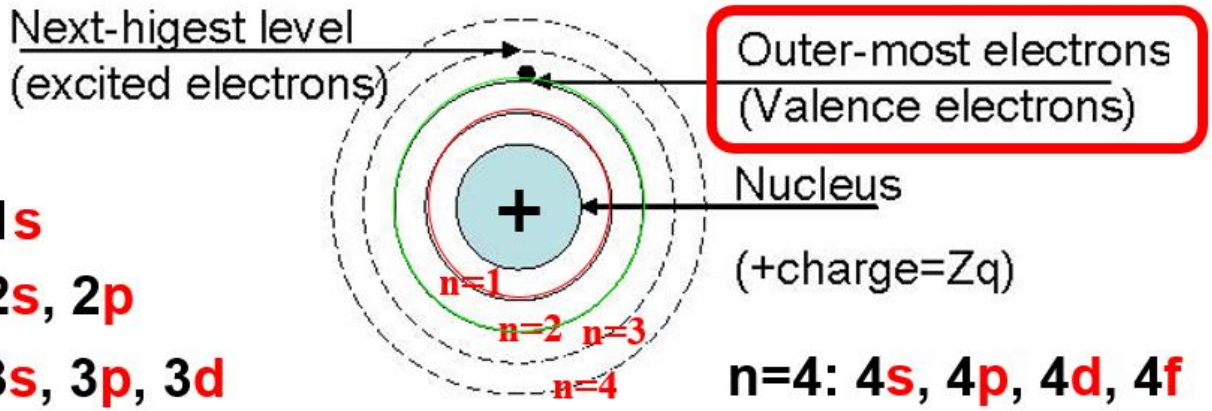
Bohr's Theory

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









n=1: 1s

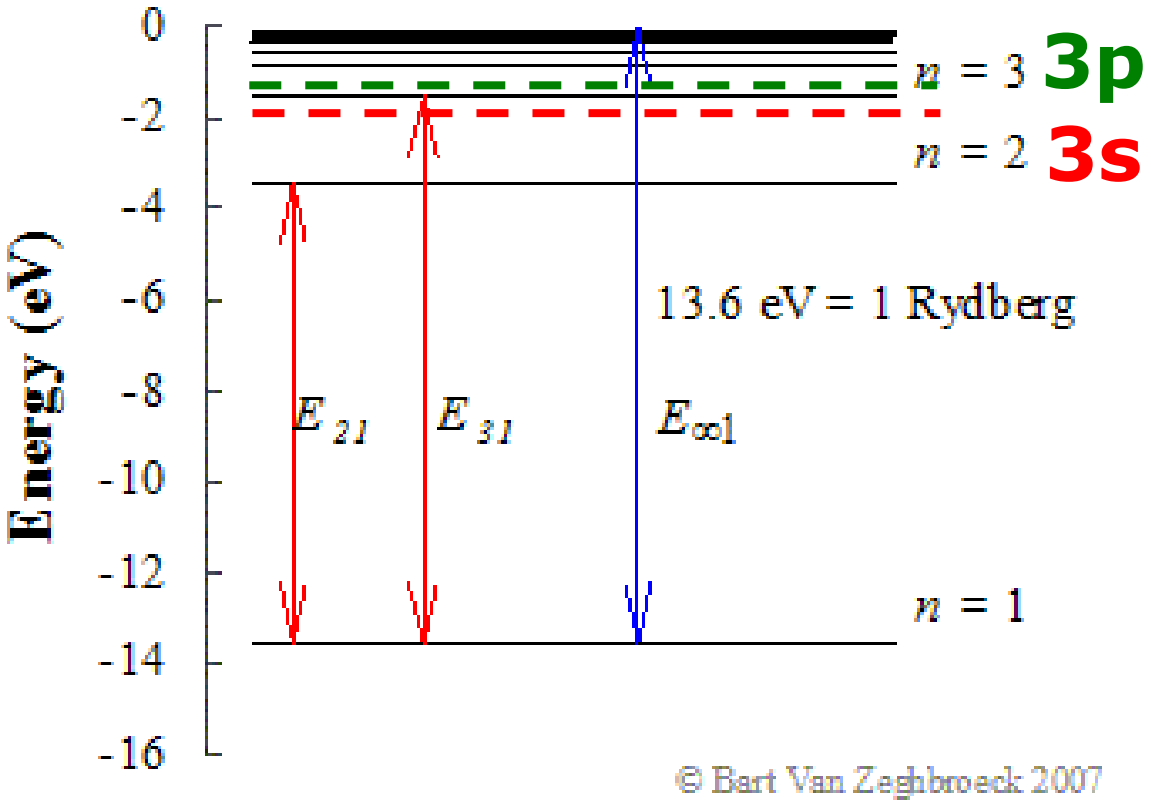
n=2: 2s, 2p

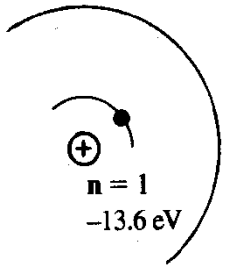
n=3: 3s, 3p, 3d

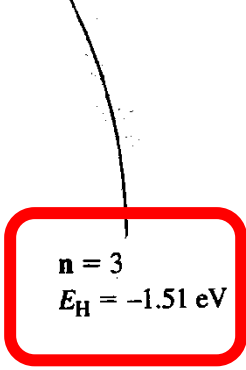
n=4: 4s, 4p, 4d, 4f

PL

The Bohr model





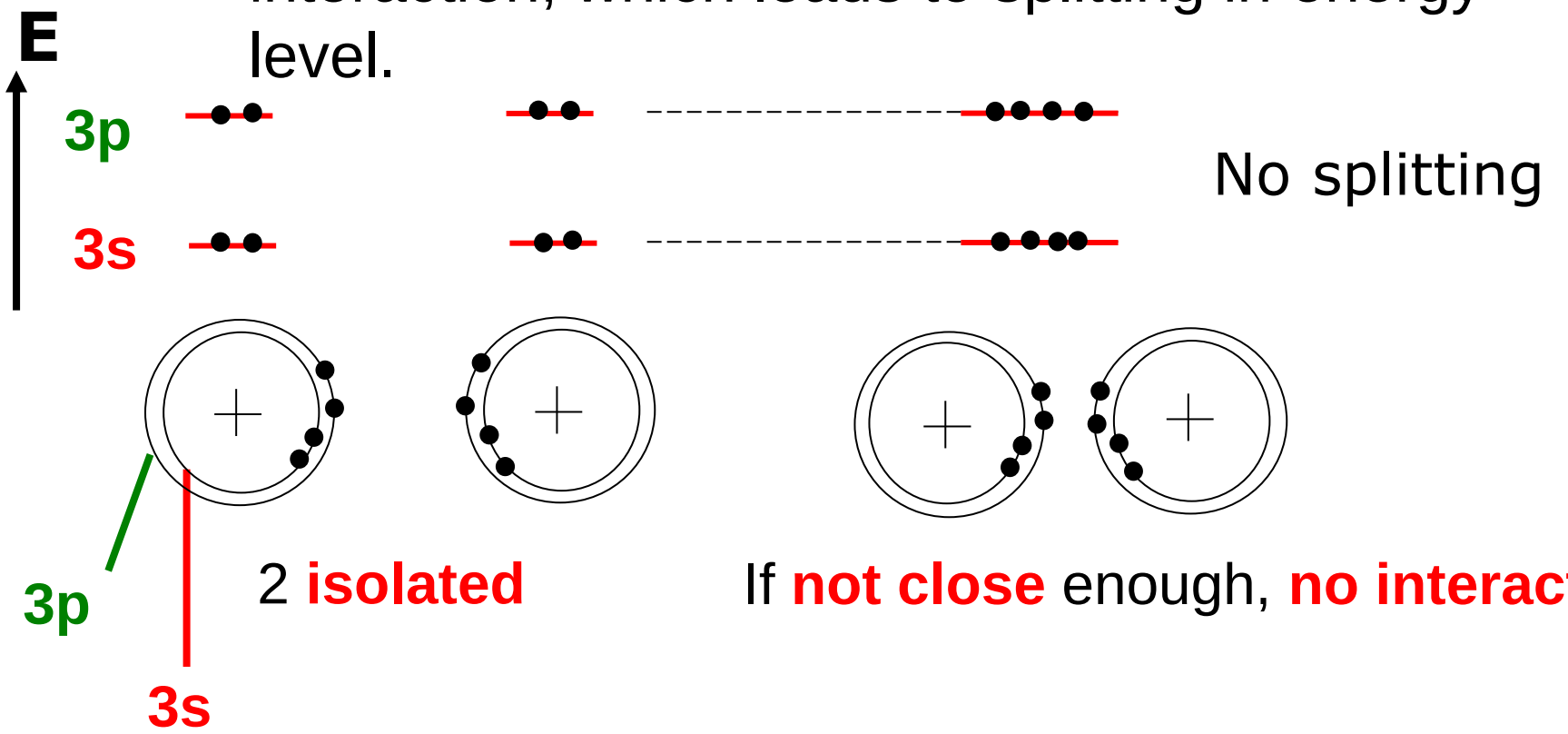


Outmost Orbit

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.



Energy Bands

- Energy level of an isolated atom
- In solids, **atoms interact with each other**
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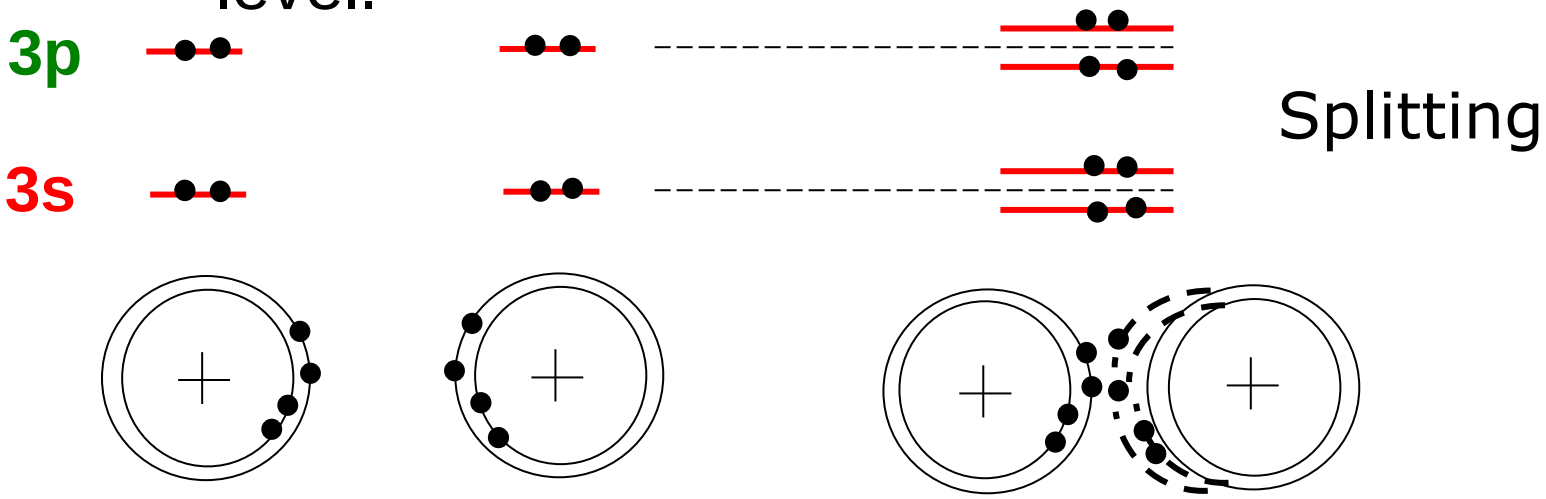
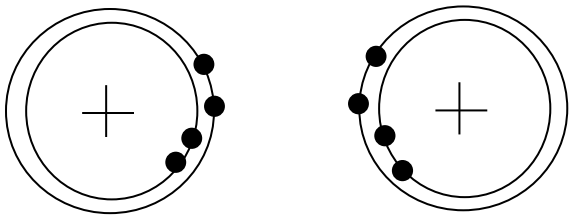


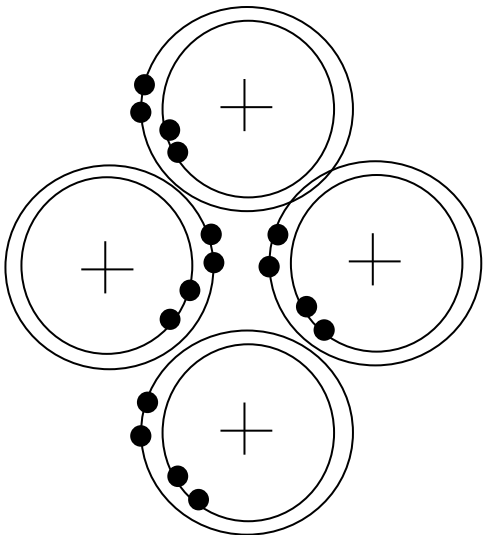
Energy Bands

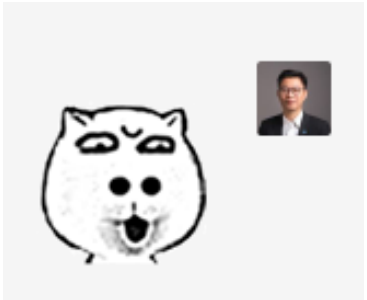
- Energy level of an isolated atom
- In solids, atoms interact with each other
- The **orbits of electrons** will be **altered** by interaction, which leads to **splitting in energy level**.

Splitting

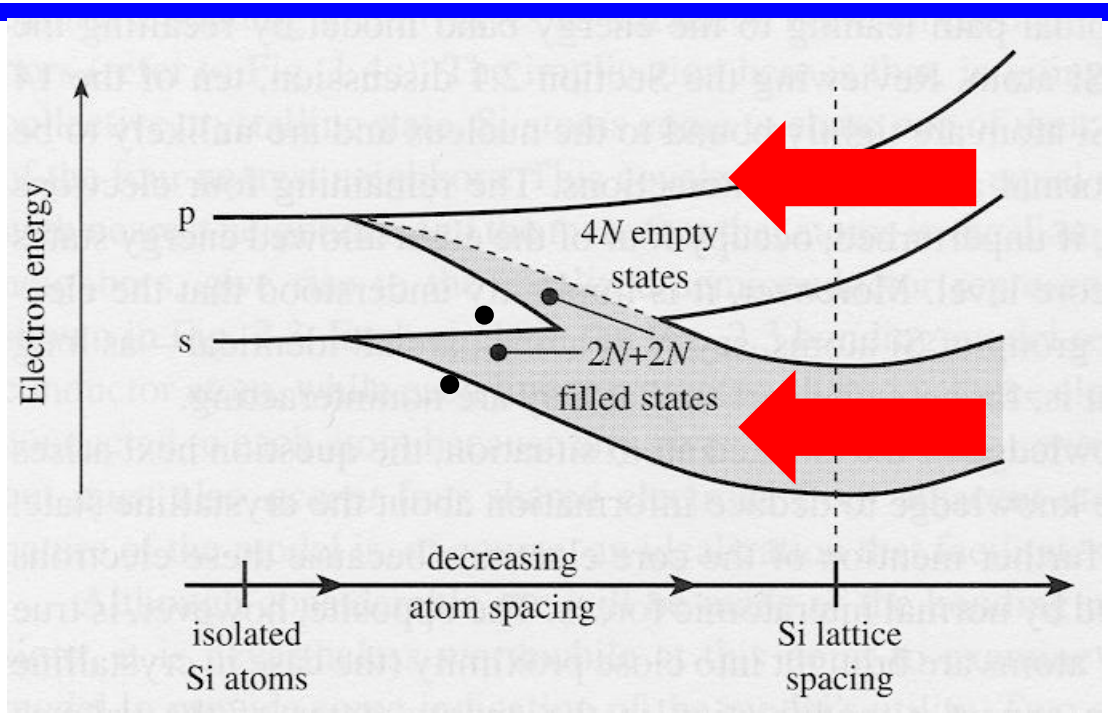


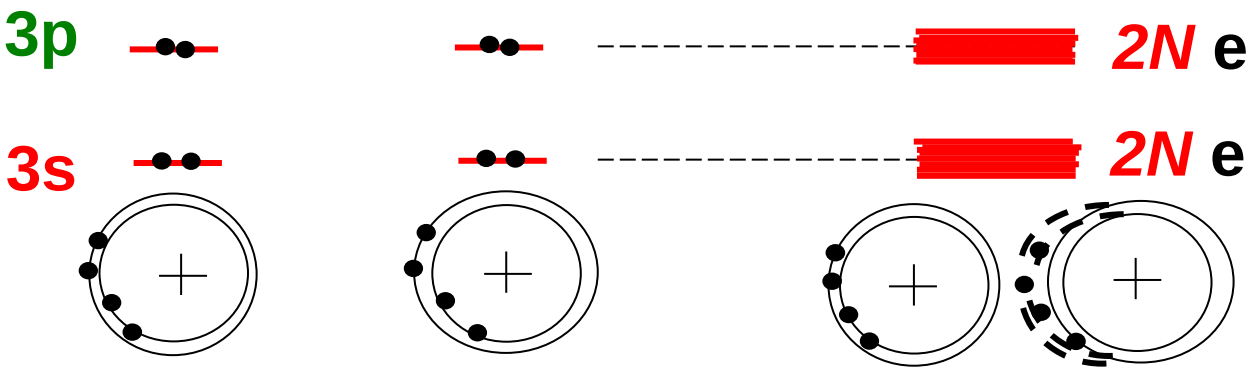
4 **isolated**



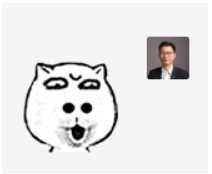


Si: From Atom to Crystal

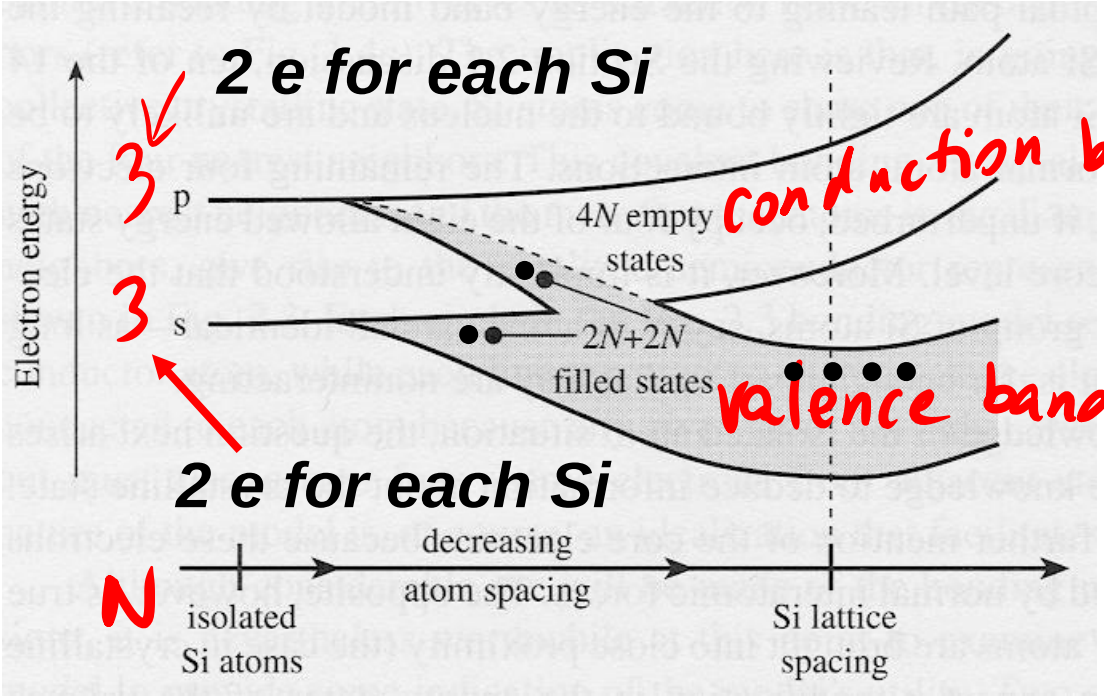




Splitting



Si: From Atom to Crystal

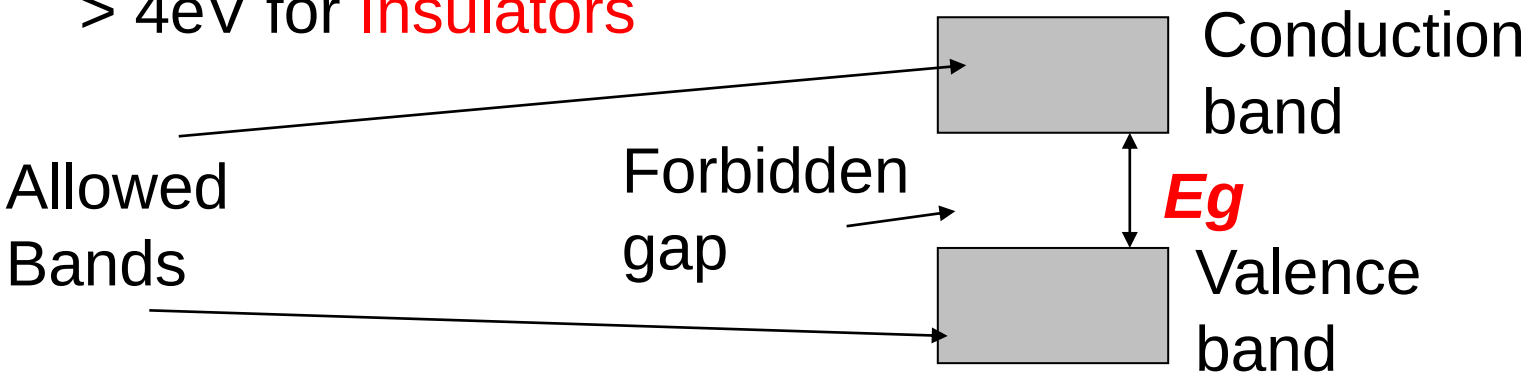


Energy **levels** in Si **atom** → **energy bands** in Si **crystal**

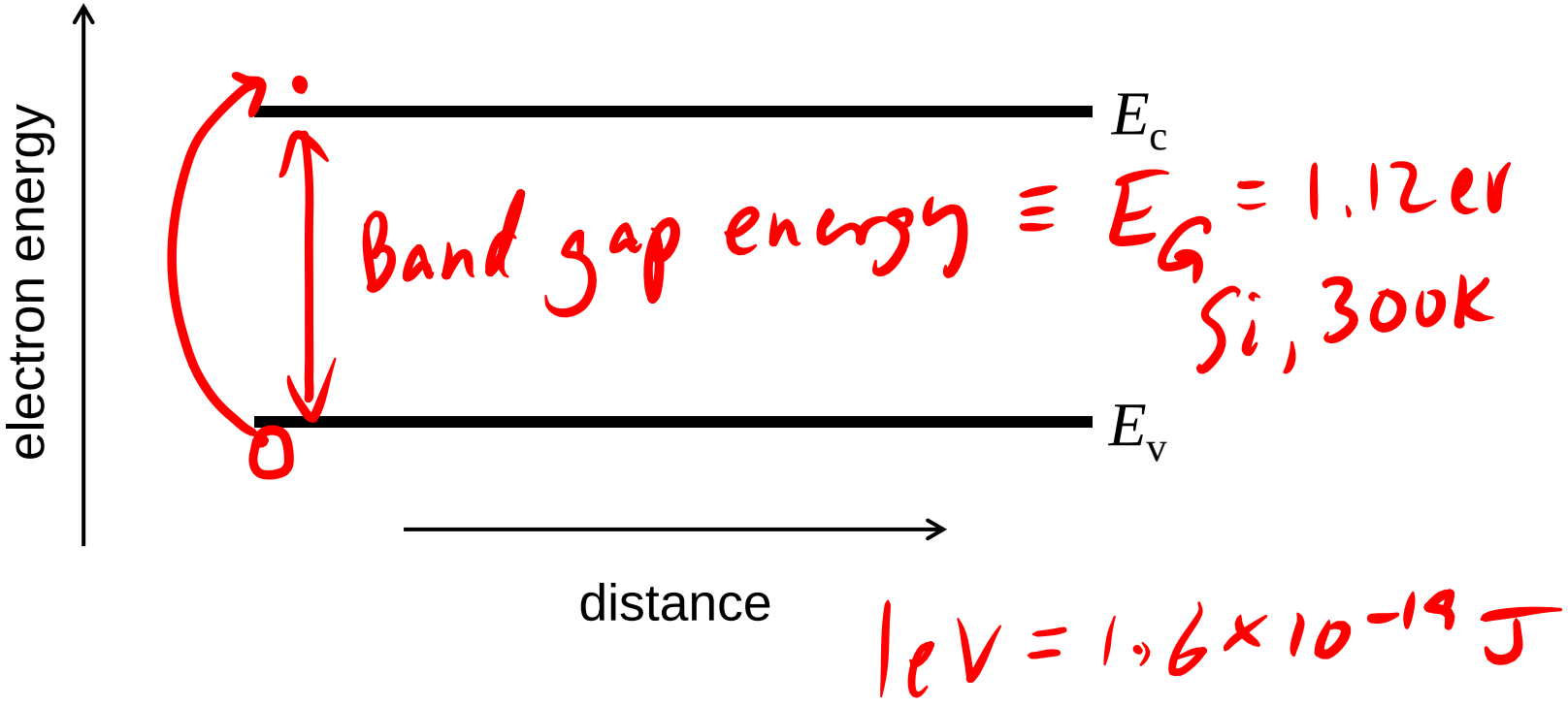
- The highest nearly-filled band is the ***valence band***
- The lowest nearly-empty band is the ***conduction band***

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**

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

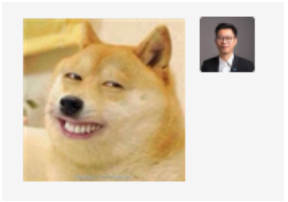
- ***Ec*, *Ev* and *Eg***

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