University of Global Village

Department of Electrical & Electronics Engineering

OBE Curriculum

SEMICONDUCTOR DEVICES

Code: EEE 311
Core Course
Exam Hours: 03

Credits: 03
CIE Marks: 90
SEE Marks: 60

SEMICONDUCTOR DEVICES

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RATIONALE OF THE COURSE

This course is vital for understanding semiconductor devices, the core of modern electronics and technology. It equips students with essential knowledge and skills for careers in electronics, telecommunications, and the semiconductor industry. By covering topics like energy bands, charge carriers, and device behavior, it prepares individuals to innovate and address industry challenges. A strong foundation in these principles is essential for technological advancement.

OBJECTIVES OF THE COURSE

01

- *Provide insights into the impact of temperature and doping on semiconductor characteristics.*

02

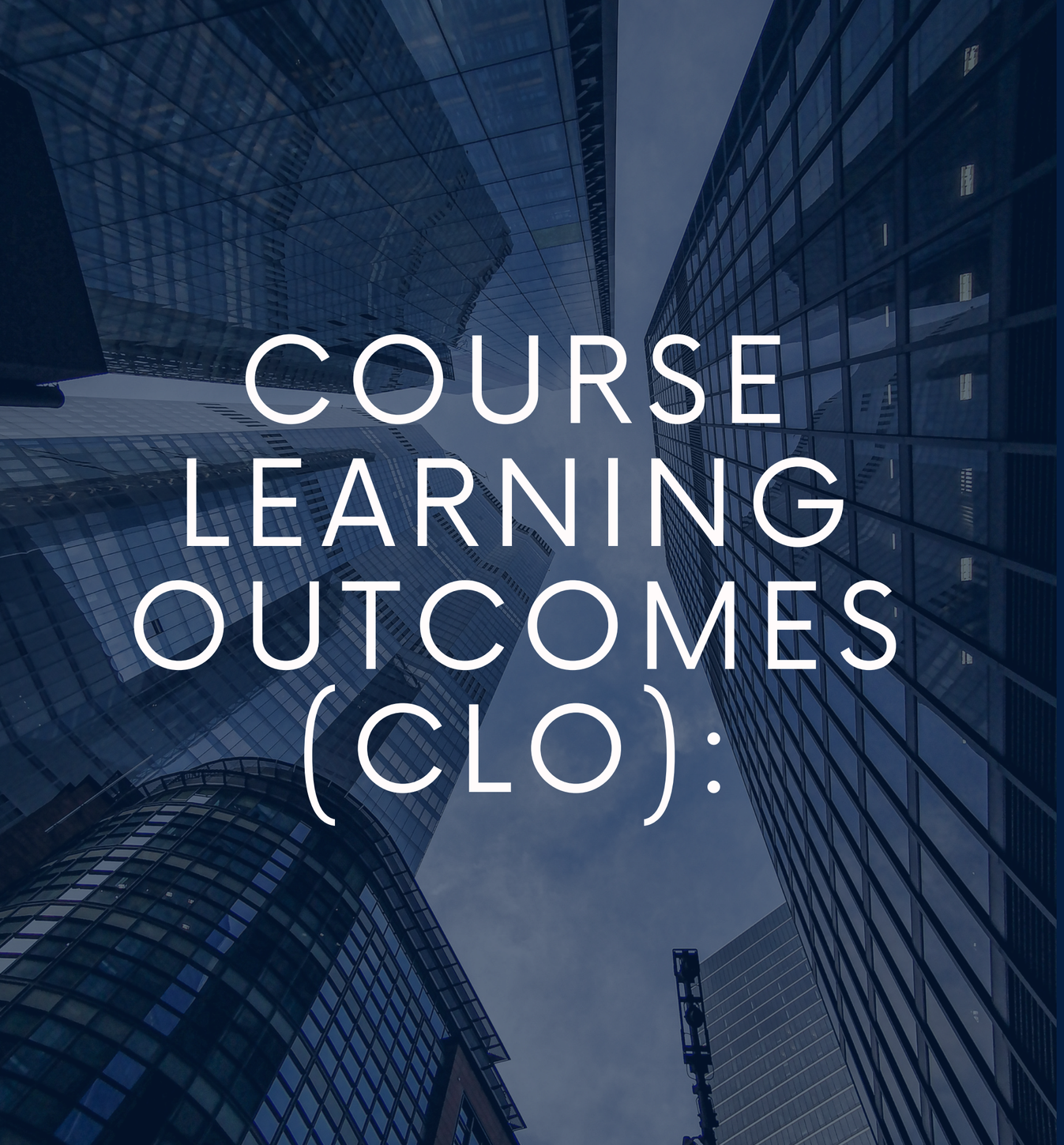
- *Explore the intricacies of junction formation and energy band diagrams.*

03

- *Analyze the behavior of minority carriers and non-ideal effects in semiconductor devices.*

04

- *Familiarize students with various semiconductor device types, including MESFETs and HEMTs.*



COURSE LEARNING OUTCOMES (CLO):

01 *Explain how the basic concepts of solid-state physics relate to the different properties of semiconductors*

02 *Determine the energy band diagrams of different semiconductor devices under different operating conditions*

03 *Calculate charge, current, voltage and capacitance of different semiconductor devices under different operating conditions*

04 *Investigate how material properties and structural parameters affect the device characteristics*

COURSE LEARNING OUTCOMES (CLO):

05 *Explain how the basic concepts of solid-state physics relate to the different properties of semiconductors*

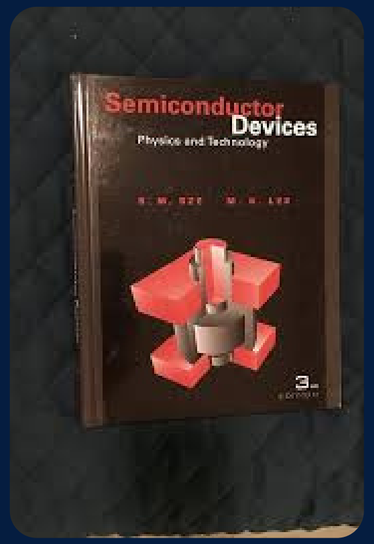
06 *Determine the energy band diagrams of different semiconductor devices under different operating conditions*

Content of Course	Hours	CLOS
Review of energy bands, metals, and semiconductors, Charge carriers, effective mass, density of states in semiconductors, Intrinsic and extrinsic semiconductor, degenerate and non-degenerate semiconductors, Electron and hole concentrations at equilibrium, temperature dependence of carrier concentrations	08	CLO 1
Compensation and space charge neutrality, Conductivity and mobility, diffusion and drift of carriers, Generation and recombination of excess charge carries, Junction formation, formation of space charge	08	CLO 2

Content of Course	Hours	CLOS
Energy band diagram, built-in fields, contact potential, Equilibrium Fermi levels, current flow in junction, Carrier injection in forward and reverse-biased junctions, Reverse-bias breakdown (Zener and Avalanche)	08	CLO 3
Reverse recovery transient, junction capacitances, Schottky barrier, rectifying contacts, Ohmic contacts, heterojunctions, Fundamentals, energy band diagram of BJT	08	CLO 4 CLO 5

Content of Course	Hours	CLOS
Minority carrier profiles, modes of operation of BJT, non-ideal effects, Basic operation of MOS, different biasing modes, Real MOS capacitor, flat band threshold voltages, I-V characteristics, short channel effects, non-ideal effects, MESFET and HEMT. Device scaling, industry trends in semiconductor devices	08	CLO 6

REFERENCE BOOKS



SEMICONDUCTOR DEVICES

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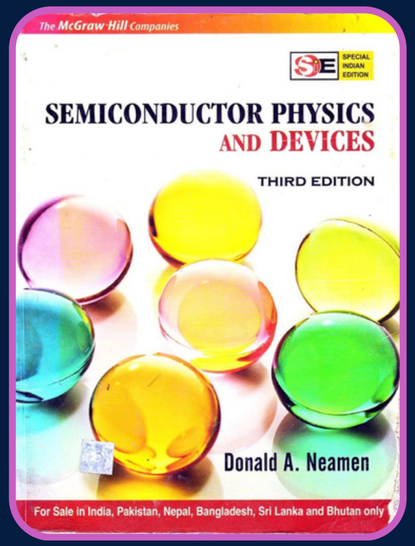
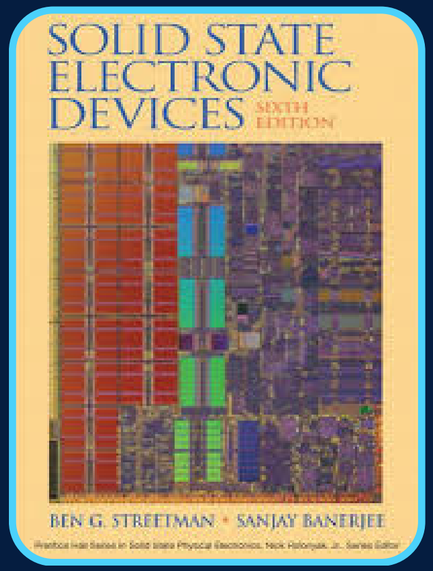


SEMICONDUCTOR PHYSICS AND DEVICES

Donald a Neamen,
Tata McGraw Hill



SOLID STATE ELECTRONIC DEVICES

B.G. Streetman

ASSESSMENT PLAN

CIE- Continuous Internal Evaluation (90 Marks)

Bloom's Category Marks (out of 90)	Exam (45)	Assignments/ Viva/ Presentation (15)	Quiz (15)	External Participation in Curricular/Co-Curricular Activities (15)
Remember	10		8	
Understand	8		7	Bloom's Affective Domain: (Attitude or will) Attendance: 15 Copy or attempt to copy: -10 Late Assignment: -10
Apply	13			
Analyze	7			
Evaluate	4			
Create	3			

ASSESSMENT PLAN

SEE- Semester End Examination (60 Marks)	
Bloom's Category	Tests
Remember	15
Understand	13
Apply	12
Analyze	10
Evaluate	5
Create	5

Course plan specifying content, CLOs, teaching learning and assessment strategy mapped with CLOs				
Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
1 (1 & 2)	The Crystal Structure of Solids	-To have a formal interaction with the students and know about the proceedings of the subjectmatter. -Course outline will be discussedin detail -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Animation, Simulation, Link) -Group discussion	Quiz, Written exam -Collect feedback by questioning and answering -Collect feedback from group discussion	CLO1

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
2 (1& 2)	Atomic Bonding Imperfections and Impurities in Solids	Recap main points -Forward Plan -Discussion aboutthe subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Animation, Simulation, Link) -To be supplied Lessonmaterials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO1

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
3 (1 & 2)	Introduction to Quantum Mechanics PRINCIPLES OF QUANTUM MECHANICS , SCHRODINGER'S WAVE EQUATION	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Animation, Simulation, Link) -To be supplied Lesson materials notes, Hard copy, Audiovideo materials/Link -Group discussion	Quiz, Written exam,Collect feedback by questioning and answering from group discussion -Collect feedback from Midterm and ClassTest 1 -Assessment of LOs	CLO1, CLO2

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
4 (1 & 2)	APPLICATIONS OF SCHRODINGER'S WAVE EQUATION	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO2

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
5 (1 & 2)	Compensation (Compensation and space charge neutrality)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO2, CLO4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
6 (1 & 2)	Conductivity and mobility (Conductivity and mobility, diffusion and drift of carriers)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO2, CLO4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
7 (1 & 2)	Excess carriers (Generation and recombination of excess charge carries)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO2, CLO4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
8 (1 & 2)	Junction formation (Junction formation, formation of space)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO1, CLO2, CLO4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
9 (1 & 2)	Energy bands (Energy band diagram, built-in fields, contact potential)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO1, CLO2

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
10 (1 & 2)	Equilibrium level (Equilibrium Fermi levels, current flow in junction)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO1, CLO3

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
11 (1 & 2)	Carrier injection (Carrier injection in forward and reverse-biased junctions)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 1, CLO 3, CLO 4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
12 (1 & 2)	Reverse-bias breakdown (Reverse-bias breakdown (Zener and Avalanche))	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 1, CLO 3, CLO 4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
13 (1 & 2)	Reverse recovery transient (Reverse recovery transient, junction capacitances)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 1, CLO 3, CLO 4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
14 (1 & 2)	Schottky barrier (Schottky barrier, rectifying contacts)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 1, CLO 4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
15 (1 & 2)	Ohmic contacts (Ohmic contacts, heterojunctions)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 3, CLO 4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
16 (1 & 2)	BJT fundamentals (Fundamentals, energy band diagram of BJT)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 2, CLO 4

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
17 (1 & 2)	Minority carrier profiles (Minority carrier profiles, modes of operation of BJT, non-ideal effects)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 3

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
18 (1 & 2)	Basic operation of MOS (Basic operation of MOS, different biasing modes)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 2 CLO 4

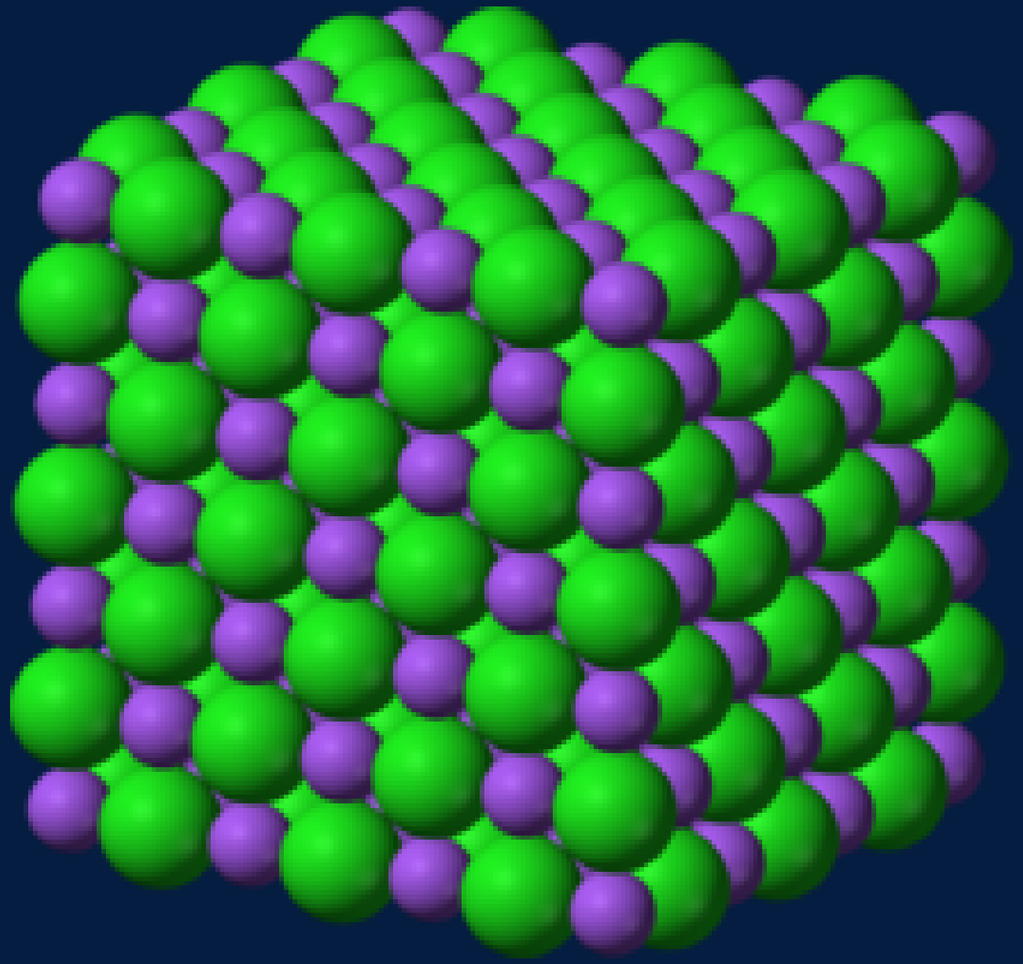
Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
19 (1 & 2)	MOS capacitor (Real MOS capacitor, flat band threshold voltages, I-V characteristics)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 3, CLO 5

Week & Class No	Task Details	Teaching Learning strategy(s)	Assessment strategy(s)	Alignment to CLOs
20 (1 & 2)	Short channel effects (Short channel effects, non-ideal effects. MESFET and HEMT. Device scaling, industry trends in semiconductor devices)	-Recap main points -Forward Plan -Discussion about the subject content with the students -Interactive discussion -Lecture with aid of multimedia (Using Document, Slide, PDF, Video, Link Animation, Simulation) -To be supplied Lesson materials notes, Hard copy,Audio video materials/Link -Group discussion	Quiz, Written exam Collect feedback by questioning and answering -Collect feedback from group discussion -Collect feedback from Midterm and Class Test 1 -Assessment of LOs	CLO 6

STUDENT SUPPORT DOCUMENTS

WEEK 1
CLASS 1

The Crystal Structure of Solids



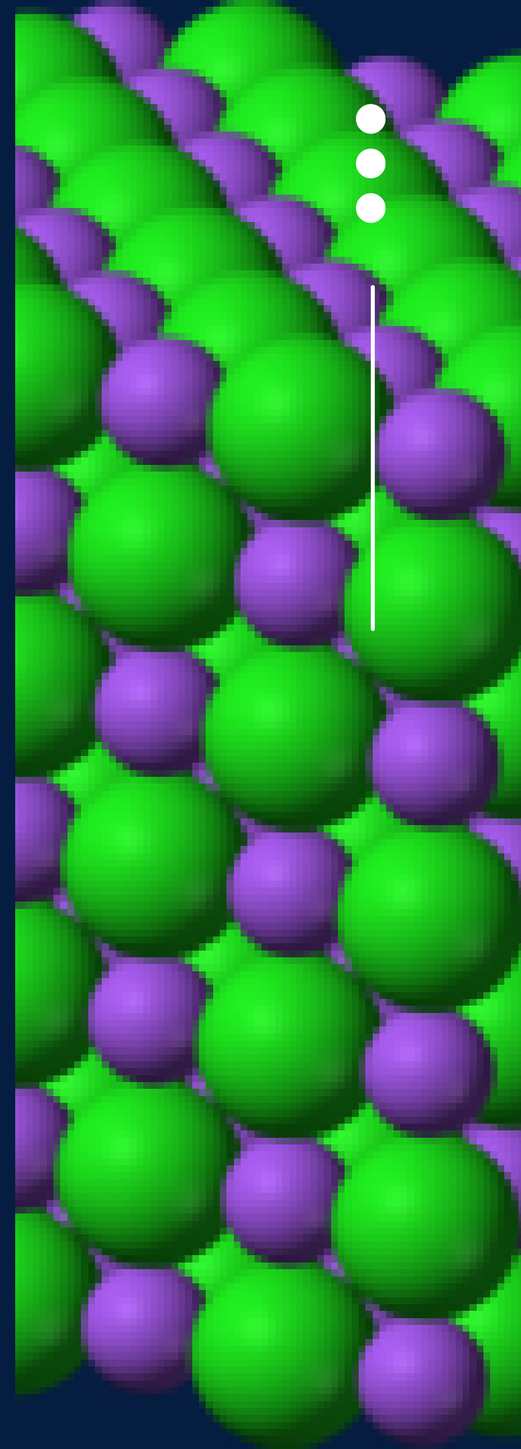
SEMICONDUCTOR MATERIALS

Table 1.1 | A portion of the periodic table

III	IV	V
B	C	
Al	Si	P
Ga	Ge	As
In		Sb

Table 1.2 | A list of some semiconductor materials

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



Elemental and Compound Semiconductors

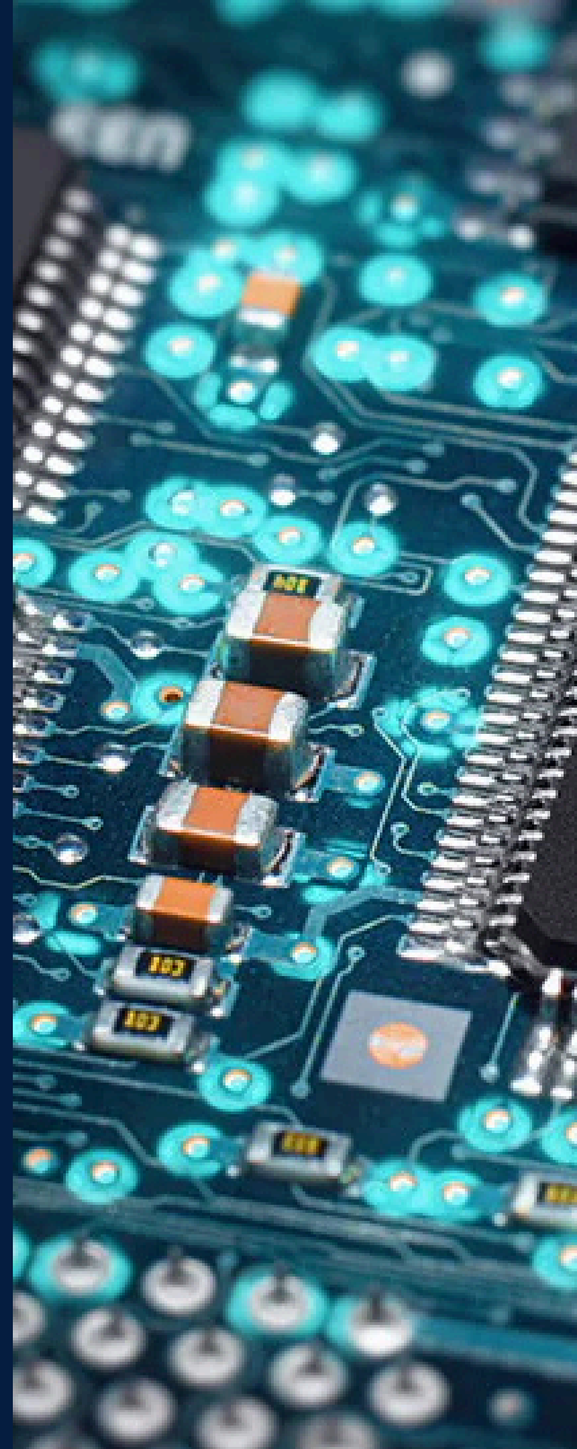
Binary Semiconductor (2 elements):
$Si_{1-x}Ge_x$, SiC

Ternary Semiconductor (3 elements):
$Al_xGa_{1-x}P$

Quaternary Semiconductor (4 elements) : AlGaAsP

- Single element à elemental semiconductor
- More than one element à compound semiconductor

Properties of comp semi can be controlled by changing the concn of the elements



Gallium nitride (GaN) and zinc oxide (ZnO) are recently discovered semiconductor materials which are promising materials for laser diodes (blue light).

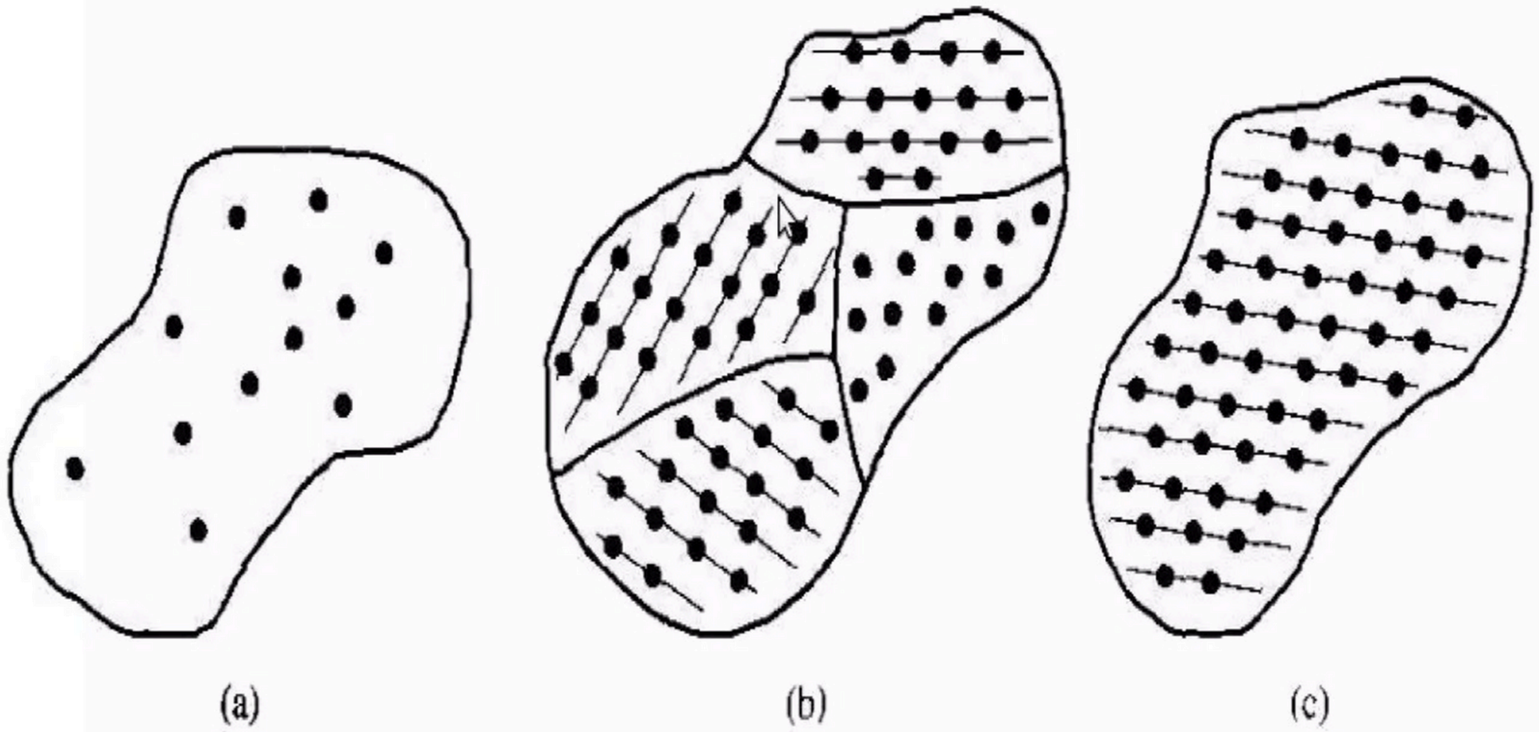
These laser diodes are used in blue-ray DVD recorders. Blue light having smaller wavelength helps in lowering the resolution and increasing the packing density of bits.

A light emitting diode

Types of Solids

Characterized by the size of an *ordered region* within the material.

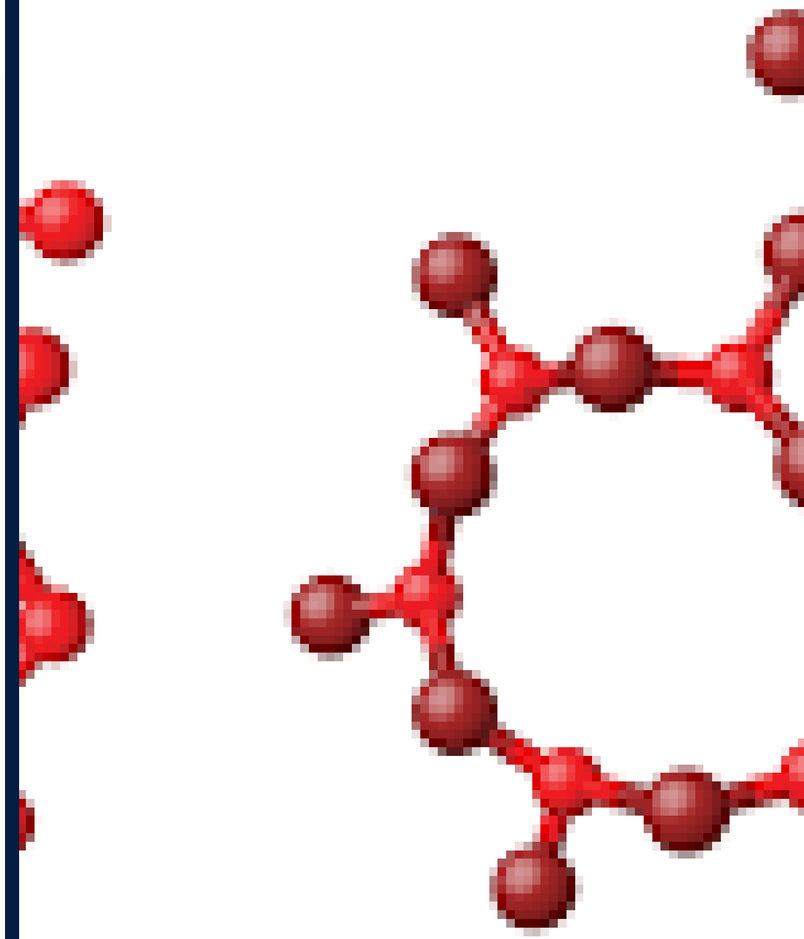
Ordered region is a spatial volume in which atoms or molecules have a regular geometric arrangement or periodicity.



Amorphous

Polycrystalline

Single Crystal



Amorphous Si

Amorphous silicon (a-Si) is a non-crystalline form of silicon with a disordered atomic structure

Advantages

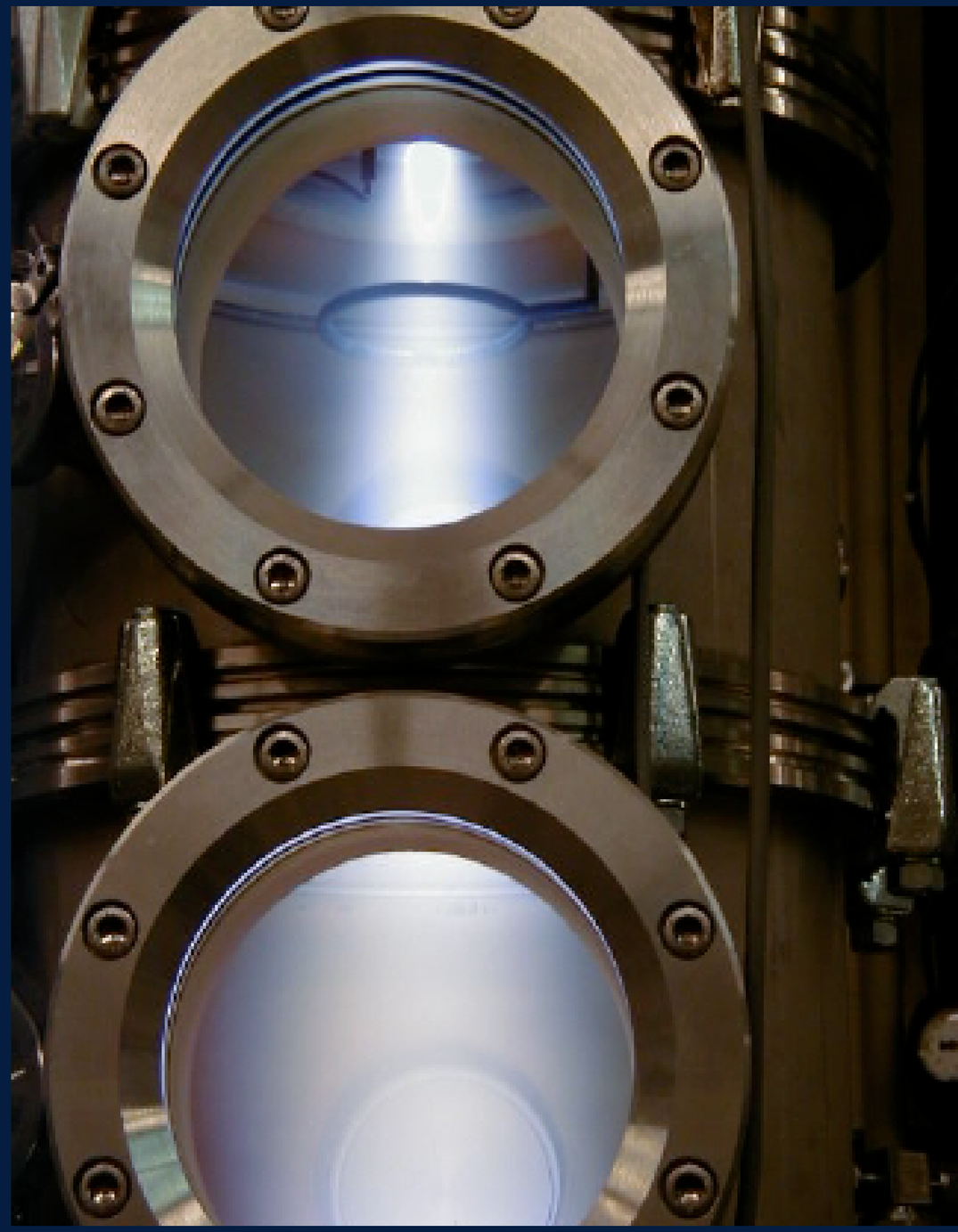
Low temperature deposition (~ 250°C)

Large Area deposition possible at low cost

Disadvantages

- Low conductivity

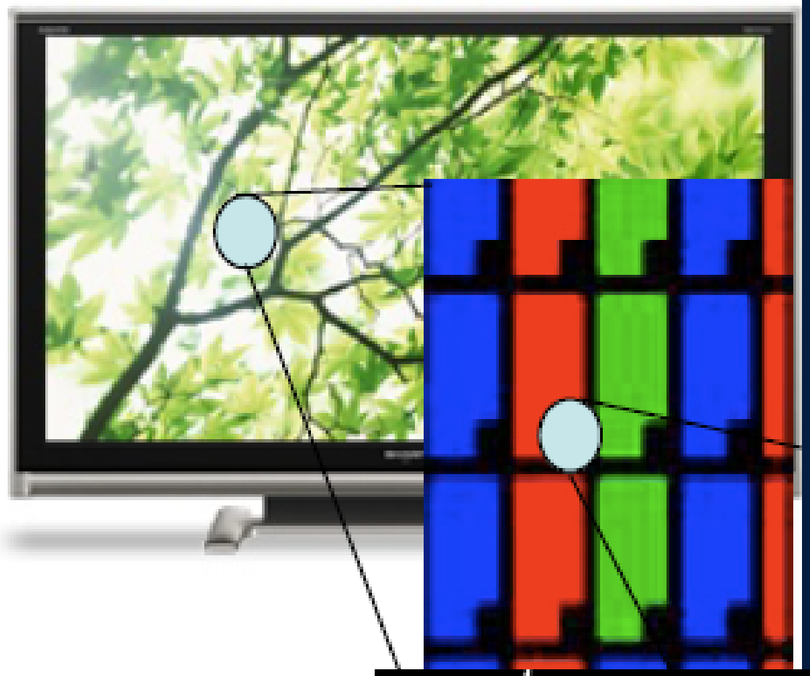
Cannot be used for High speed circuits

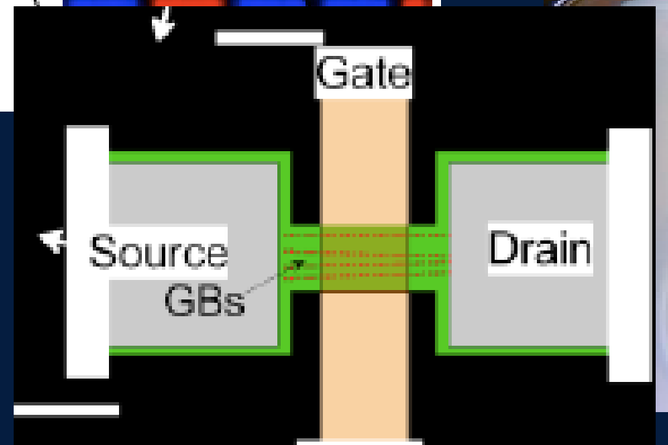


Uses of amorphous-Si

Solar cells

hin Film Transistors for LCDs





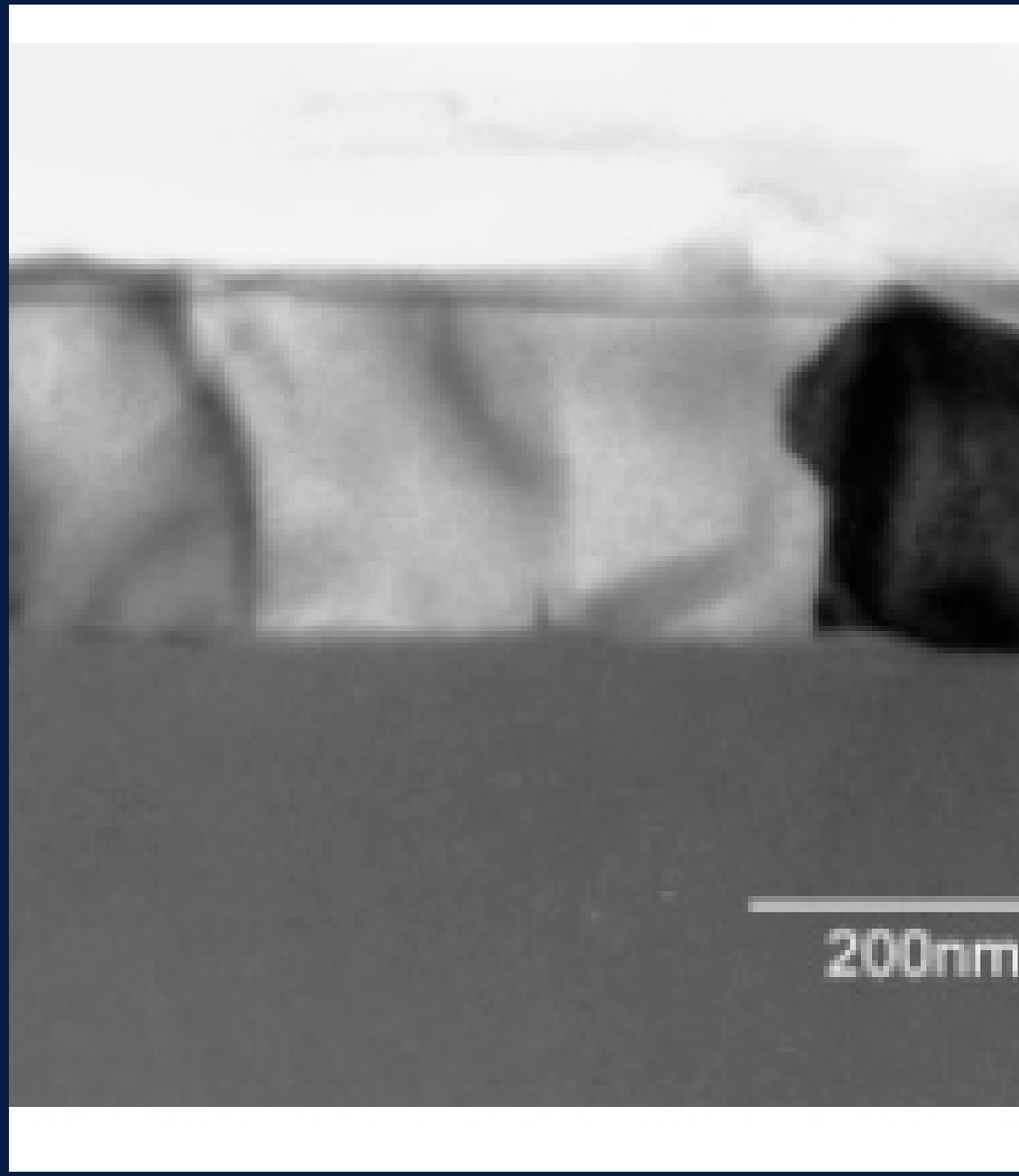
Efficiency: 6-10%

polycrystalline-Si

Polycrystalline silicon (polysilicon, poly, polysi) is defined as high-purity silicon metal with a structure of multiple small crystals.

Gate for MOSFETs Semiconductor layer for TFTs (recent development)

Polycrystalline silicon has higher conductivity as compared to amorphous silicon.



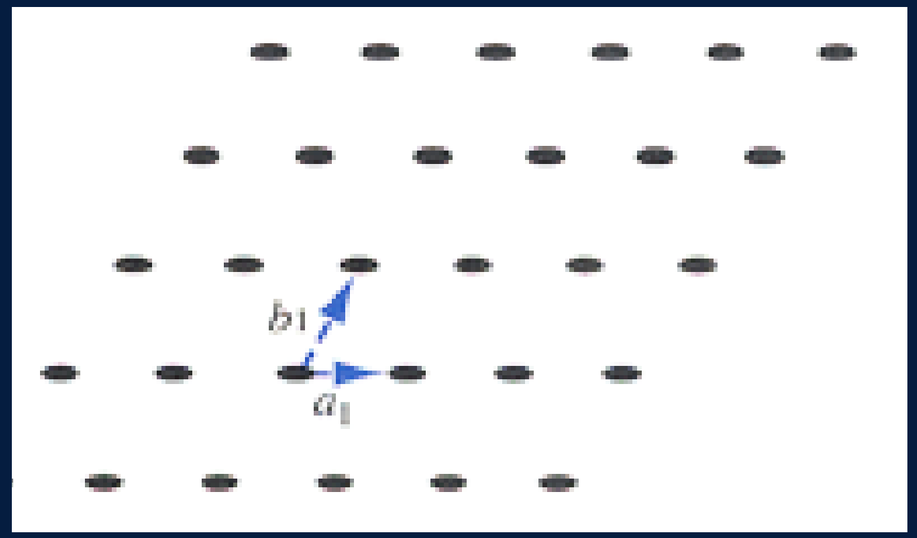
Crystal

In a very broad sense crystal means something that repeats.
So even a wall paper with a repeating pattern is a crystal !!

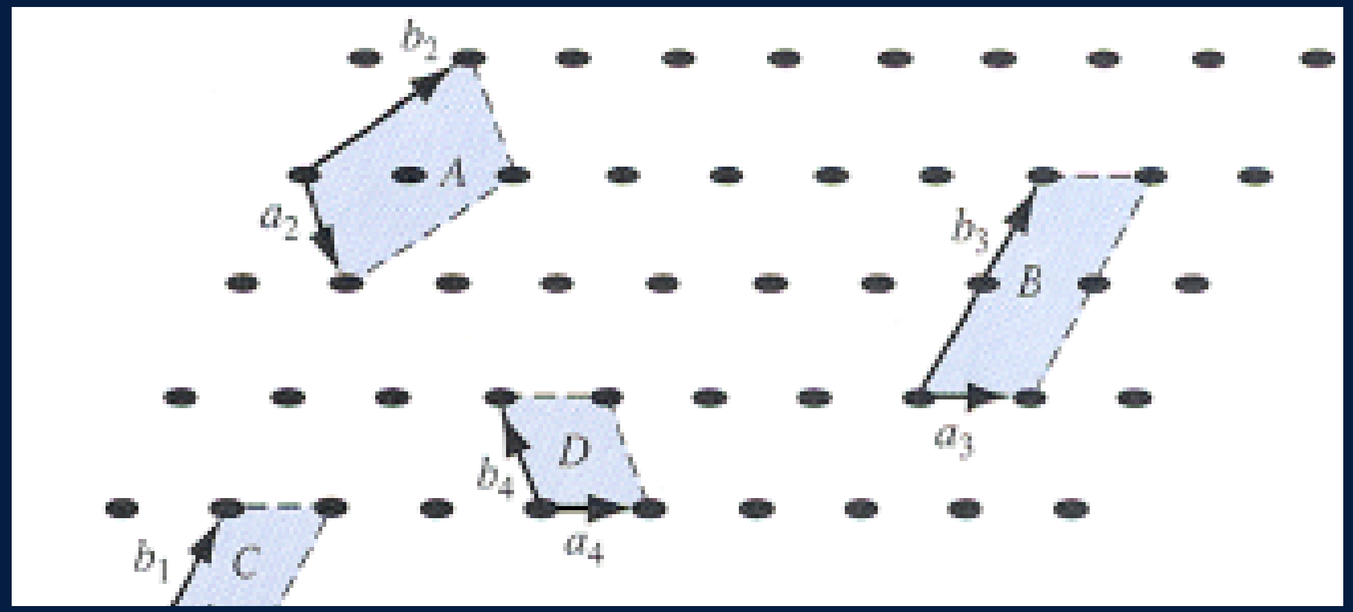
Lattice and unit cell

Lattice : A regular periodic arrangement of points in space as in the arrangement of atoms or molecules in a crystal.
Each point in the lattice is a lattice point. It can be an atom, a group of atoms, an ion or a molecule.

Unit cell : A small volume of a crystal that can be used to reproduce the entire crystal



Two dimensional representation of a single crystal lattice

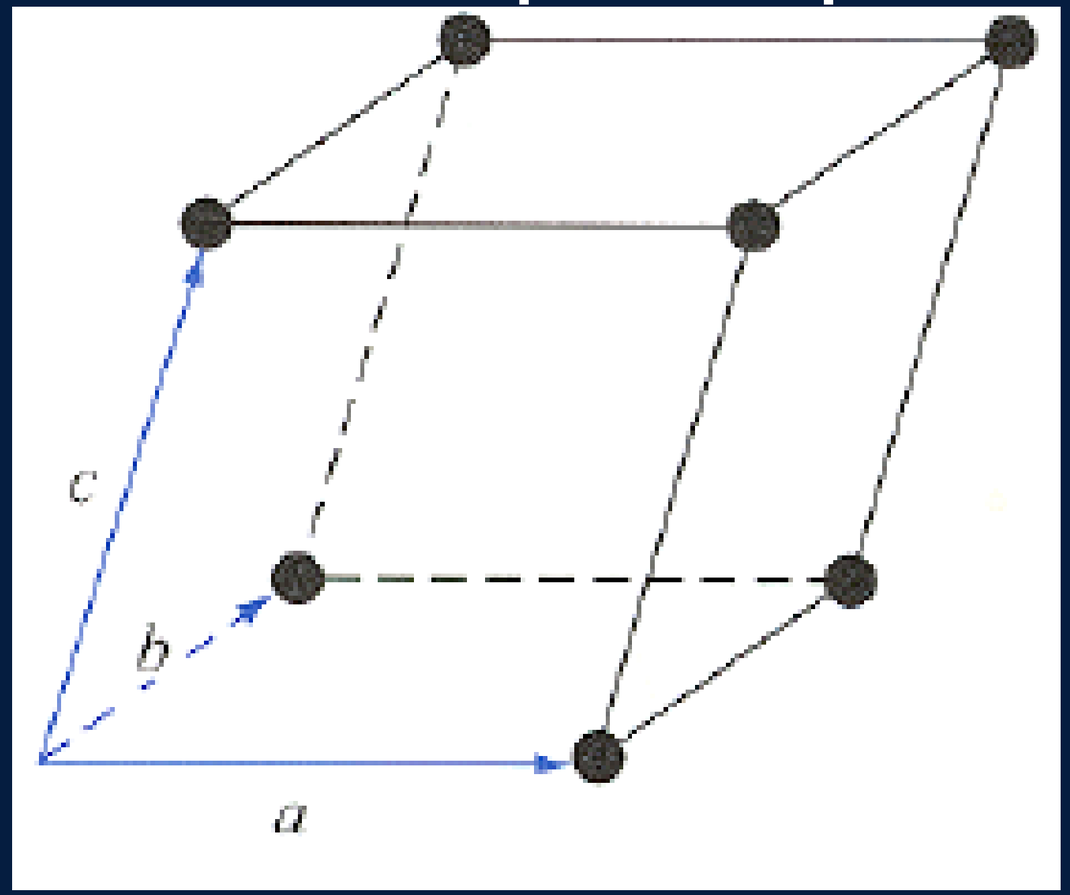


Two dimensional representation of a single crystal lattice with various possible unit cells

WEEK 1
CLASS 2

The relationship between the cell and the lattice is characterized by three vectors a, b and c. These vectors need not to be perpendicular to each other and need not to be of the same length. Every equivalent lattice point in the crystal can be found using the equation –

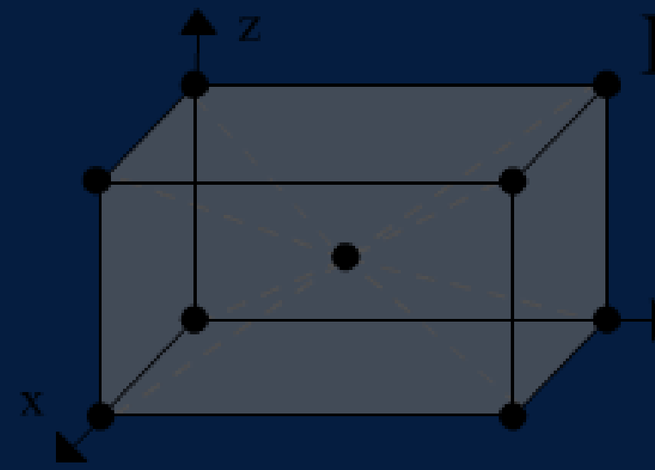
$$r = pa + qb + sc$$

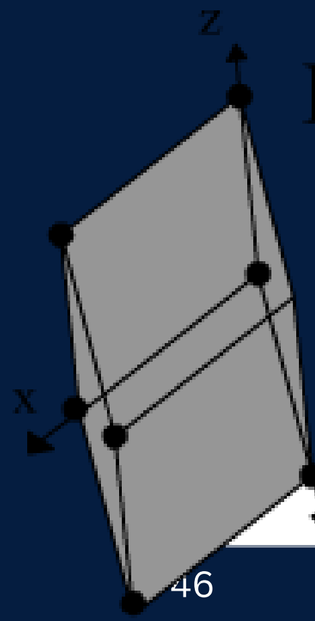


A generalized primitive unit cell

A PRIMITIVE CELL is the Smallest unit cell!

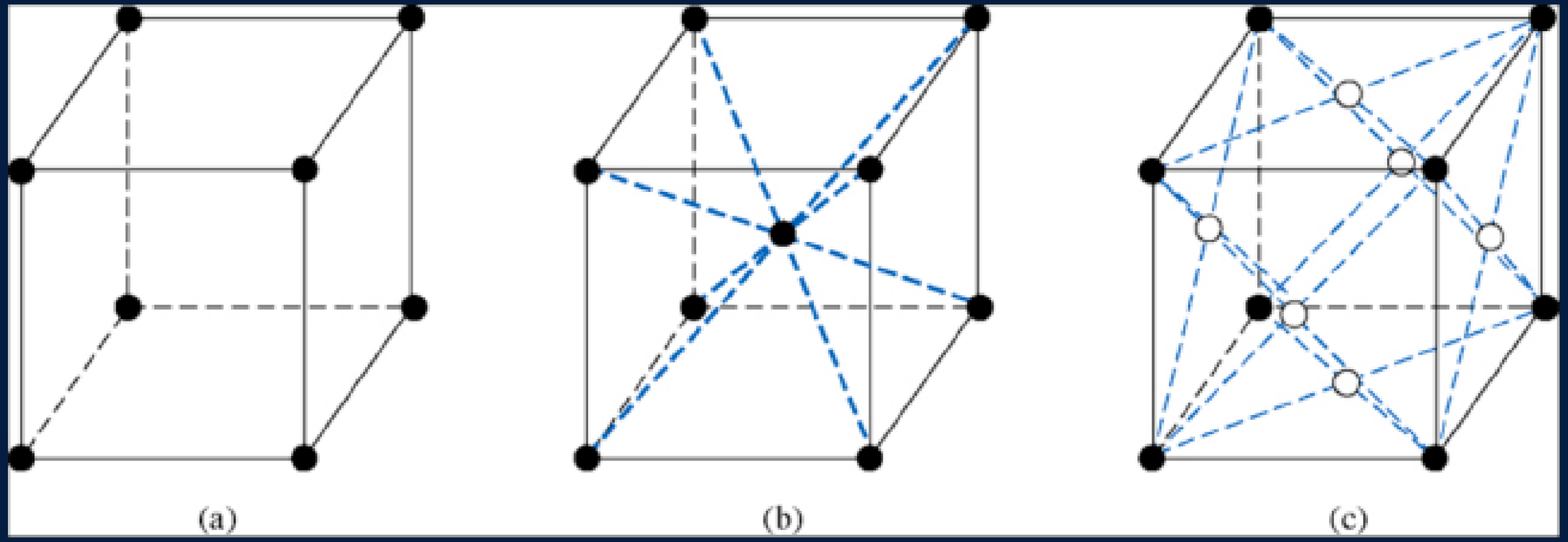
Body Centred





Basic Crystal Structures

The easiest 3-D lattice to work with is the simple cubic lattice (SCC) which has lattice points on all the corners of a cube. The Cubic (Isometric) crystal system is characterized by its total symmetry. It has three crystallographic axes that are all perpendicular to each other and equal in length. The cubic system has one lattice point on each of the cube's four corners.



Simple

Body centered

Face centered

Different possible cubic lattices

Lattice constant

Basic Crystal Structures

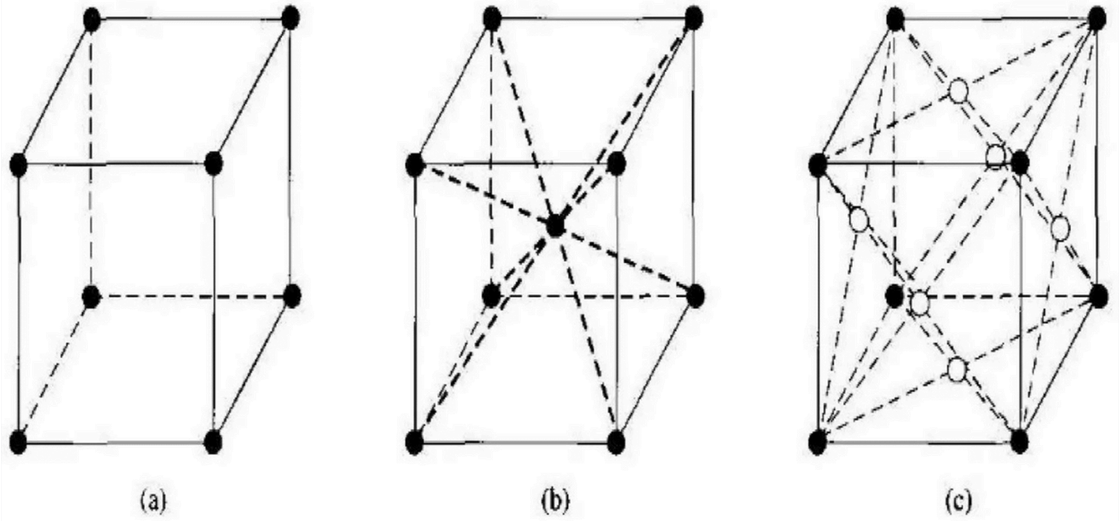
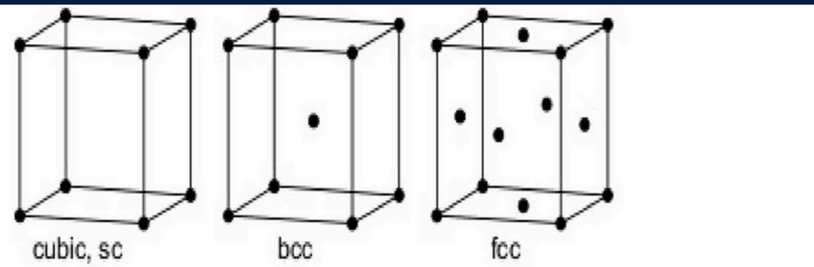
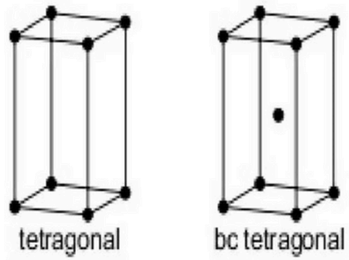
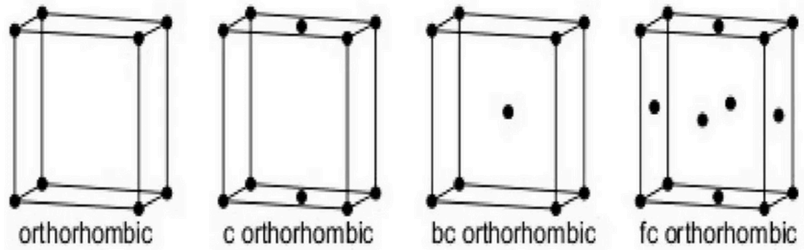
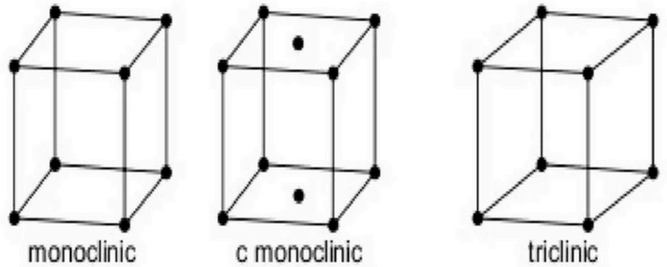


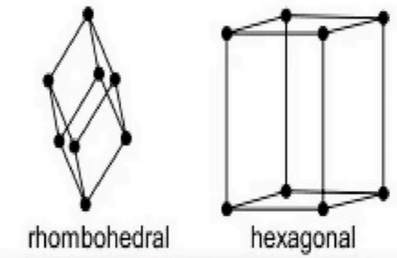
Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.





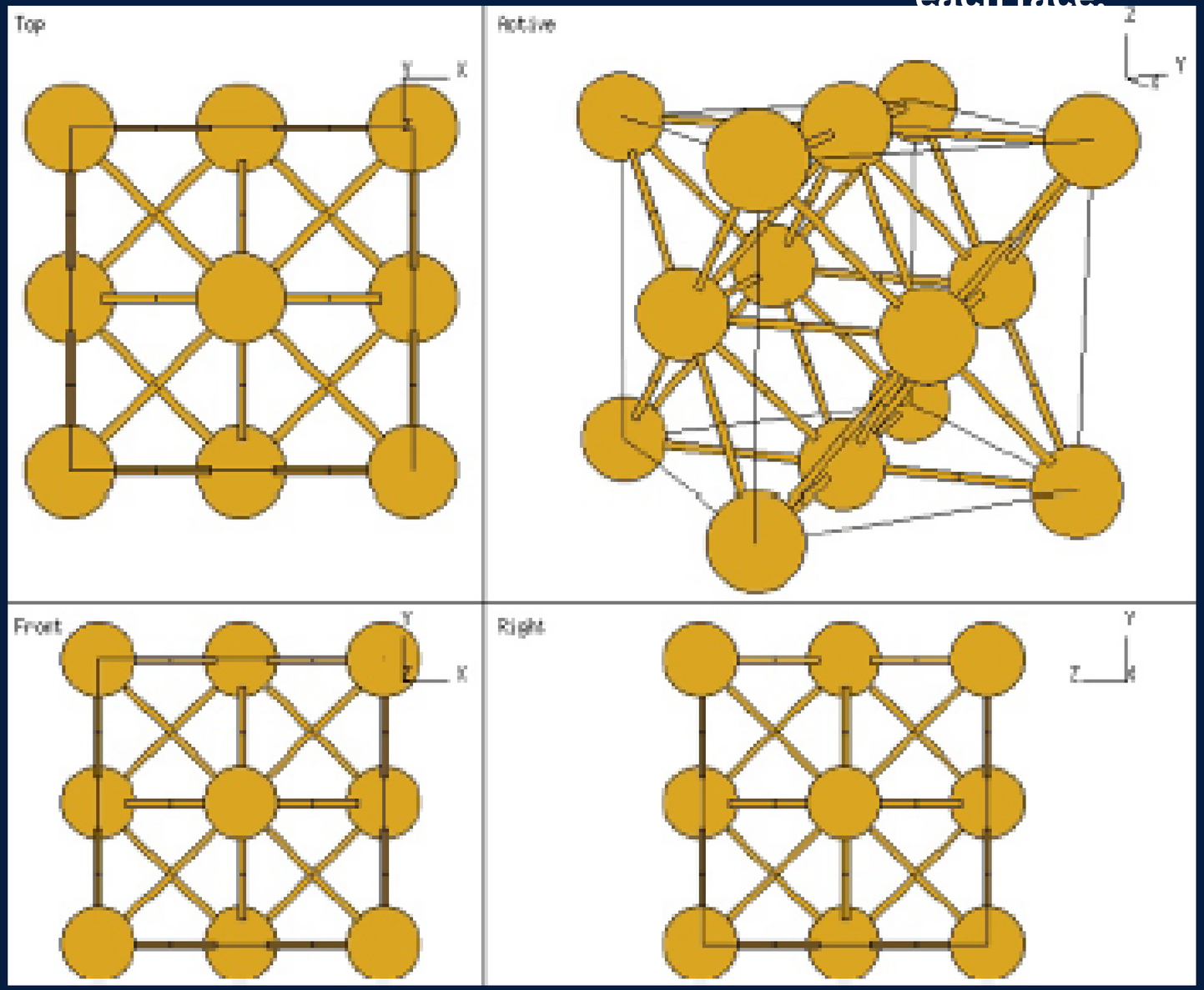






FCC

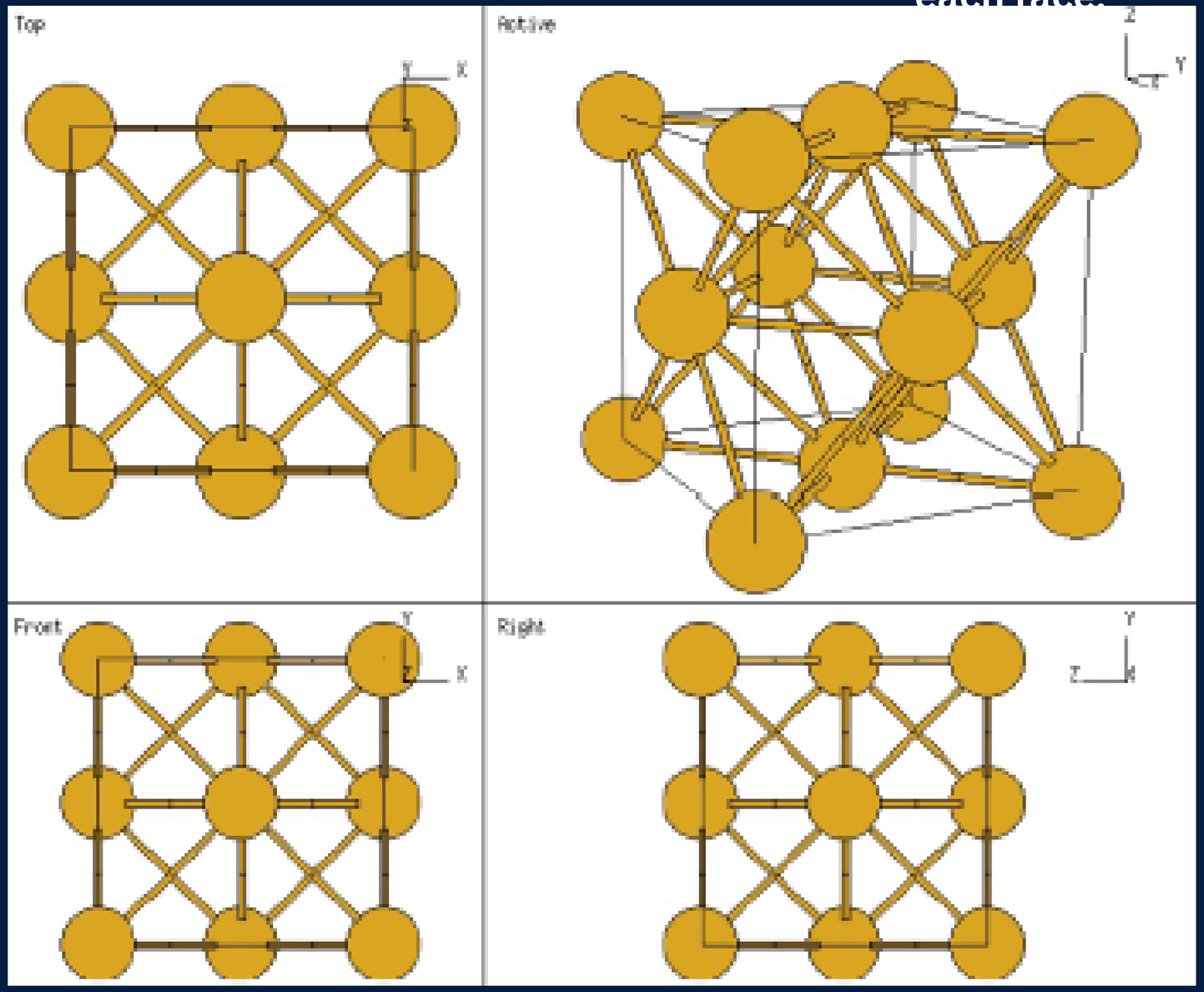
A face centered cubic (FCC) lattice is a crystal structure where atoms are arranged in a cube with one atom at each corner and one at the center of each face.



Al, Cu, Ni, Pd, Ag, Ce, Pt, Au, Pb...

FCC lattice structure has high packing density

A face centered cubic (FCC) lattice is a crystal structure where atoms are arranged in a cube with one atom at each corner and one at the center of each face.

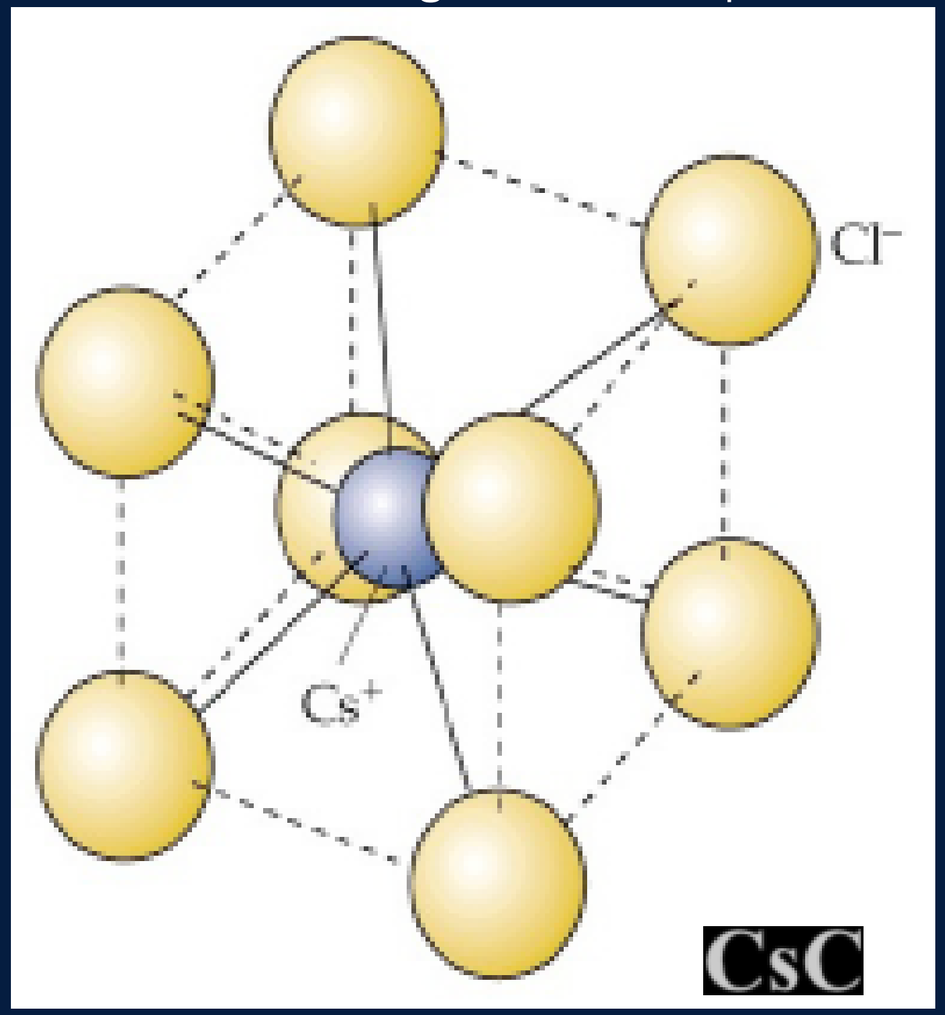


Al, Cu, Ni, Pd, Ag, Ce, Pt, Au, Pb...

FCC lattice structure has high packing density

BCC

A body-centered cubic (BCC) lattice is a type of crystal structure where atoms are arranged in a cubic pattern with one atom at the center of the cube and one at each corner

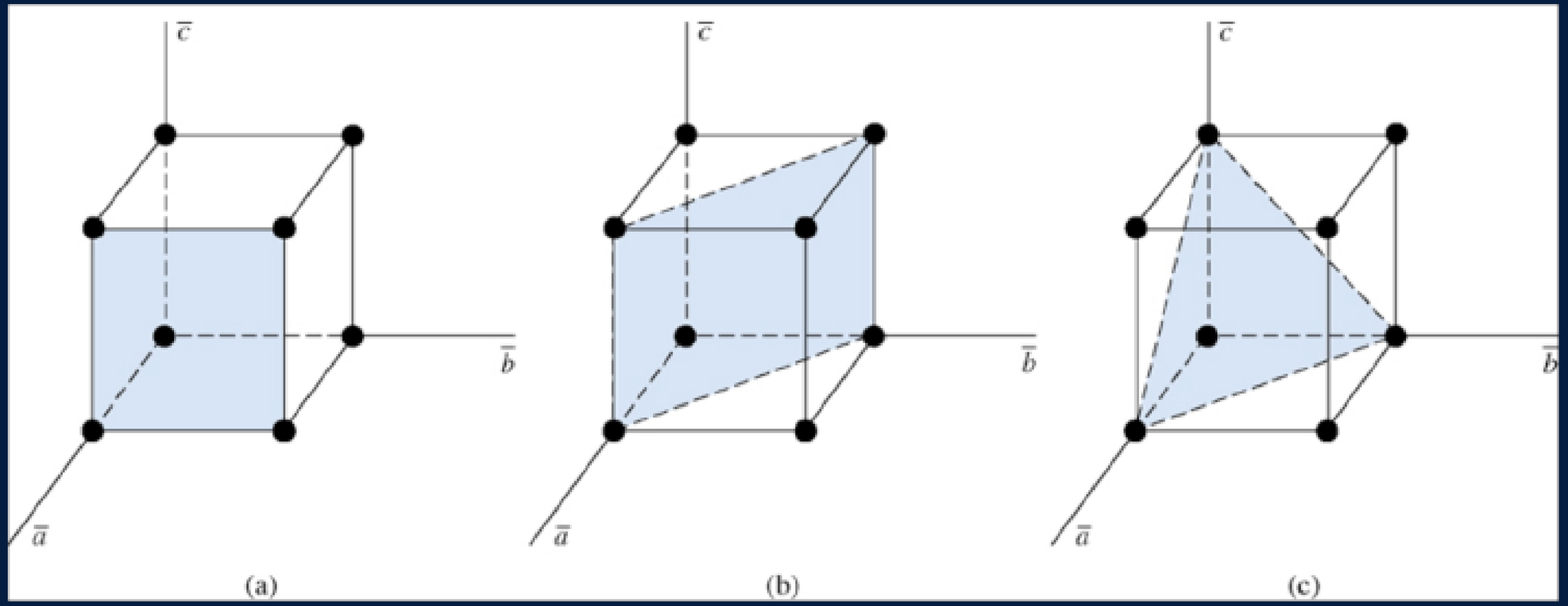


SCC is the most spacious crystal structure with least packing density. So nature does not prefer it !!

Almost no naturally occurring crystal has SCC structure.

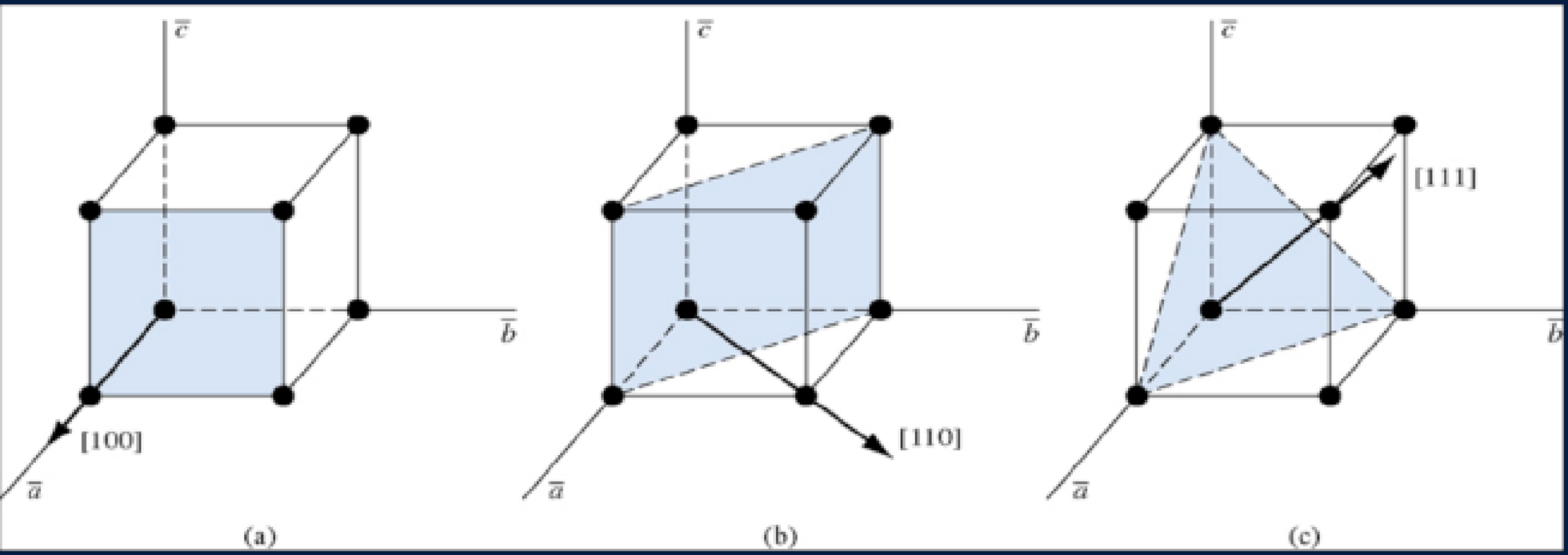
Crystal plane and Miller Indices

Surface or plane through the crystal can be described by the intercepts of the plane along the a, b and c axes used for the lattice. Reciprocal of these intercepts are called the miller indices.

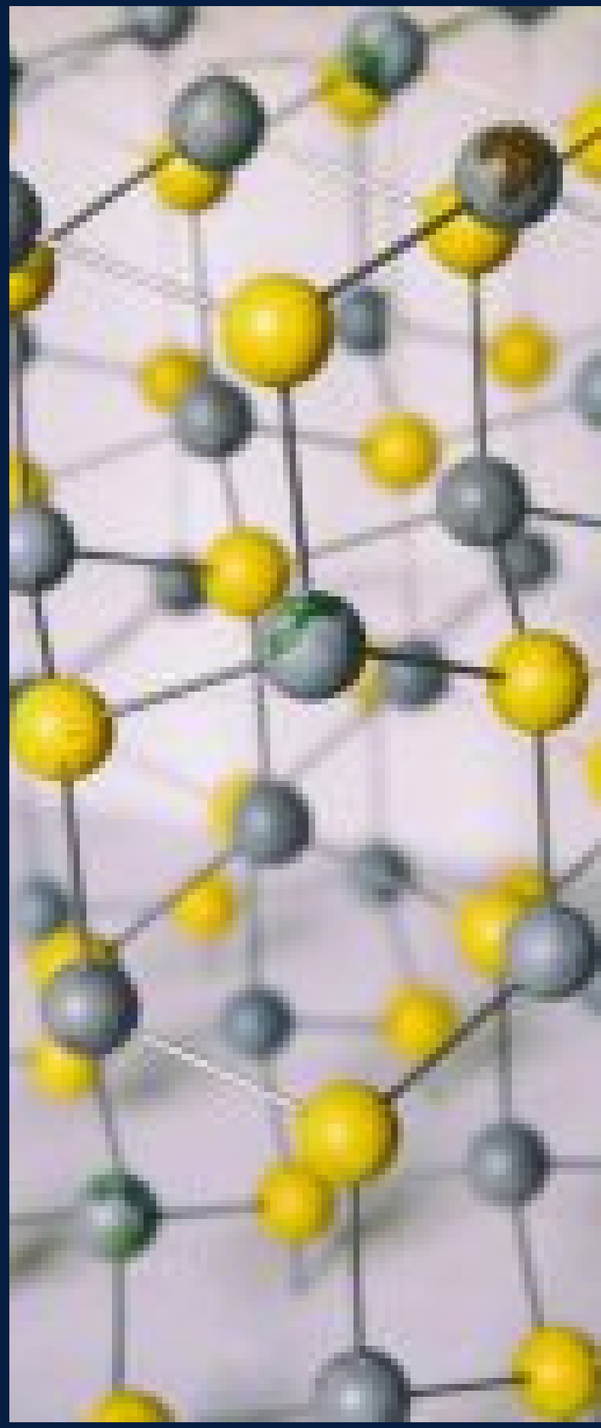


Three lattice planes – (a) (100) plane, (b) (110) plane and (c) (111) plane

Miller indices



The plane (a) is parallel to the b and c axes so the intercepts are given as 1, infinite and infinite. Taking reciprocal, we obtain Miller indices as (1,0,0), so the plane is referred to as (100) plane. Any plane parallel to this is equivalent and is referred to as the (100) plane.



Atomic Bonding

Covalent bonding

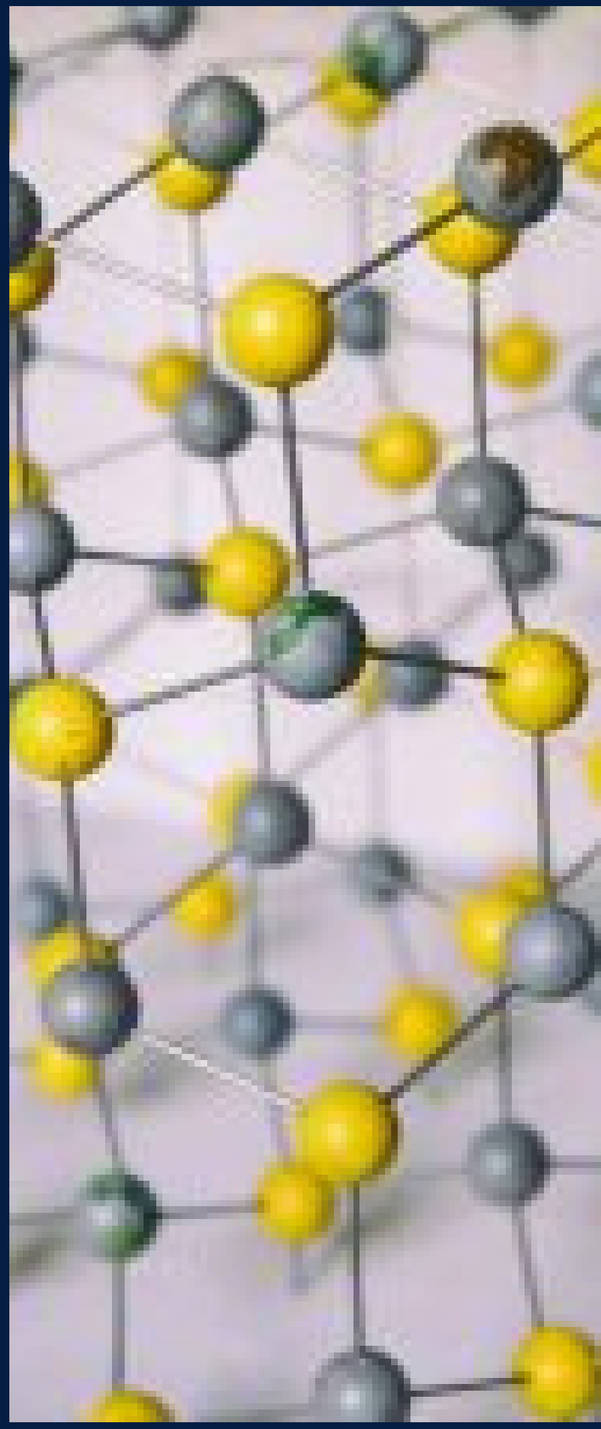
Ionic bonding

Metallic bonding

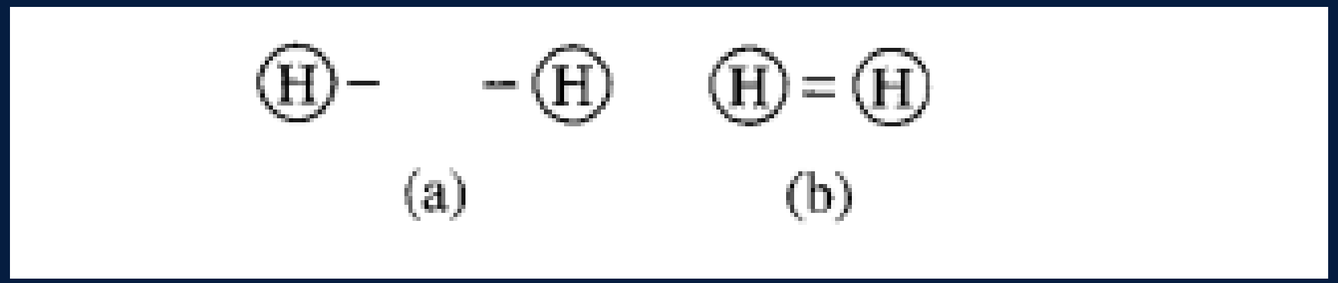
Van der Waals bonding

Strong

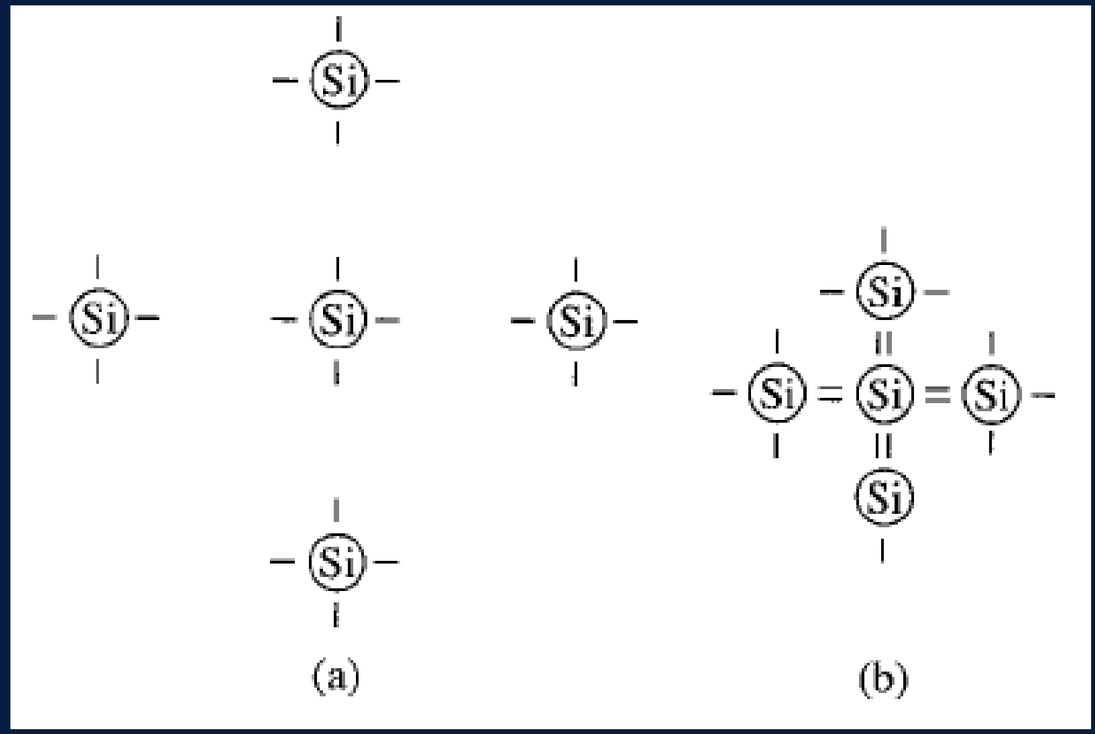
Weak



Covalent bonding



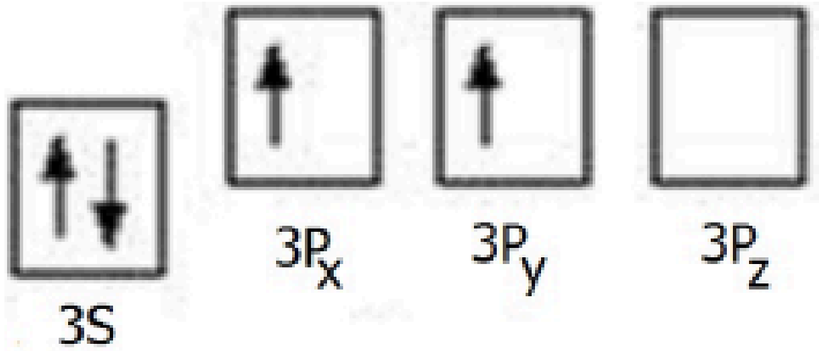
Representation of (a) hydrogen valence electrons and (b) covalent bonding in hydrogen molecule



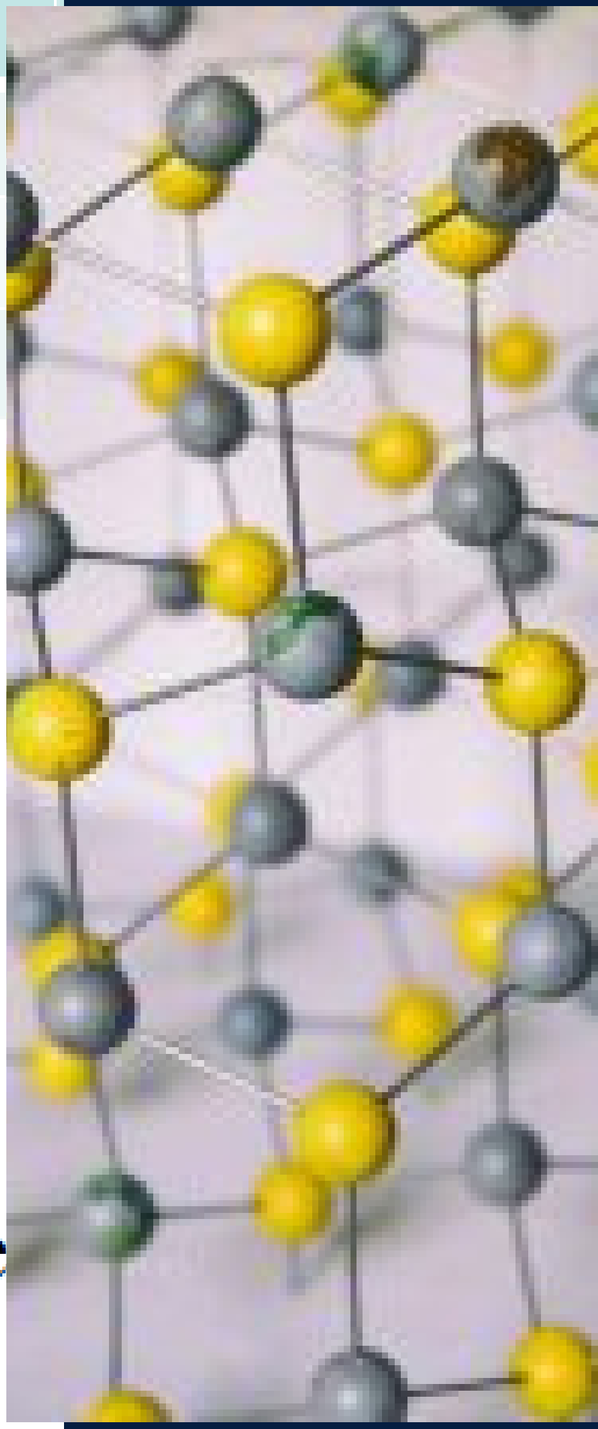
Representation of (a) silicon valence electrons and (b) covalent bonding in the silicon crystal

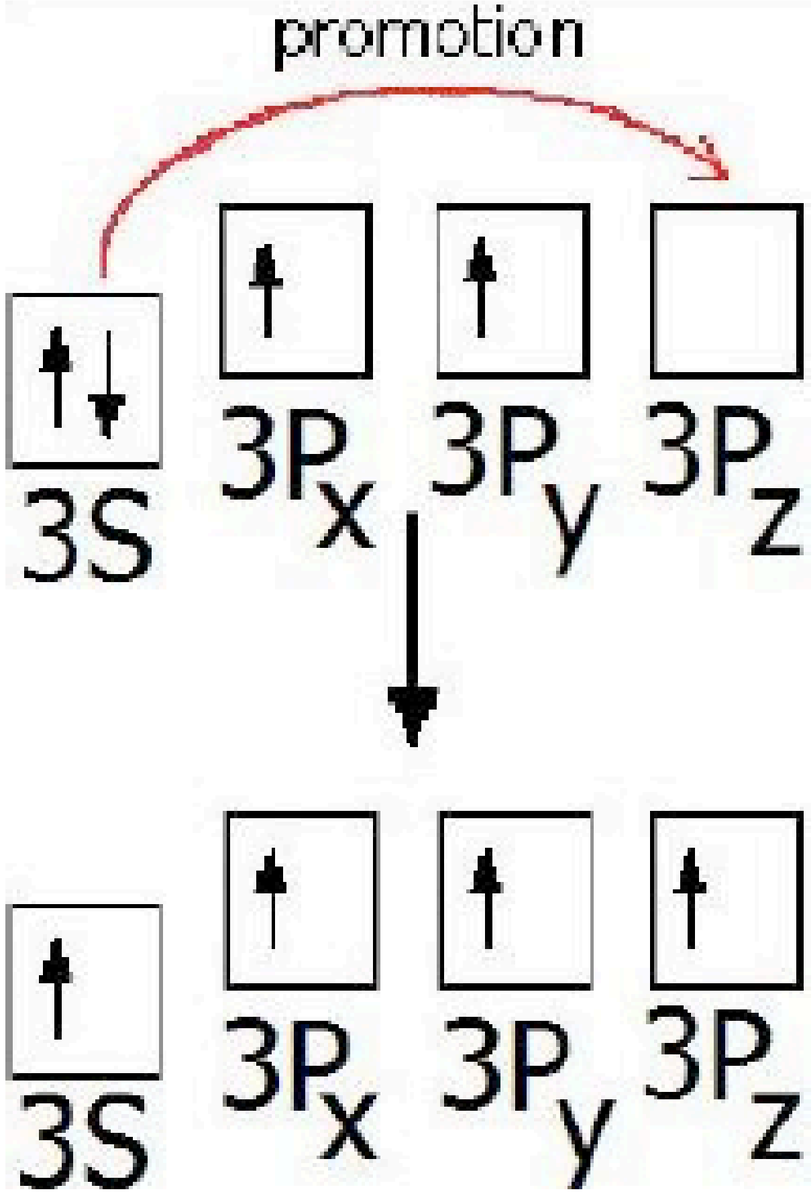
		K	L	M
6	C	$1s^2$	$2s^22p^2$	
14	Si	$1s^2$	$2s^22p^6$	$3s^23p^2$
32	Ge	$1s^2$	$2s^22p^6$	$3s^23p^63d^{10}$

Atomic structure for C, Si and Ge

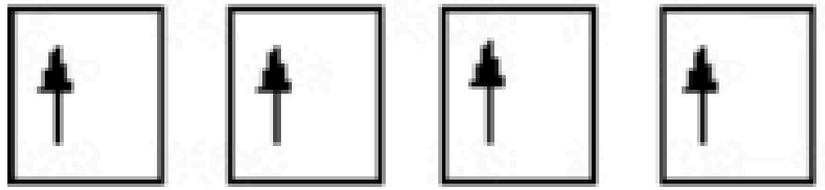


Silicon has only 2 unpaired electrons. Then why doe
covalent bonds?





Hybridization

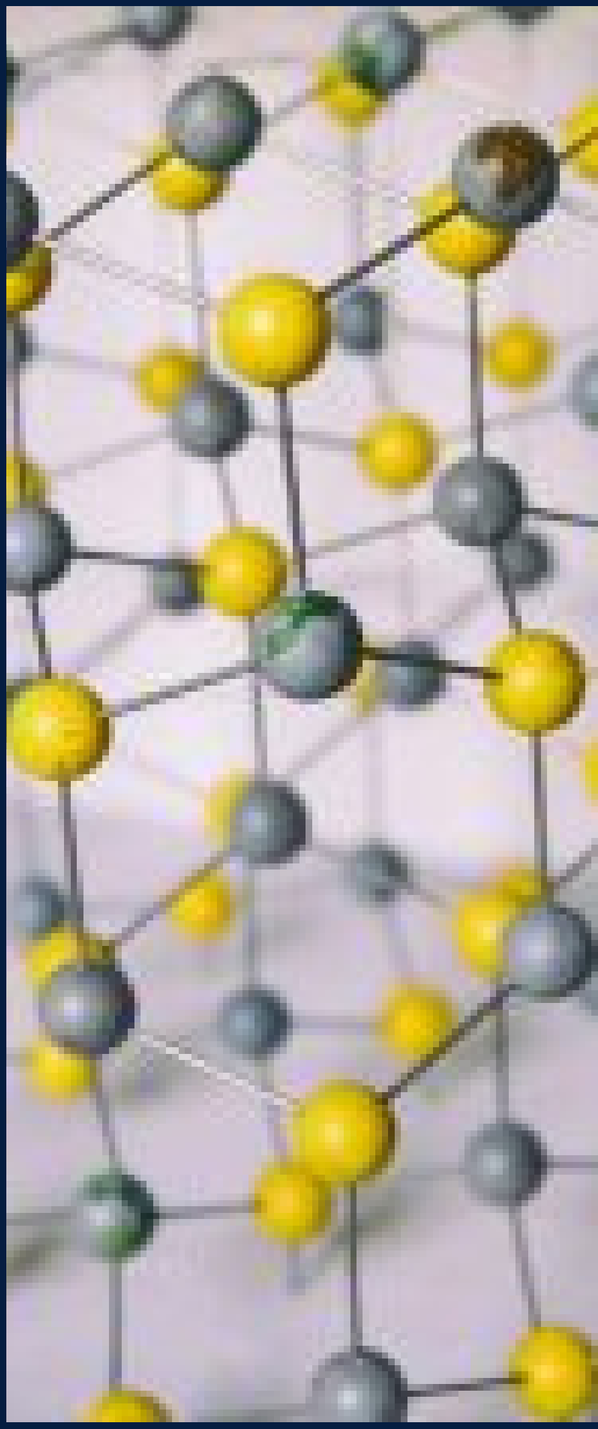


sp^3 hybrid orbitals

Atomic Bonding

Promotion of one electron from s-orbital to p-orbital to form four orbitals of equal energy is hybridisation. This happens so that all available energy states in the outermost shell are occupied. Else it will lead to instability.

With electrons in two different kinds of orbitals, we cannot get four identical covalent bonds. Hybridisation results in four similar electronis and hence ideantical bonds.

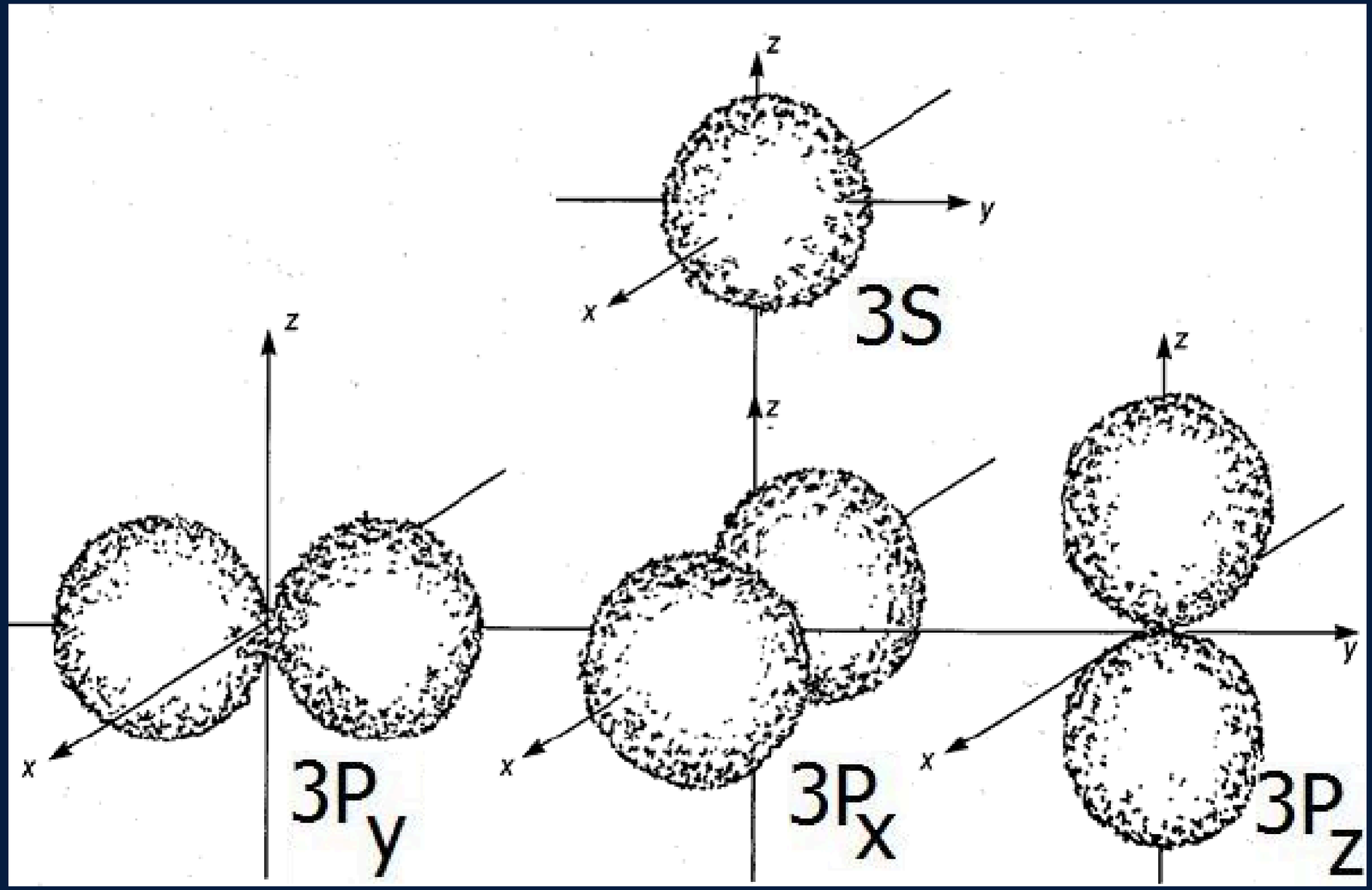


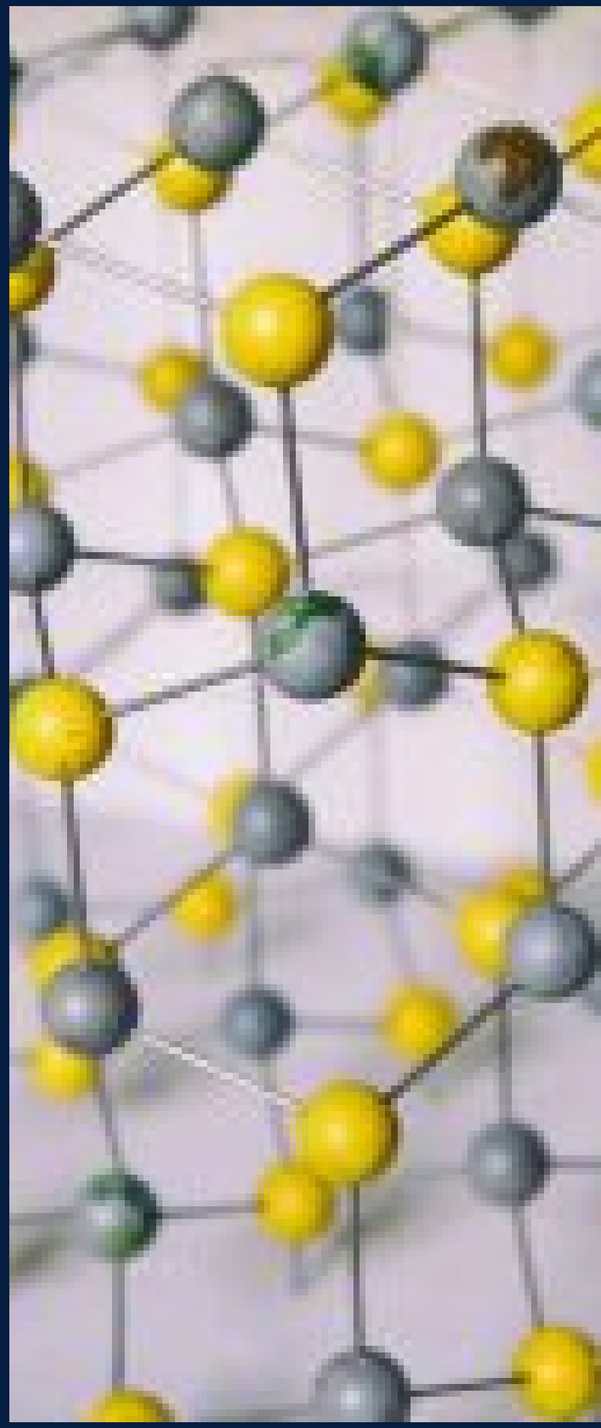
WEEK 2 CLASS 1

Exercise

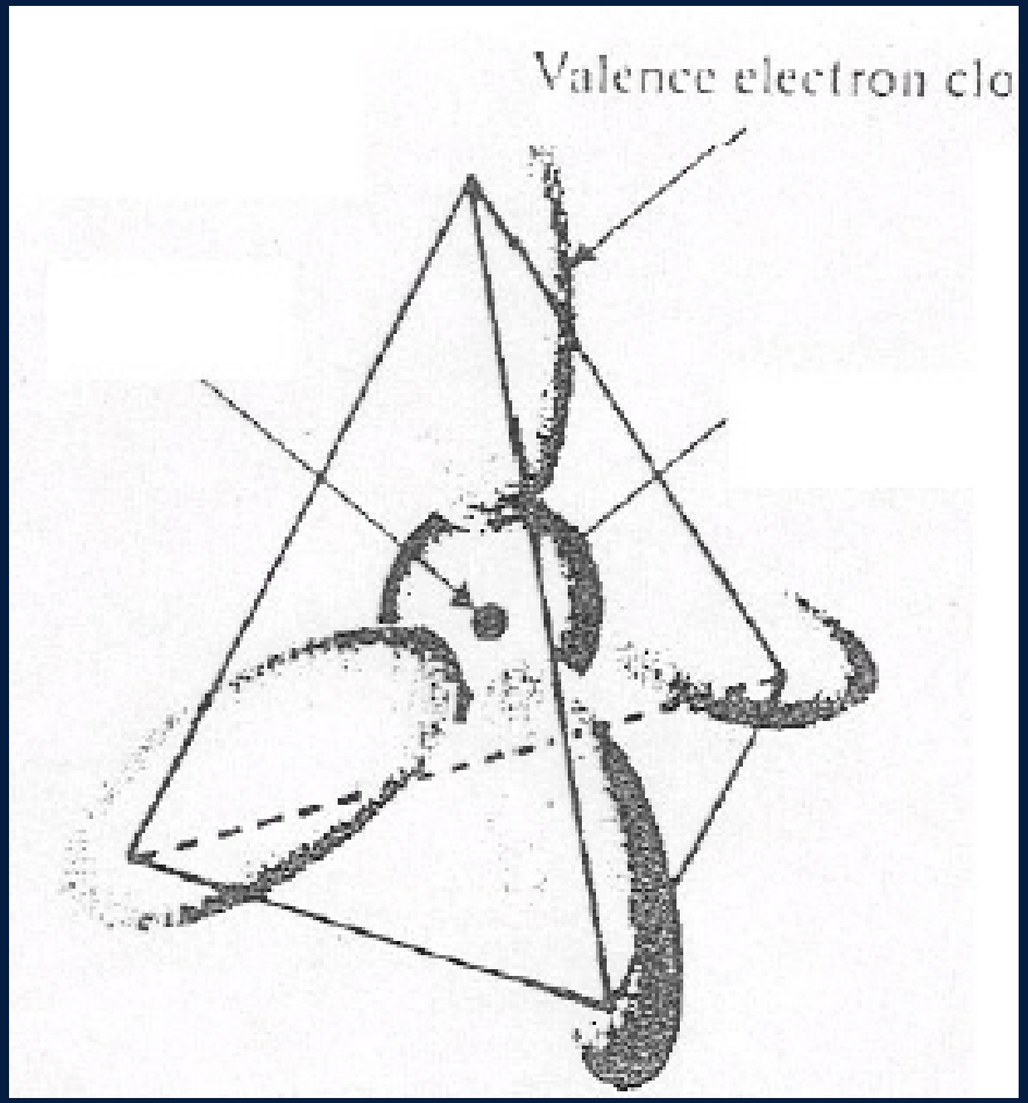
- To calculate the surface density of atoms on a perpendicular plane in a crystal.
- Consider the body-centered cubic structure and the (110) plane shown in Figure. Assume the atoms can be represented as hard spheres with the closest atoms touching reach other. Assume the lattice constant is a, = 5 A. Figure shows how the atoms are cut by the (110) plane.

Shape of s & p orbitals in n=3 shell before hybridisation.

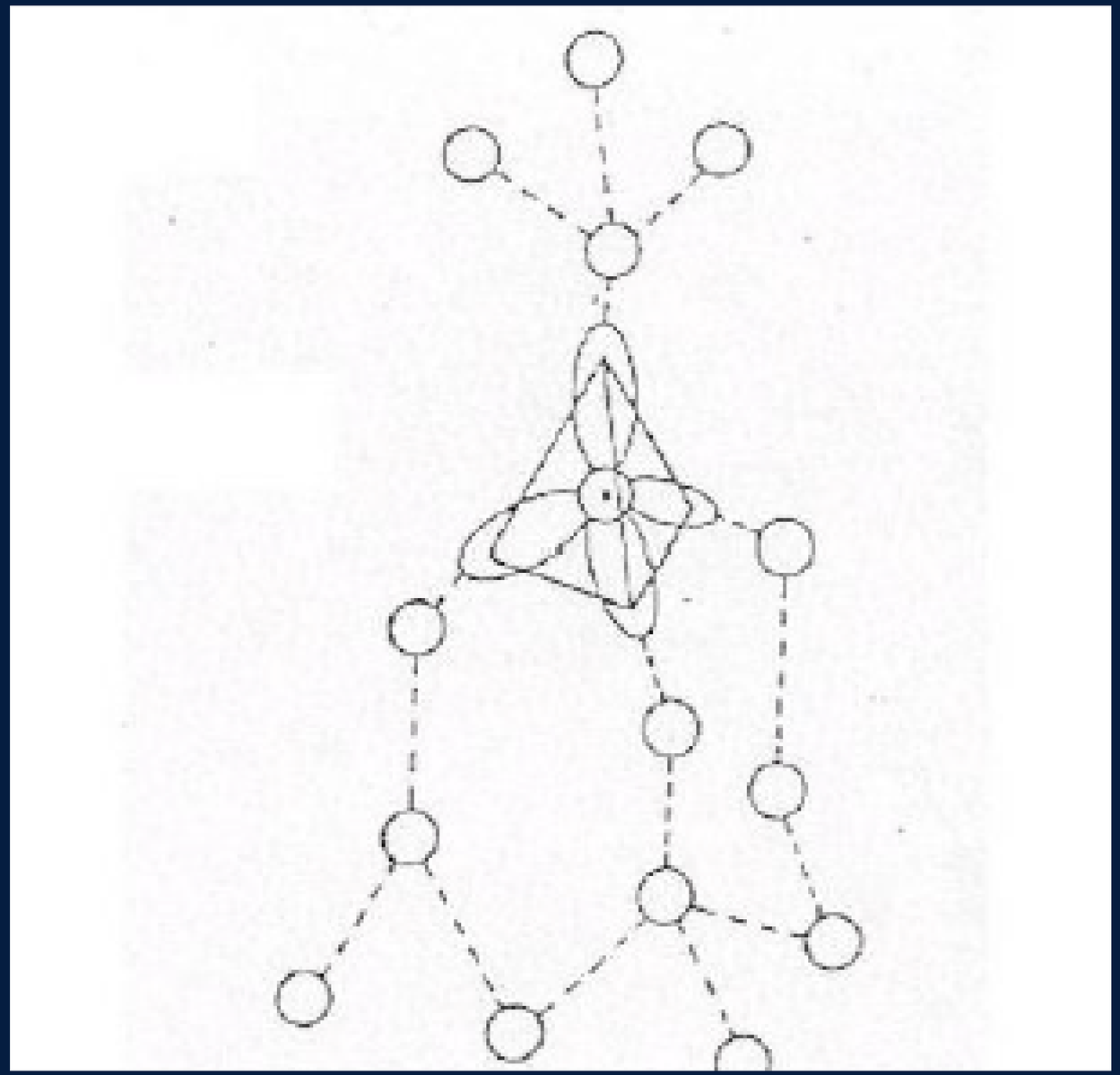




Valence electron cloud

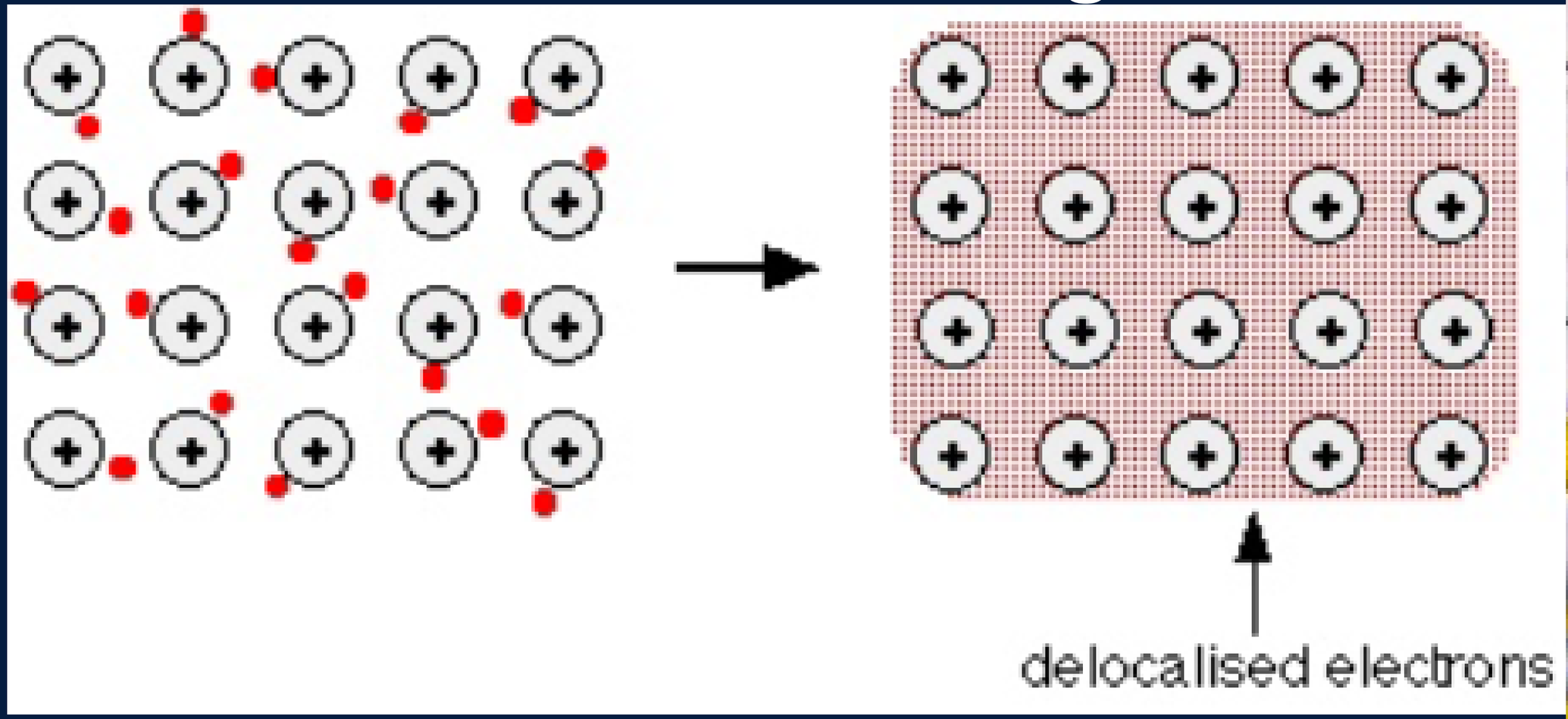


Orbitals in n=3 shell after hybridisation

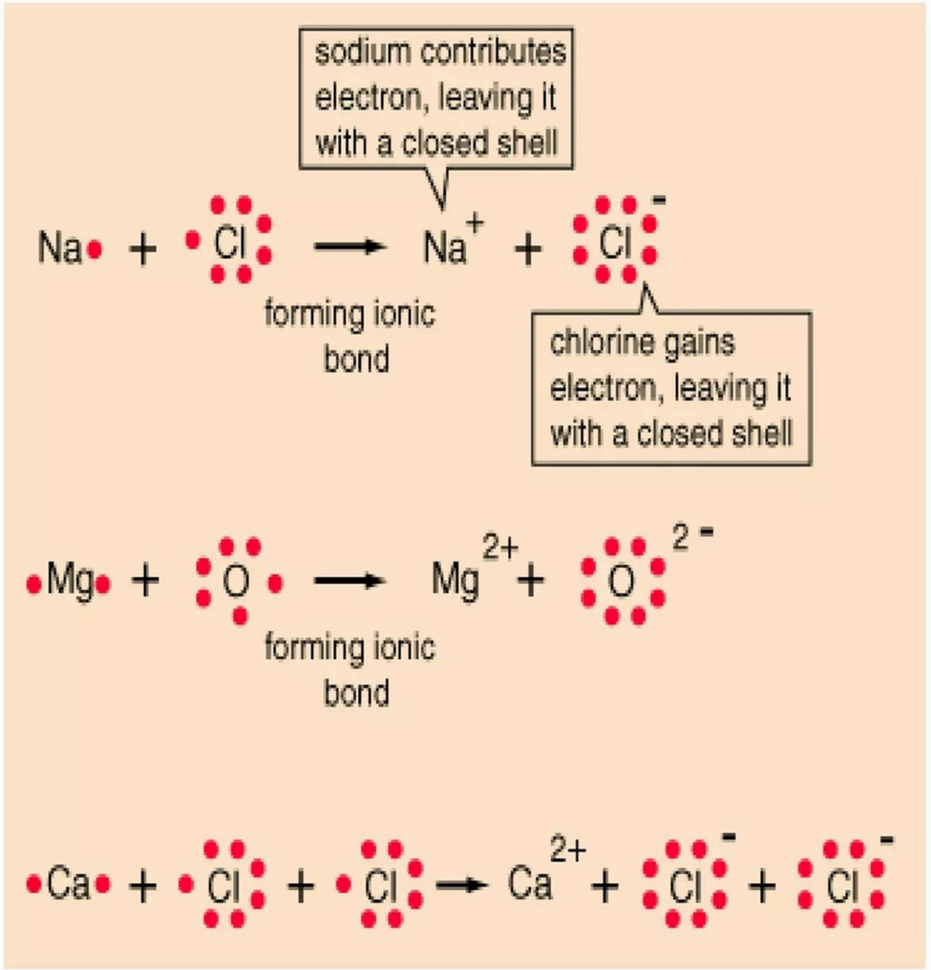


The silicon atom in its crystalline surroundings has a similarly shaped electron cloud

Metallic bonding

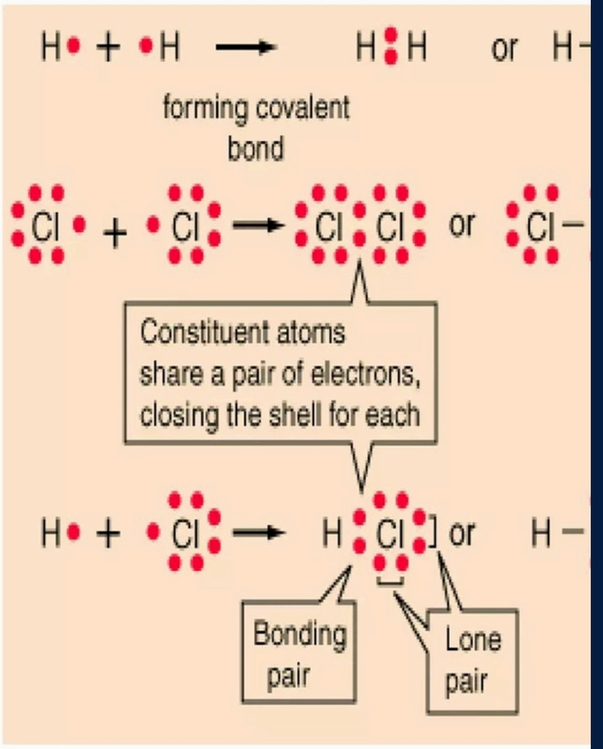


Sodium has the electronic structure 1s22s22p63s1. When sodium atoms come together, the electron in the 3s atomic orbital of one sodium atom shares space with the corresponding electron on a neighbouring atom to form a molecular orbital - in much the same sort of way that a covalent bond is formed.



Covalent bond

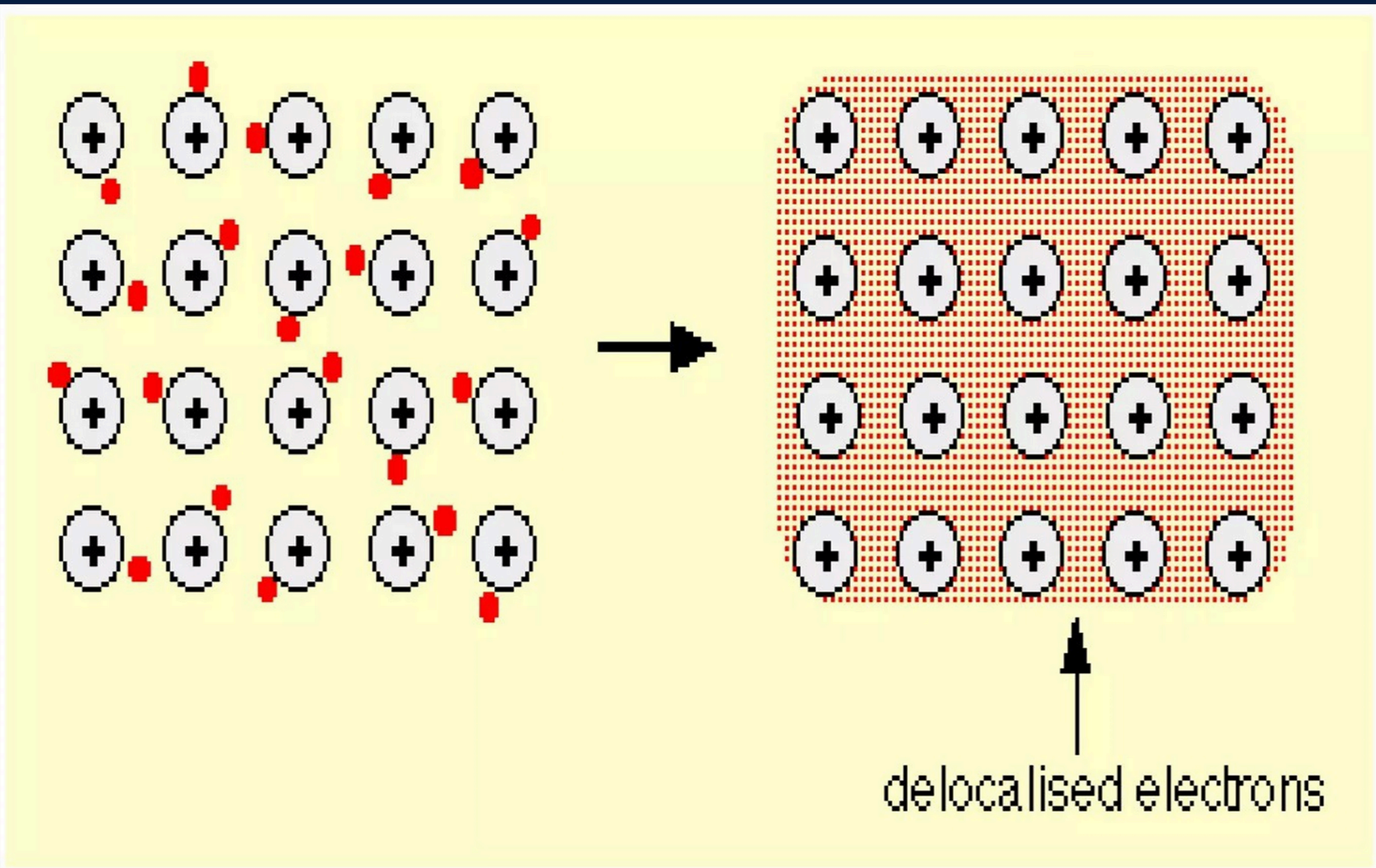
Covalent chemical bonds involve the sharing of a pair of valence electrons by two atoms, in contrast to the transfer of electrons in ionic bonds. Such bonds lead to stable molecules if they share electrons in such a way as to create a noble gas configuration for each atom.



WEEK 2 CLASS 2

Metallic bond

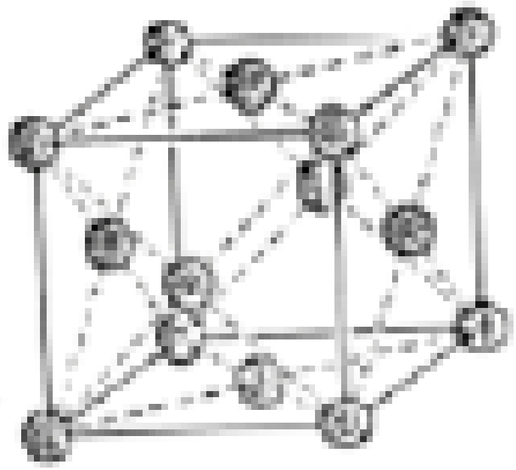
- In the metallic bond, an atom achieves a more stable configuration by sharing the electrons in its outer shell with many other atoms. Metallic bonds prevail in elements in which the valence electrons are not tightly bound with the nucleus, namely metals, thus the name metallic bonding. In this type of bond, each atom in a metal crystal contributes all the electrons in its valence shell to all other atoms in the crystal

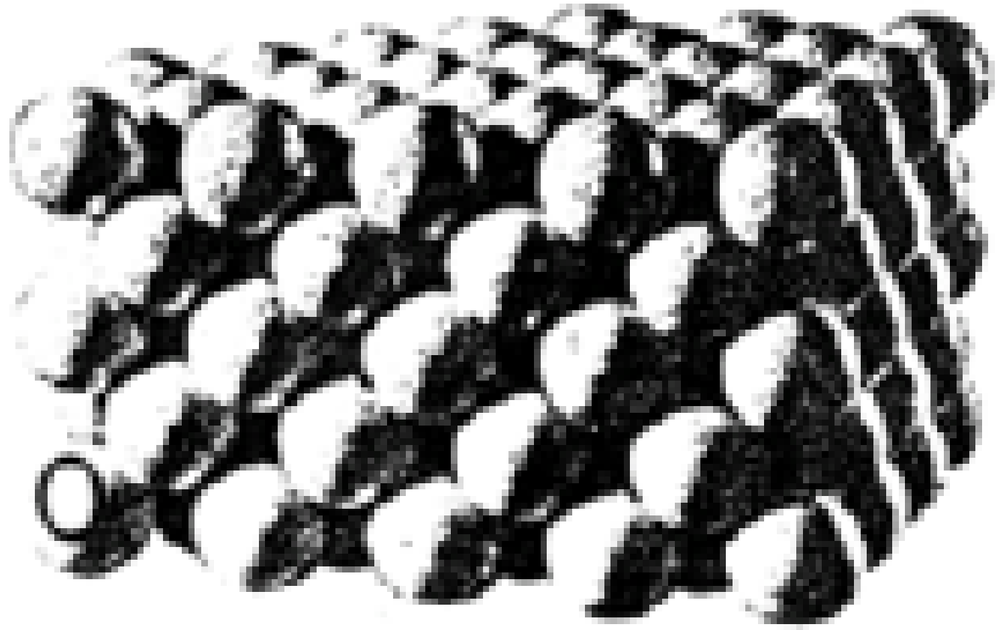

delocalised electrons

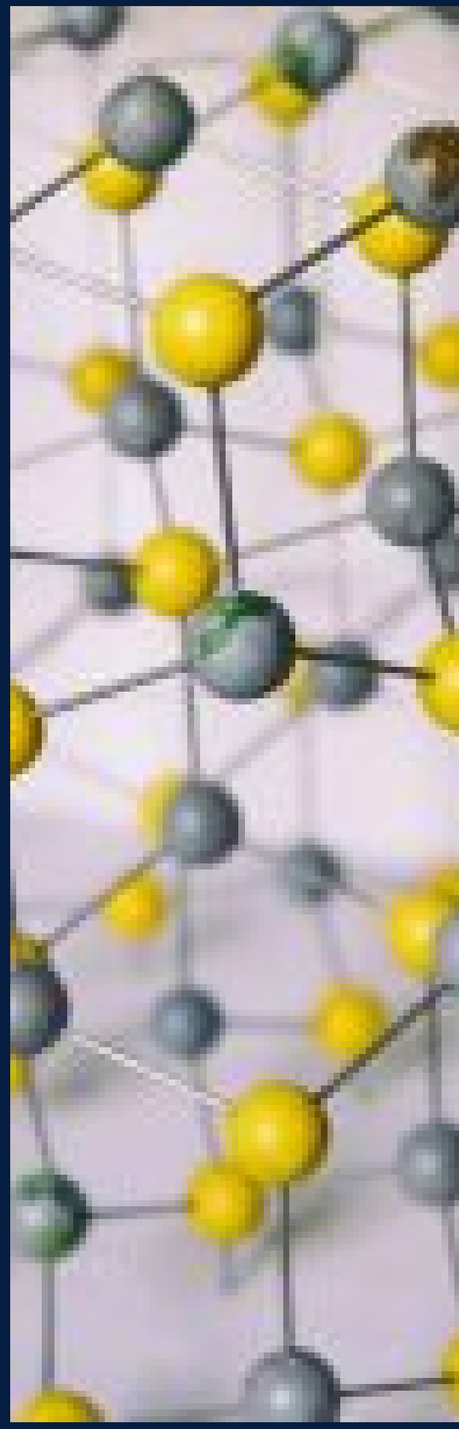
Van der Waals bond

Effective center of the positive charge is not the same as the negative one, e.g., HF molecule.
The electric dipole interacts with the other dipole.

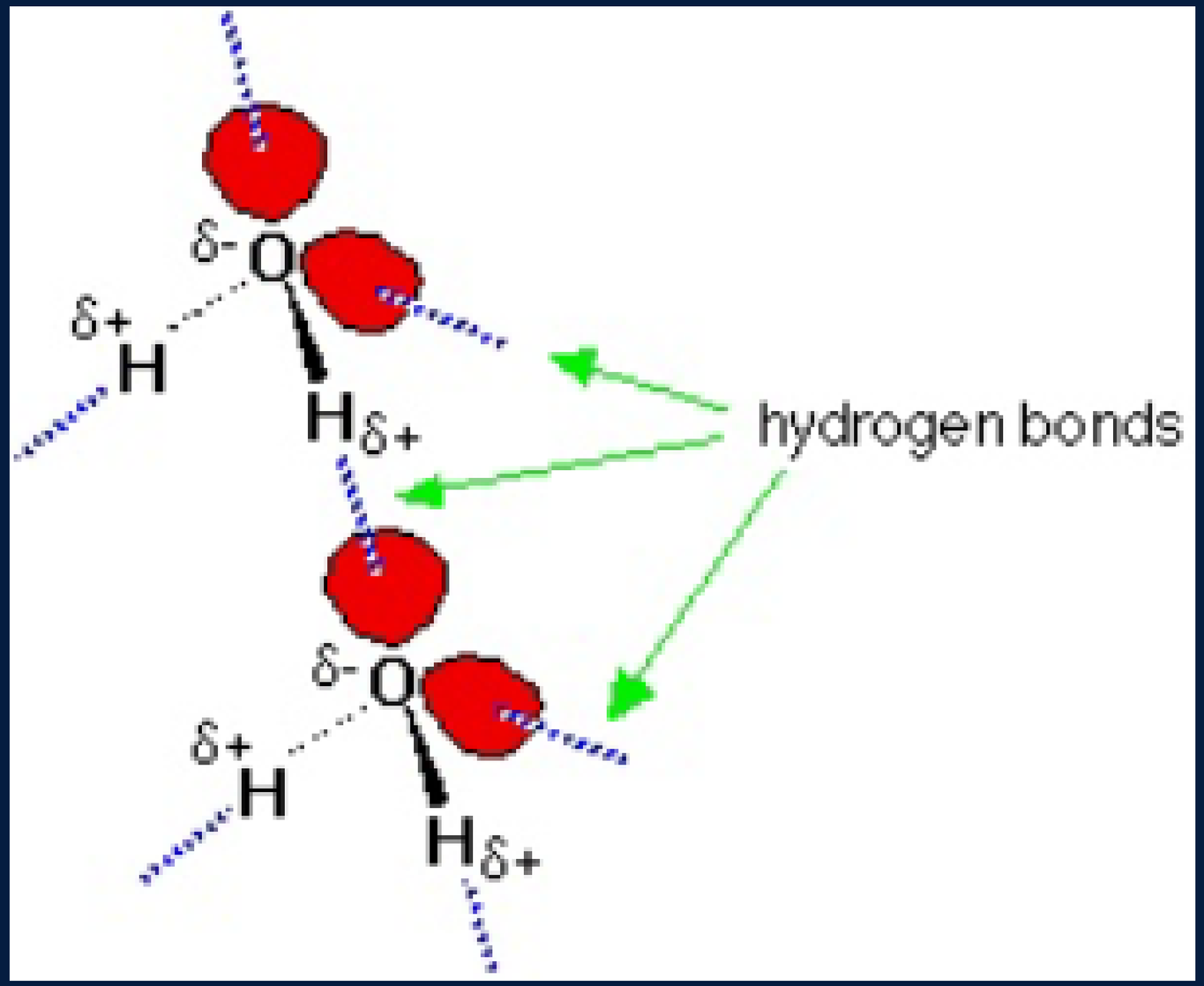
Inert Gas Elements – He, Ne, Ar, Kr, Xe



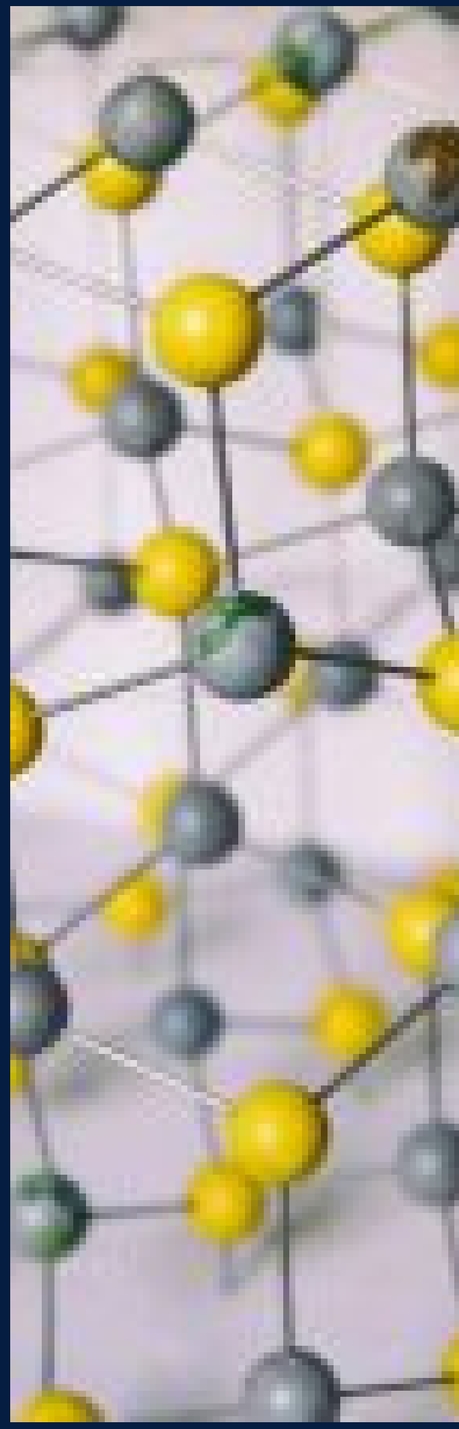




Hydrogen bonding



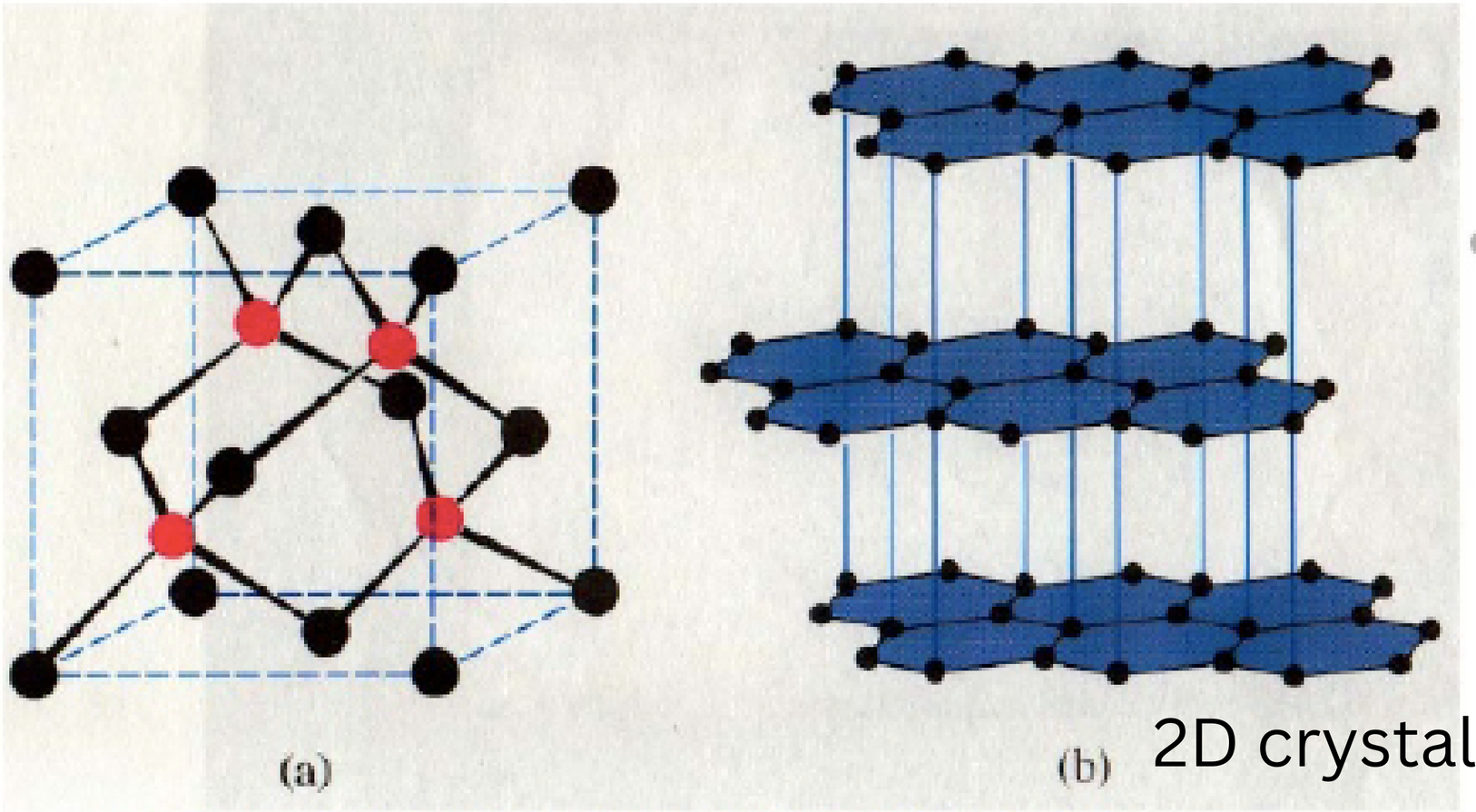
Van der Waal’s bonds in water



WEEK 3 CLASS 1

3D crystal

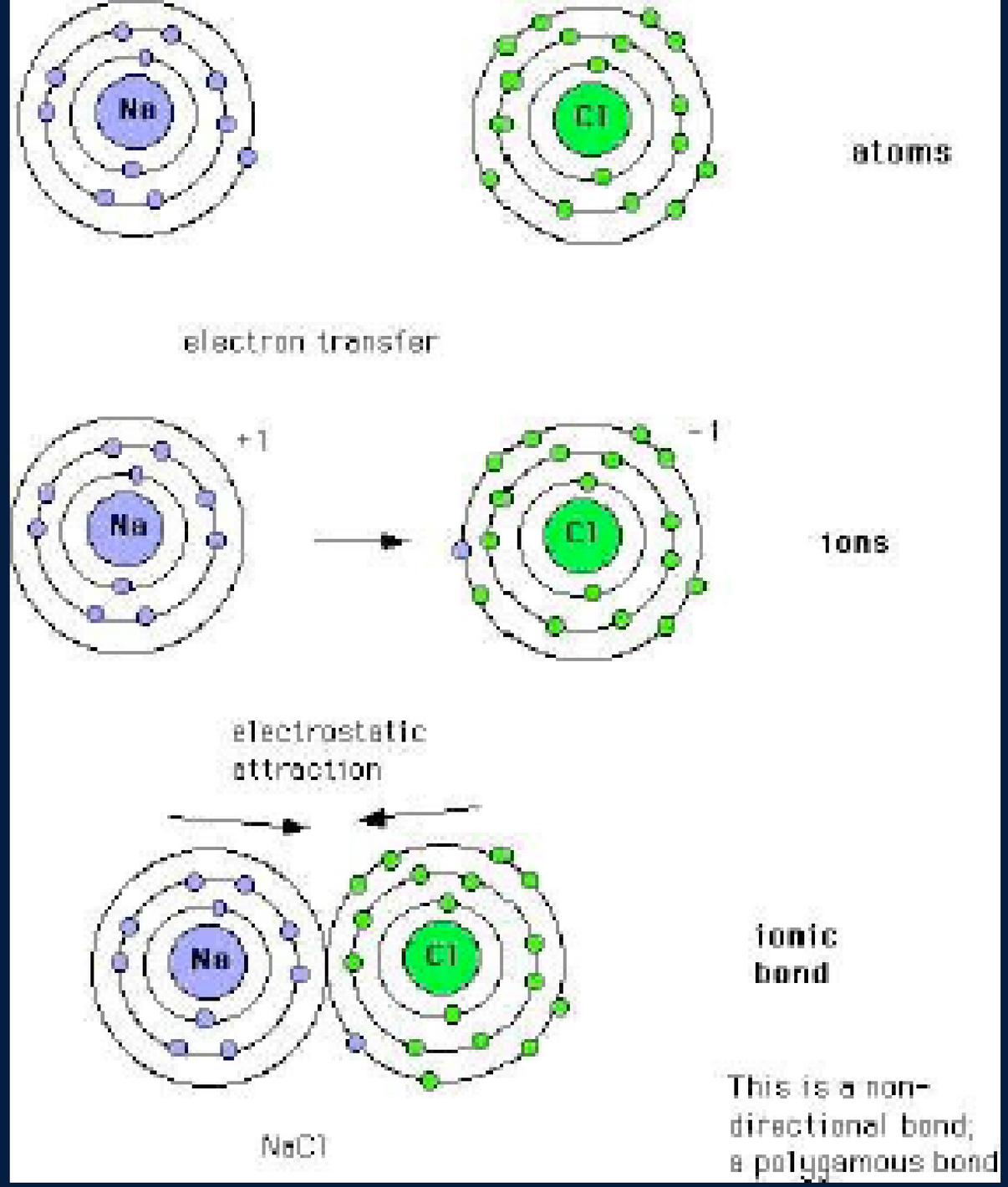
- Diamond
- Graphite



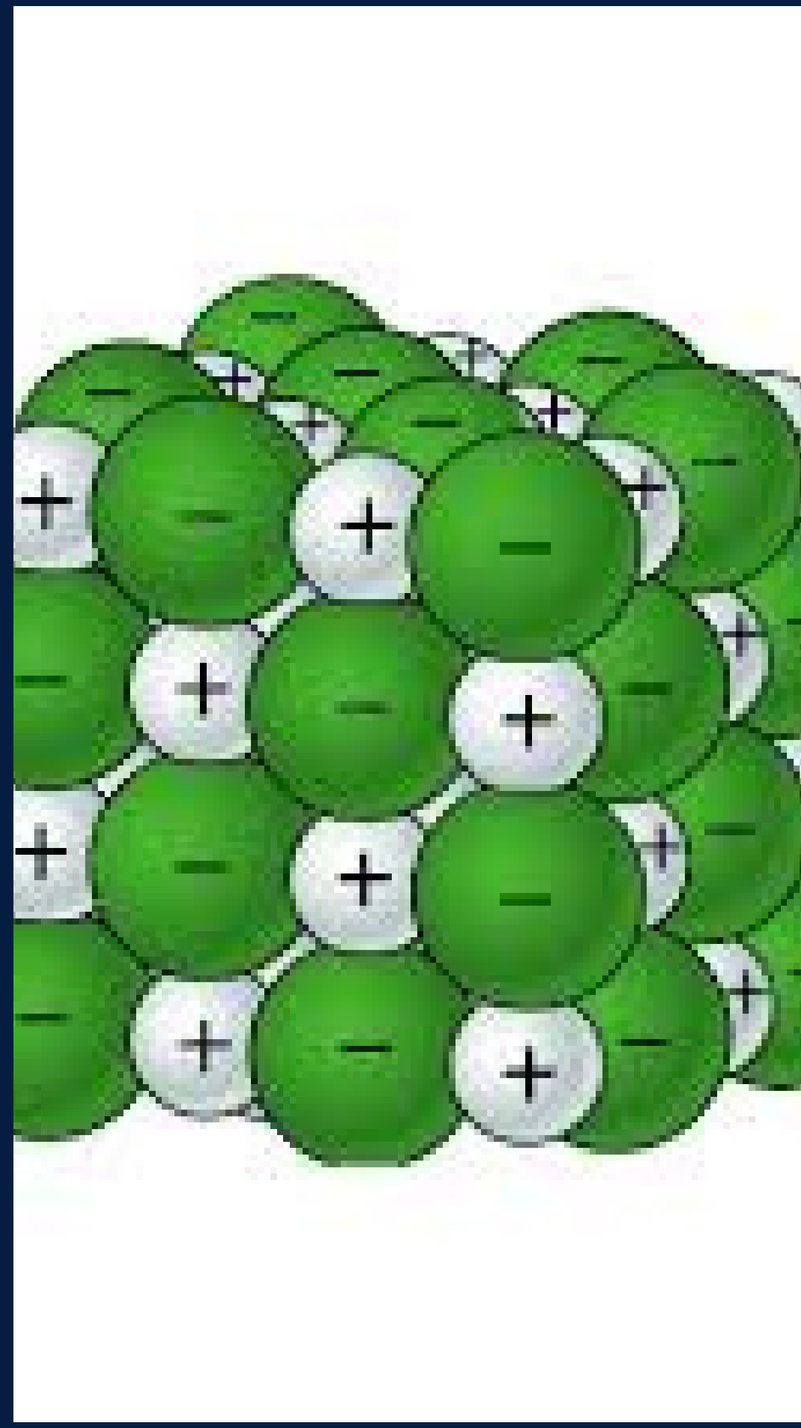
http://library.tedankara.k12.tr/chemistry/vol2/allotropy/h76.jpg

Diamond is one of the hardest material in nature because covalent bonding is very strong. In graphite, bonding between 2 graphene layers is weak Van der Waals bonding. This makes graphite very soft and graphene layers can be easily separated.

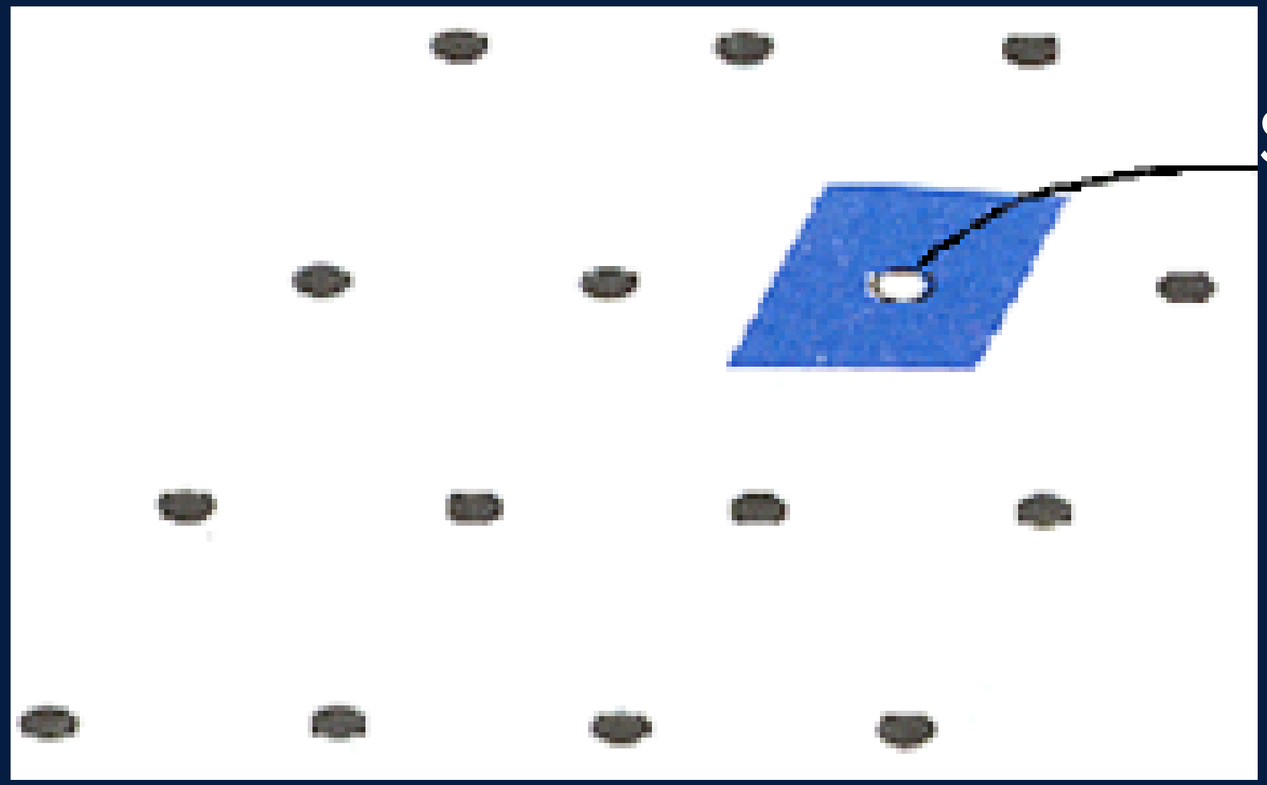
Ionic Bond



Bond between two oppositely charged ions.



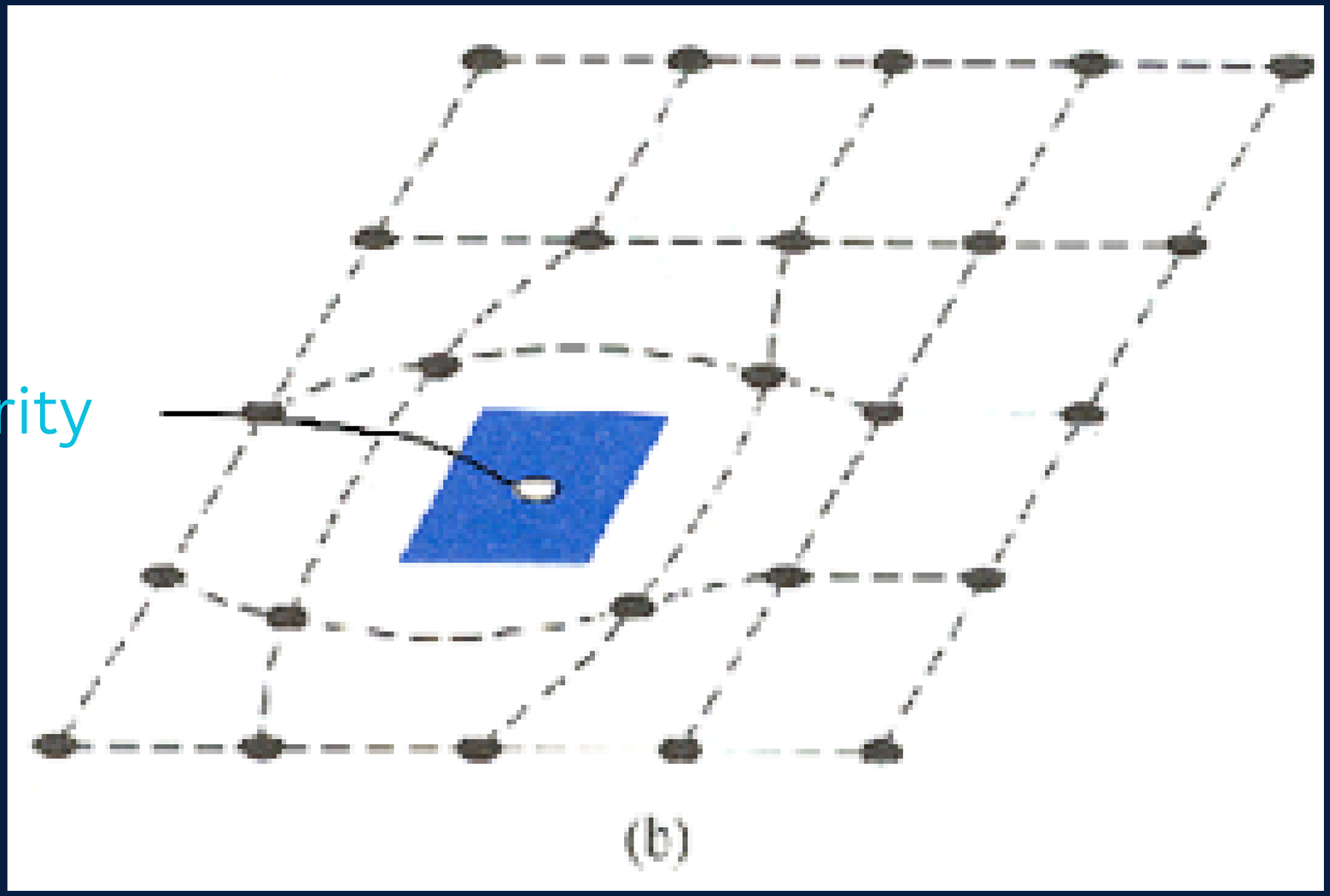
Imperfections in solids



Substitutional impurity
or a vacancy
Point defects

Lattice imperfection is any deviation from perfect periodic arrangement of lattice points. Point defects can be in the form of vacancy (missing atom), substitutional impurity (atom replaced by another atom) or interstitial impurity (additional impurity not at lattice point)

Interstitial impurity

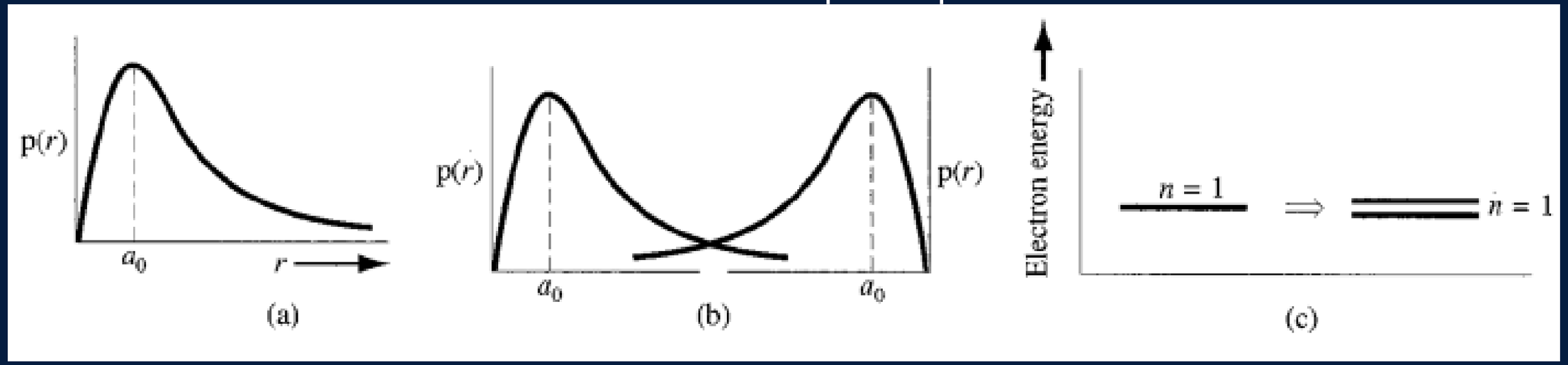


Growth of Semiconductor Materials

•	Growth from Melt
•	Epitaxial growth

Formation of Energy Bands

When two hydrogen atoms are brought close enough for the wave functions of n=1 electrons to start interacting, the n=1 state splits into two different energies, in accordance with Pauli exclusion principle.



(a) Probability density function of n=1 electron in an isolated hydrogen atom.

(b) Overlapping probability density functions in two adjacent hydrogen atoms.

(c)splitting of n=1 state.

WEEK 3
CLASS 2

wafer fabrication

SiO2

Metallic Si

$SiC + SiO2 \rightarrow Si + SiO + CO$

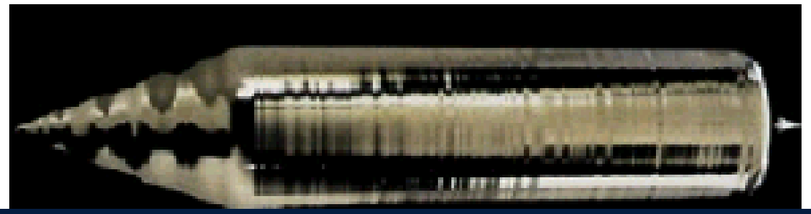
Pure trichlorosilane

$Si + 3SiCl4 + 2H2 \rightarrow 4SiHCl3$

Pure poly-Si

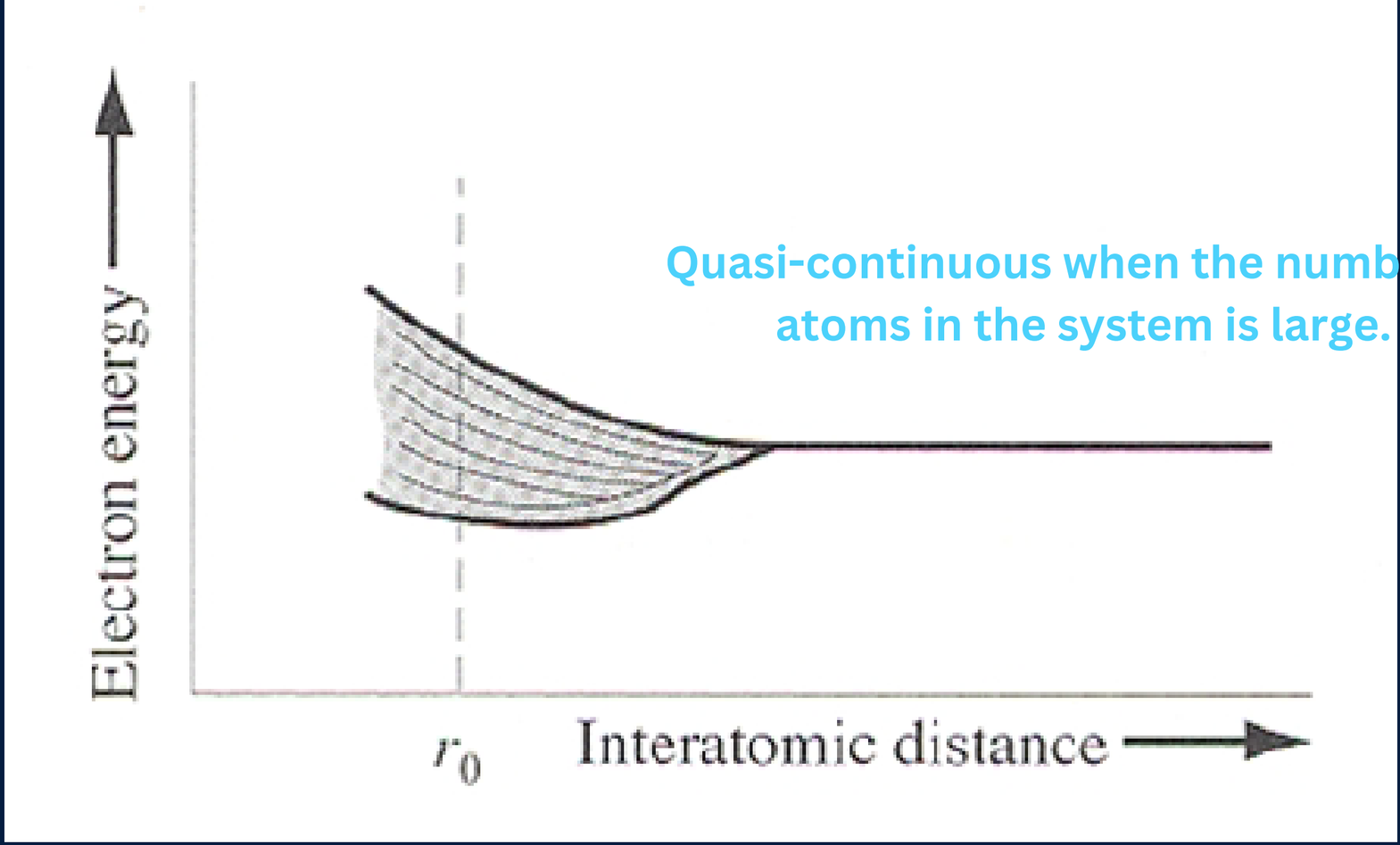
99.999999999%

Single-crystalline Si



Wafer

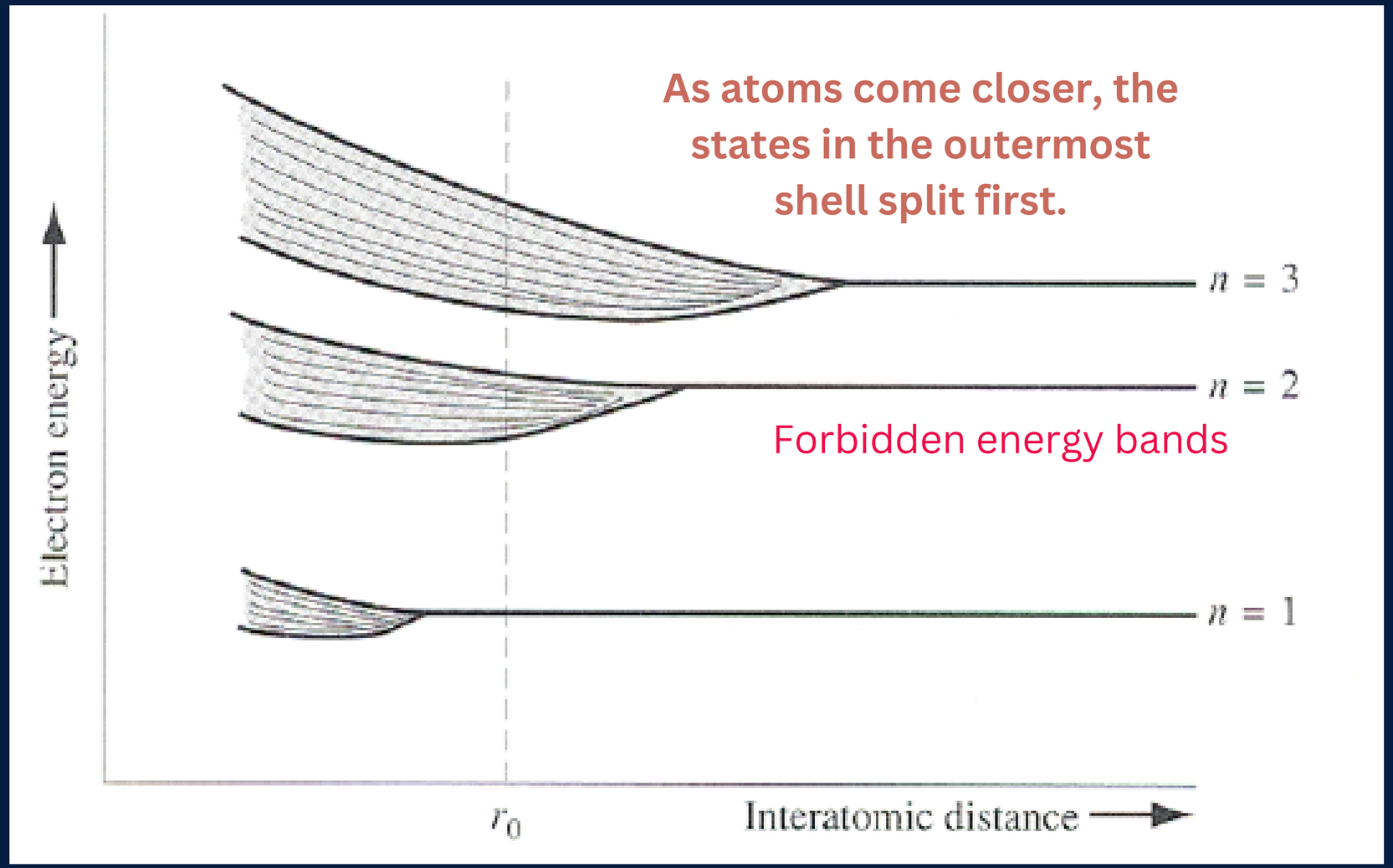
Hypothetically, if we have a periodic arrangement of many hydrogen atoms and they are brought close enough à initial quantized energy level will split into band of discrete levels.



Quasi-continuous when the number of atoms in the system is large.

The splitting of an energy state into a band of allowed energies (r0 is the equilibrium inter-atomic distance in the crystal)

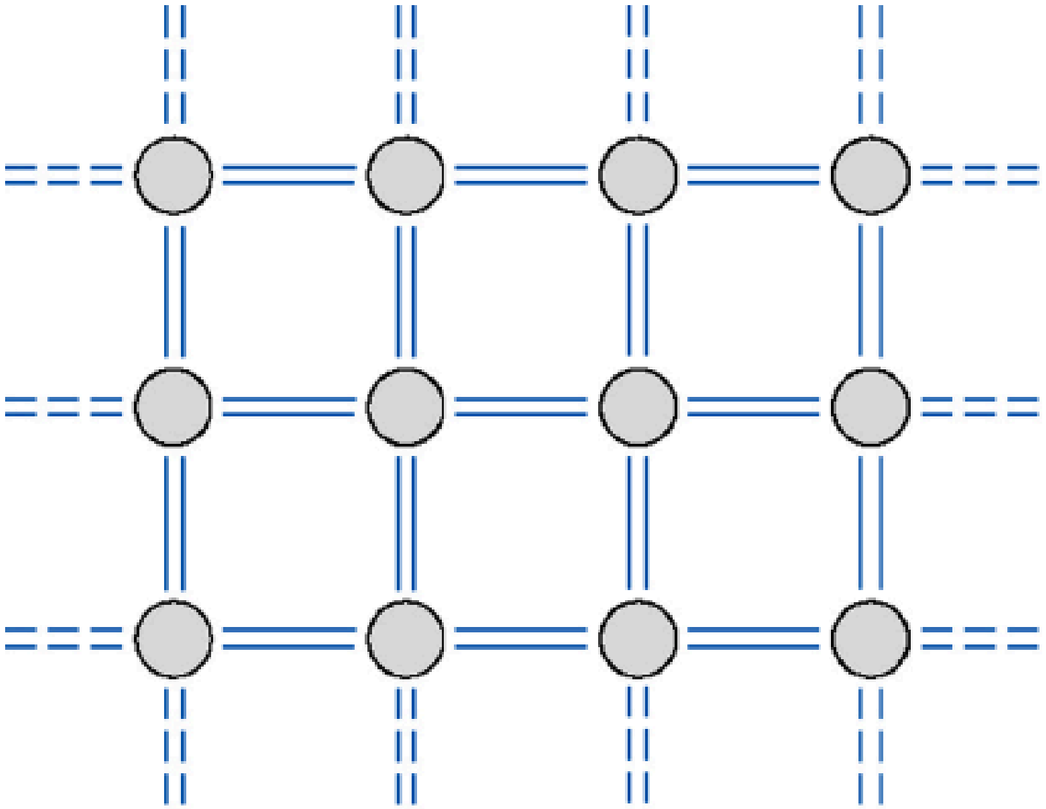
What happens in an atom containing many more electrons?



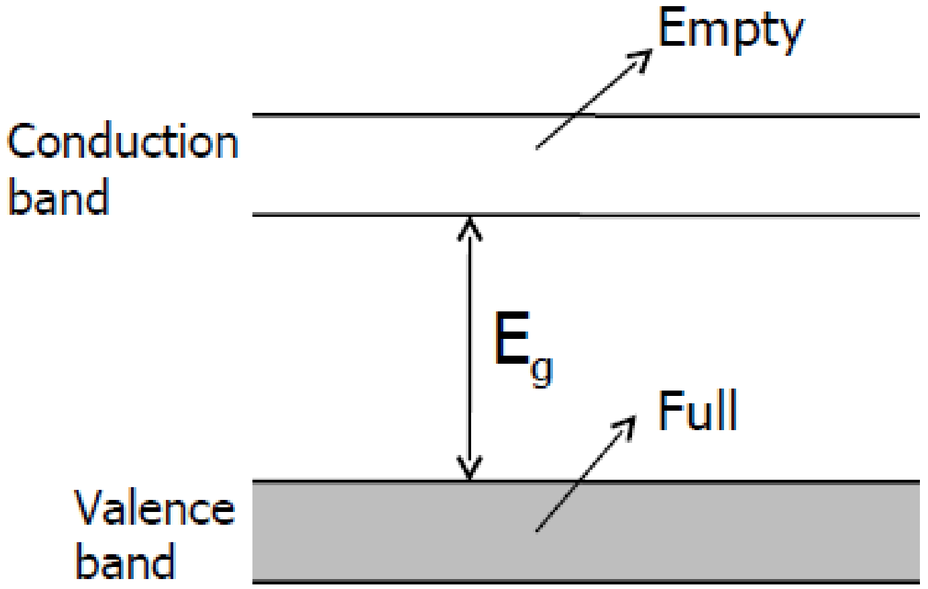
Based on rO, other energy states may or may not split

Splitting of energy states into allowed bands of energies in an atom containing electrons up to n=3.

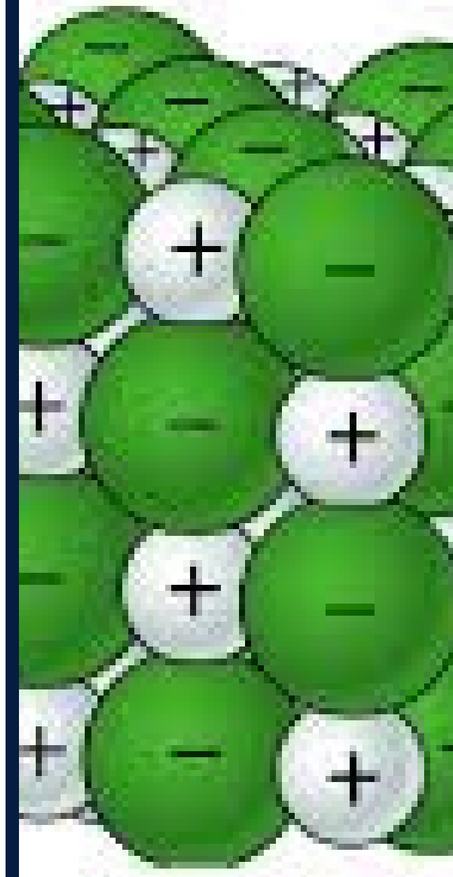
T=0K



(a) Covalent bonding in Si

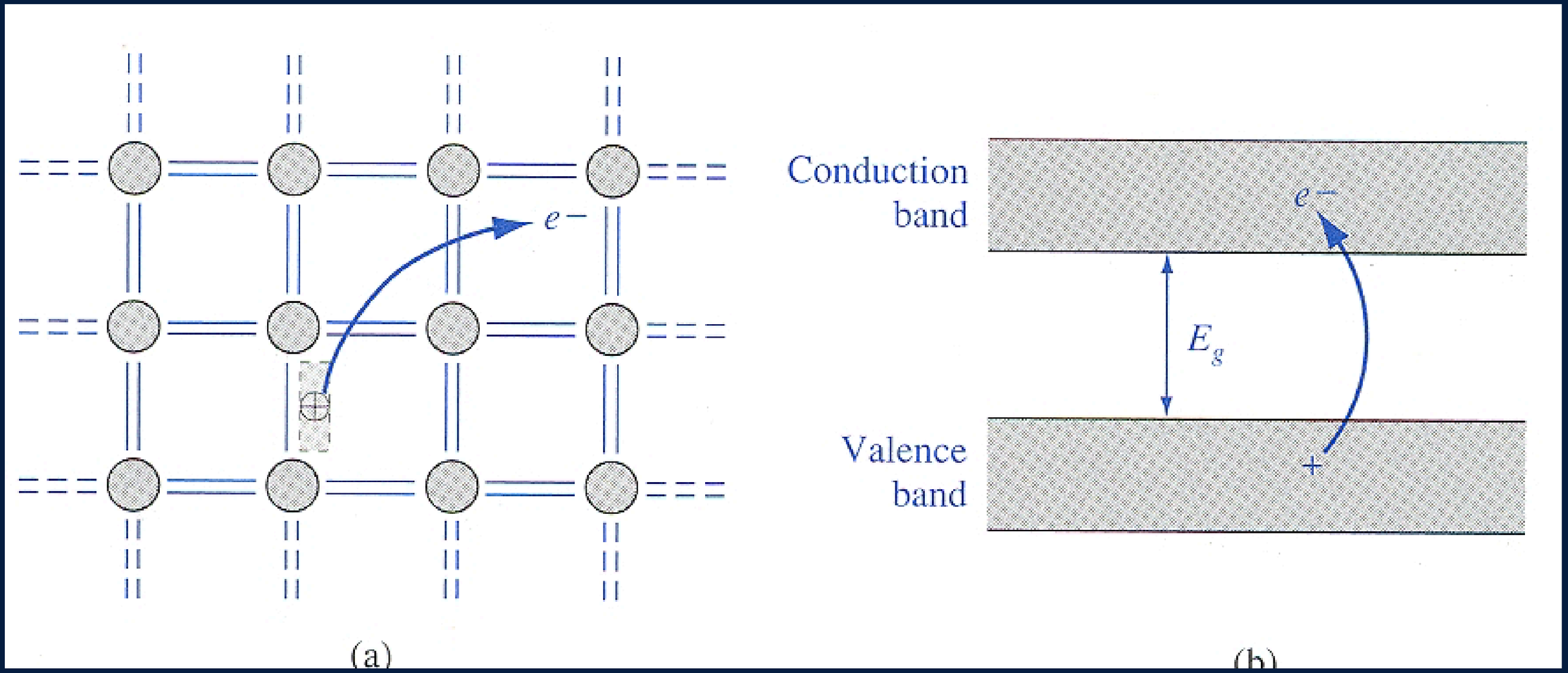


(b) line representation of energy band diagram



Band-gap energy in some covalent elements

Element	E_g (eV)
C (diamond)	5.48
Si	1.1
Ge	0.7
Sn (gray)	0.08



Two dimensional representation of breaking of a covalent bond.

At T>OK, some covalent bonds break giving rise to positively charged empty states and electrons

Drift current

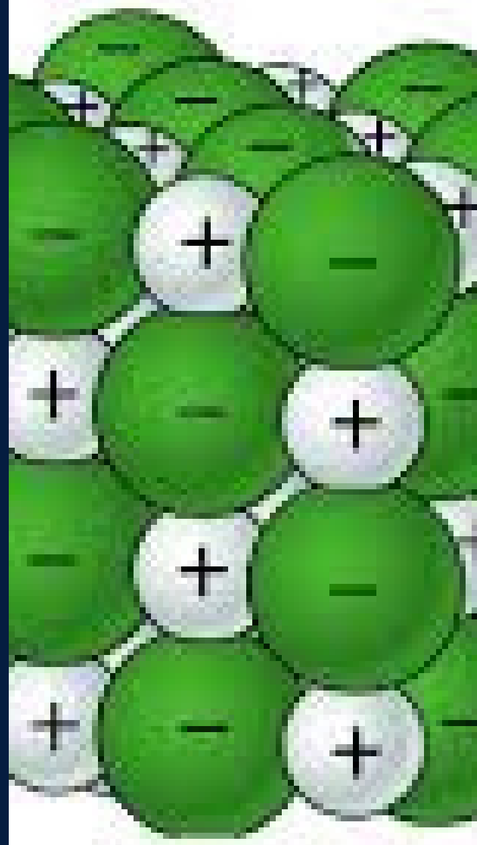
$$J = qNv_d(\mathrm{A/cm^2})$$

q → electron charge
N → charge density (C/cm^3)
V_d → drift velocity of electron

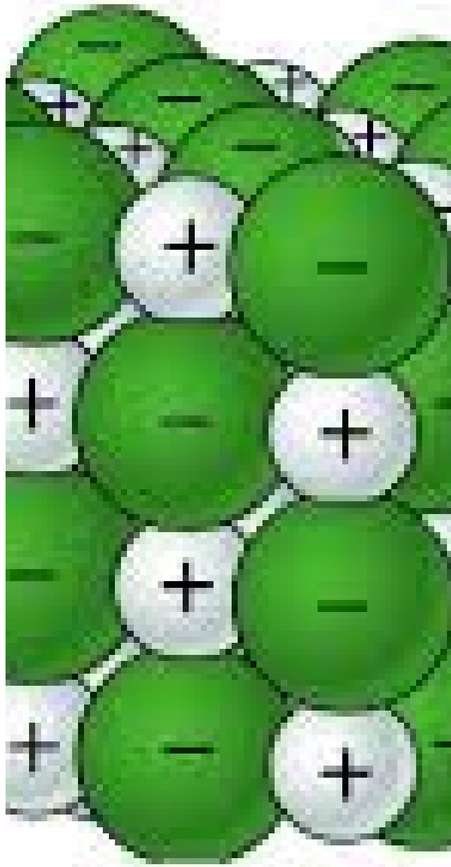
Considering individual electron velocities

$$J = q\sum_{i=1}^{N} v_i$$

(summation taken over unit volume)



Drift current



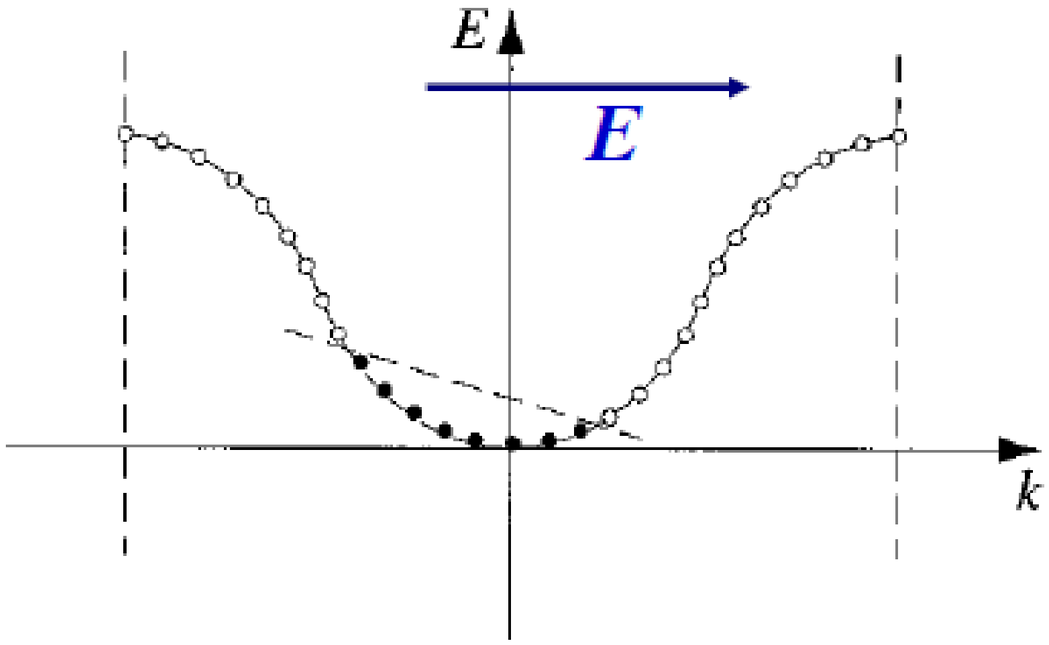
No external force → No of electrons with +|k| value = No of electrons with -|k| value. → k related to momentum. So drift current J = 0

When ext force (electric field) applied → Electrons move into empty energy states in conduction band, gain net energy and a net momentum.

Drift current density due to motion of electrons -

$$J = -e \sum_{i=1}^{n} v_i$$

(summation taken over unit volume)



Asymmetric distribution of electrons in E vs. k diagram when ext force is applied.

Electron effective mass

Total force acting on electrons in crystal –

$$F_{Total} = F_{ext} + F_{int} = ma$$

F_{int} → internal forces in the crystal due to +vely charged ions and –vely charged electrons

F_{ext} → externally applied electric field

m → rest mass of electron

a → acceleration.

Free electron:

Taking derivative of E w.r.t k,

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}, \text{ since } p = \frac{h}{\lambda} = \hbar k \quad \Rightarrow \quad \frac{dE}{dk} = \frac{\hbar^2 k}{m} = \frac{\hbar p}{m}$$

$$\frac{1}{\hbar}\frac{dE}{dk} = \frac{p}{m} = v$$

This implies that from E vs. k diagram we can get the velocity of the electron in real space.

$$\frac{1}{\hbar}\frac{dE}{dk} = \frac{p}{m} = v$$

Again taking derivative of E w.r.t k,

$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{1}{m}$$

This implies that from E vs. k diagram we can also get the effective mass of the electron in real space. For a free electron, the second derivative and hence mass is constant.

(why do we need to extract the electron mass, when we already know it ??? - read further)

Free electron

$$F = ma = -e\mathrm{E} \longrightarrow a = \frac{-e\mathrm{E}}{m}$$

Motion of electron is in opposite direction of the applied electric field due to the negative charge.

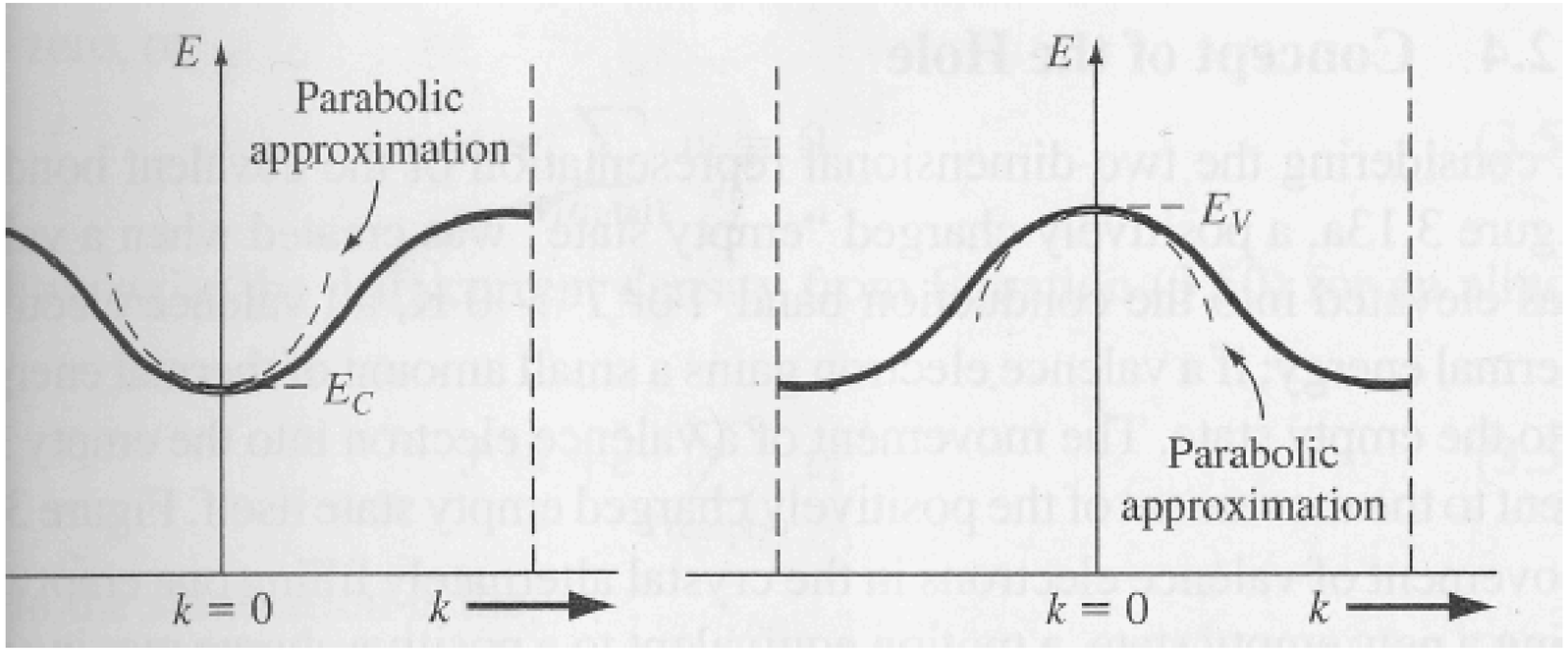
We now apply these concepts to the electrons in the crystal

Electron in conduction band

The energy of electrons at the bottom of the conduction band can be approximated as -

$$E - E_c = C_1(k)^2$$

$C_1 \rightarrow$ +ve



Conduction and valence bands in reduced k space with their parabolic approximations to compare with free electron

Electrons in conduction band

$$\frac{d^2E}{dk^2} = 2C_1$$

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{2C_1}{\hbar^2}$$

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{2C_1}{\hbar^2} = \frac{1}{m^*}$$

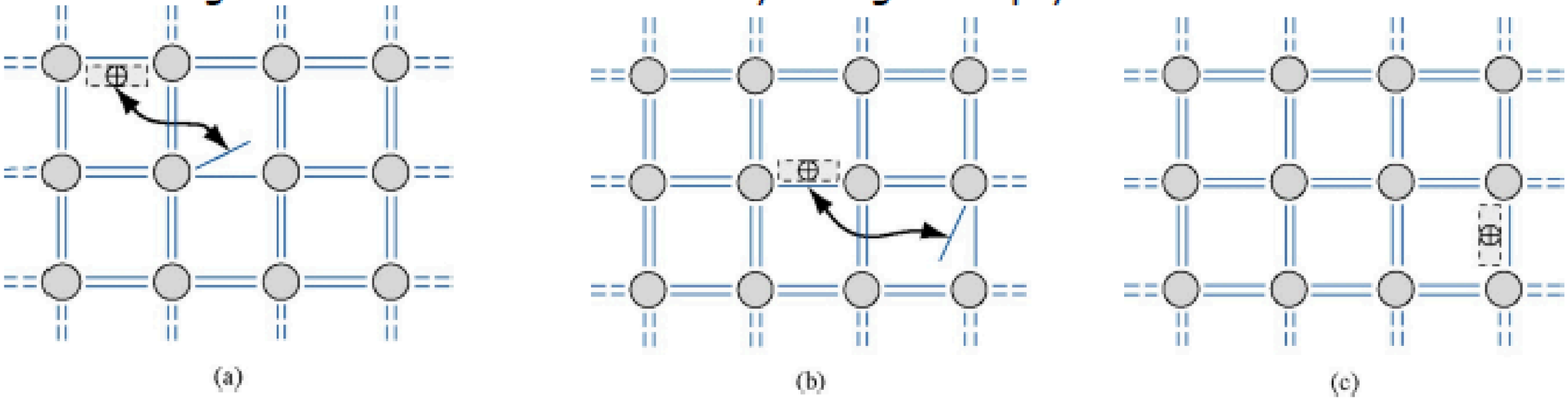
$$a = \frac{-e\mathrm{E}}{m_n^*}$$

Effective mass:

- connects quantum mechanics and classical mechanics
- effective mass varies with k, but almost constant at the bottom of the conduction band.
- positive value since C_1 is +ve

Concept of the hole

- When valence electron goes to conduction band positively charged empty state is created.
- If a valence electron gets a small amount of energy, it can occupy this empty state.
- Movement of valence electron ⟺ movement of +vely charged empty state in opposite direction.
- The charge carrier in the form of +vely charged empty state is called the hole.



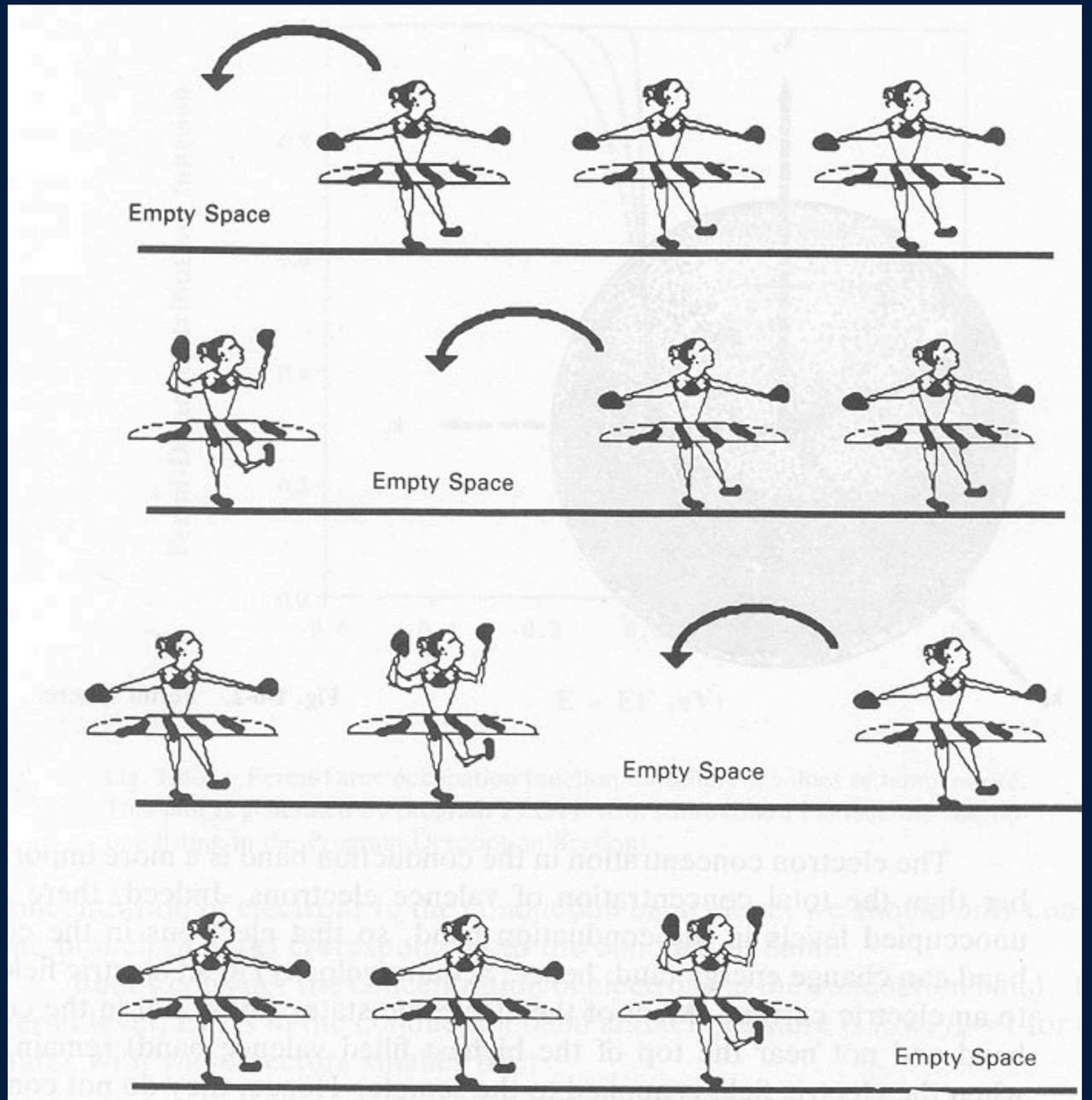


Fig. 1-6-3. Concept of a *hole*.

Drift current density due to electrons in valence band is -

$$\sum_{i(filled)} v_i = \sum_{i(total)} v_i - \sum_{i(empty)} v_i$$

$$J = -e \sum_{i(\text{filled})} v_i \longrightarrow J = -e \sum_{i(\text{total})} v_i + e \sum_{i(\text{empty})} v_i$$

Now, $v(E) = \left(\frac{1}{\hbar}\right)\left(\frac{dE}{dk}\right)$

Also in a band that is completely full, electron distribution is symmetric with respect to k. The net drift current density generated from a completely full band is then 0.

$$-e \sum_{i(\text{total})} v_i \equiv 0$$

$$J = -e \sum_{i\,(\text{total})} v_i + e \sum_{i\,(\text{empty})} v_i$$

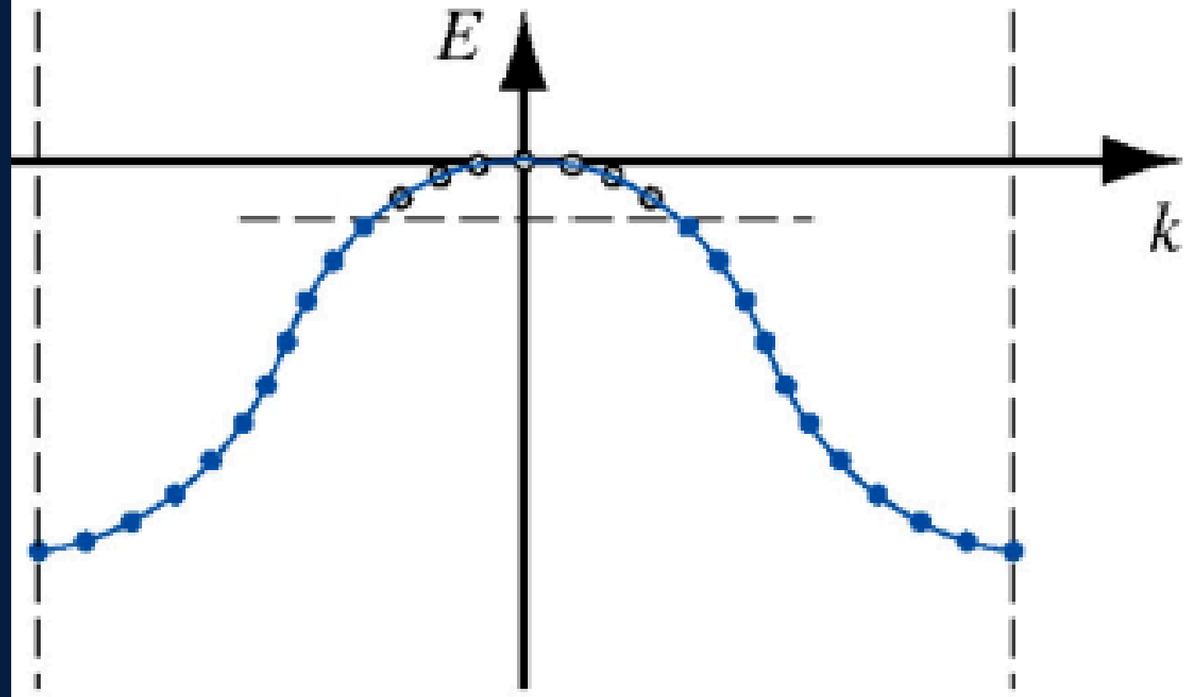
and

$$-e \sum_{i\,(\text{total})} v_i \equiv 0$$

Therefore

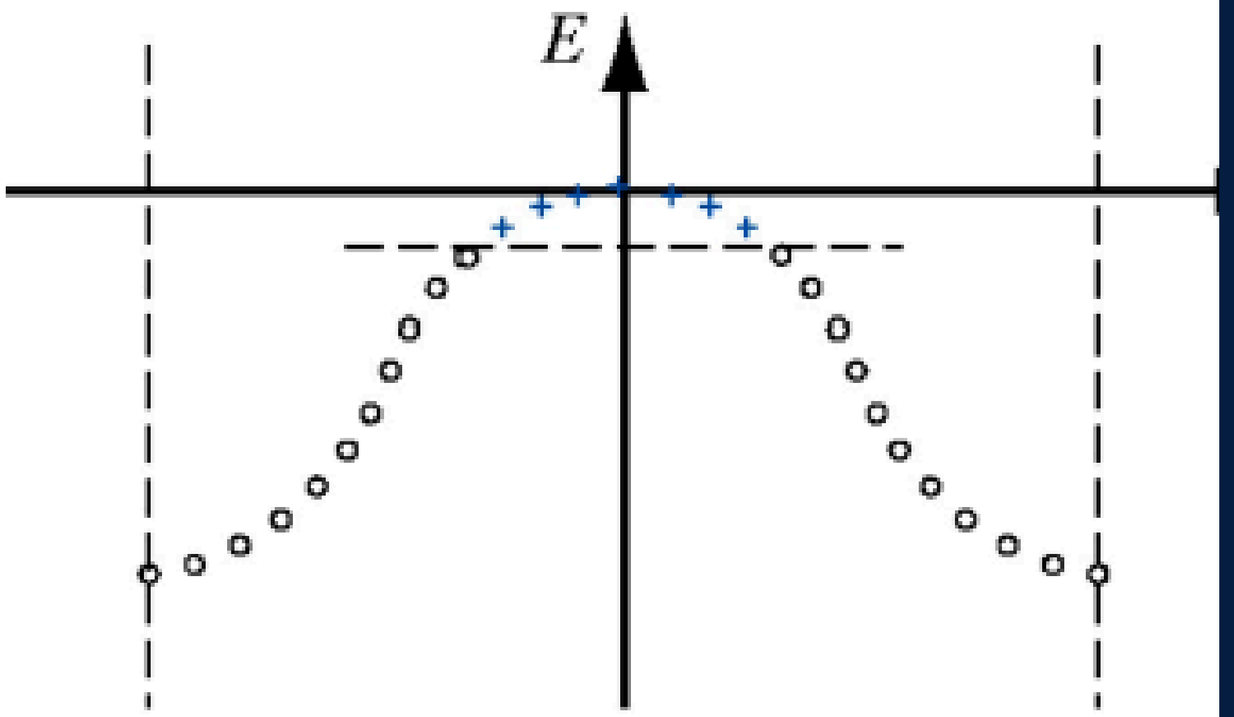
$$J = +e \sum_{i\,(\text{empty})} v_i$$

Drift current due to electrons in the filled state can also be looked at as that due to placing positively charged particles in the empty states.



(a)

Valence band with conventional electron filled states and empty states

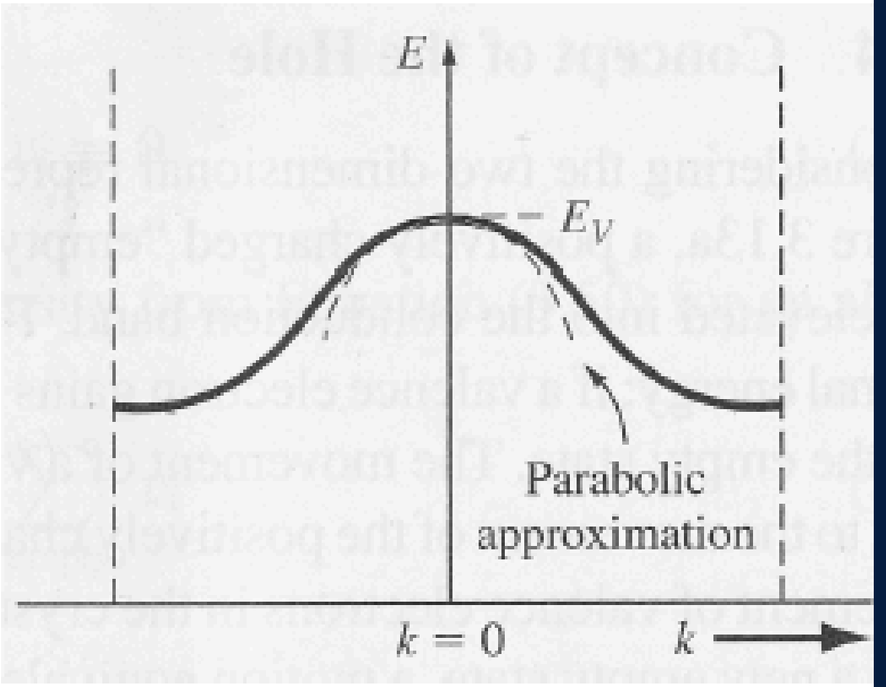


(b)

Concept of positive charges occupying the original empty states.

Energy at the top of allowed energy band can be written as -

$$(E - E_v) = -C_2(k)^2$$



$C_2 \rightarrow$ +ve

$$\frac{d^2E}{dk^2} = -2C_2$$

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{-2C_2}{\hbar^2}$$

Compare with free electron:

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{1}{m}$$

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{-2C_2}{\hbar^2} = \frac{1}{m^*}$$

Negative effective mass

Bit strange!

$$F = m^*a = -e\mathrm{E}$$

$$a = \frac{-e\mathrm{E}}{-|m^*|} = \frac{+e\mathrm{E}}{|m^*|}$$

- negative mass is a result of our attempt to relate quantum and classical mechanics. It is due to the inclusion of the effect of internal forces due to ions and other electrons.

- The net motion of electrons in the nearly full valence band can also be describe by considering the empty states, provided +ve electronic charge and +ve effective mass is associated with them

- This new particle with +ve electronic charge and +ve effective mass denoted by m_p^* is called the hole

Electrons:

- in almost empty band
- negative charge
- positive effective mass

Holes:

- in almost full band
- positive charge
- positive effective mass

Both:

$$\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{1}{m^*}$$

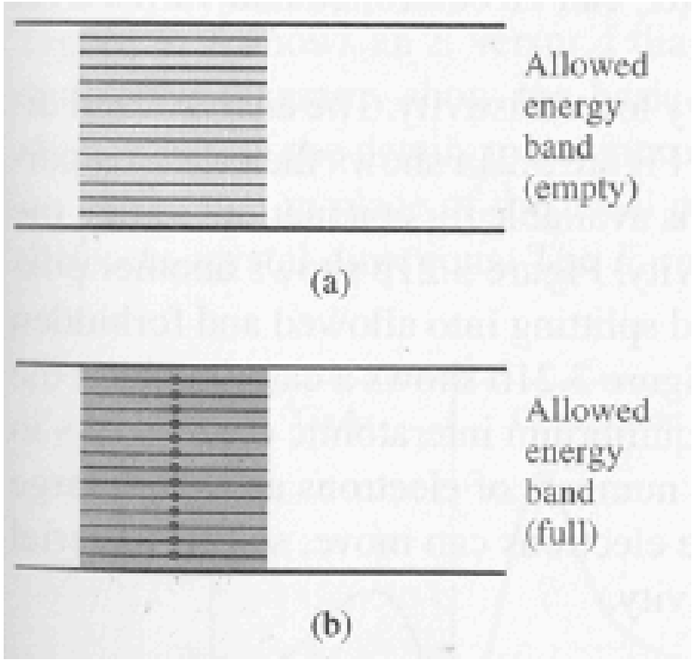
$$F = m^*a = qE$$

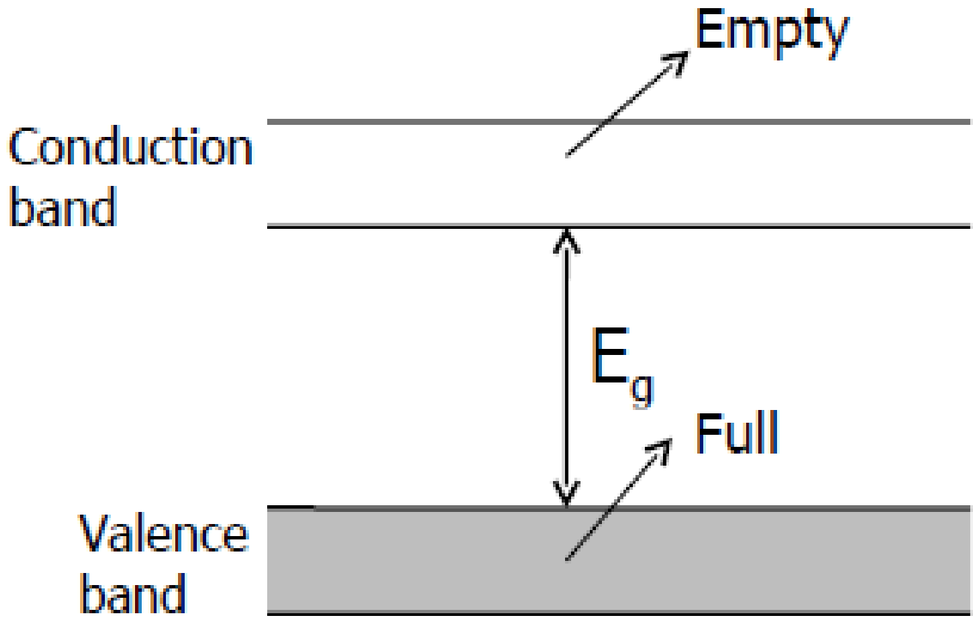
Electron and Hole effective mass in different semiconductors.

	m_n^*/m_0	m_p^*/m_0
Silicon	1.08	0.56
Gallium Arsenide	0.067	0.48
Germanium	0.55	0.37

Metals, semiconductors and insulators

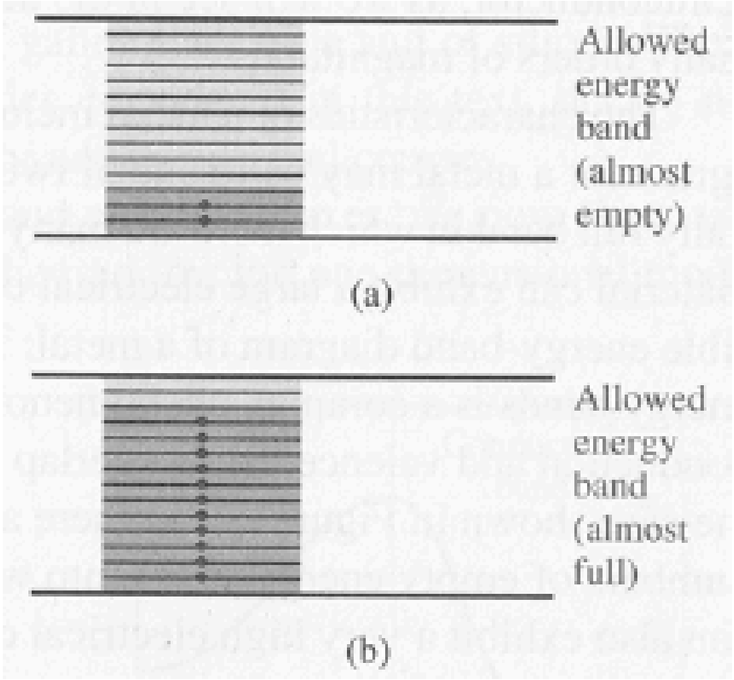
Insulators:



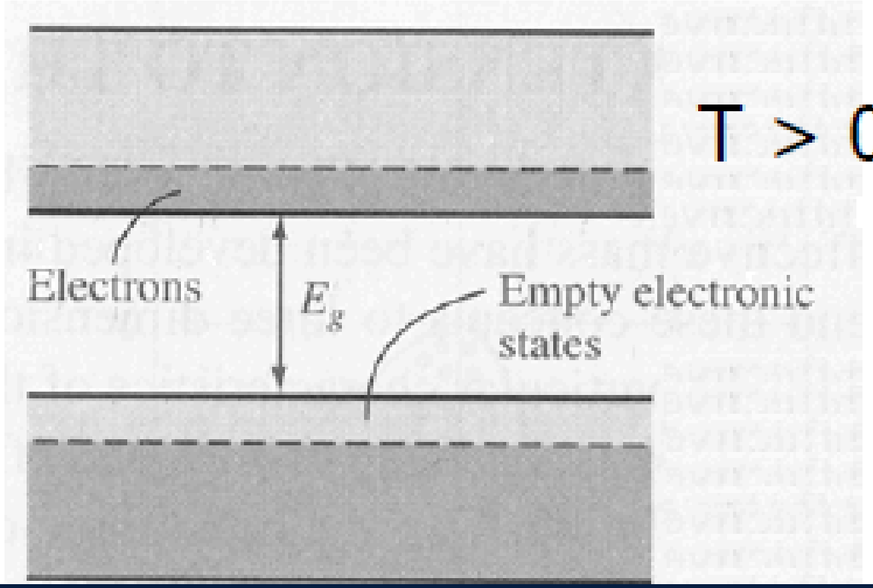


- E_g 3.5 to 6 eV or higher
- valence band full, conduction band empty
- no charged particles that contribute to drift current.

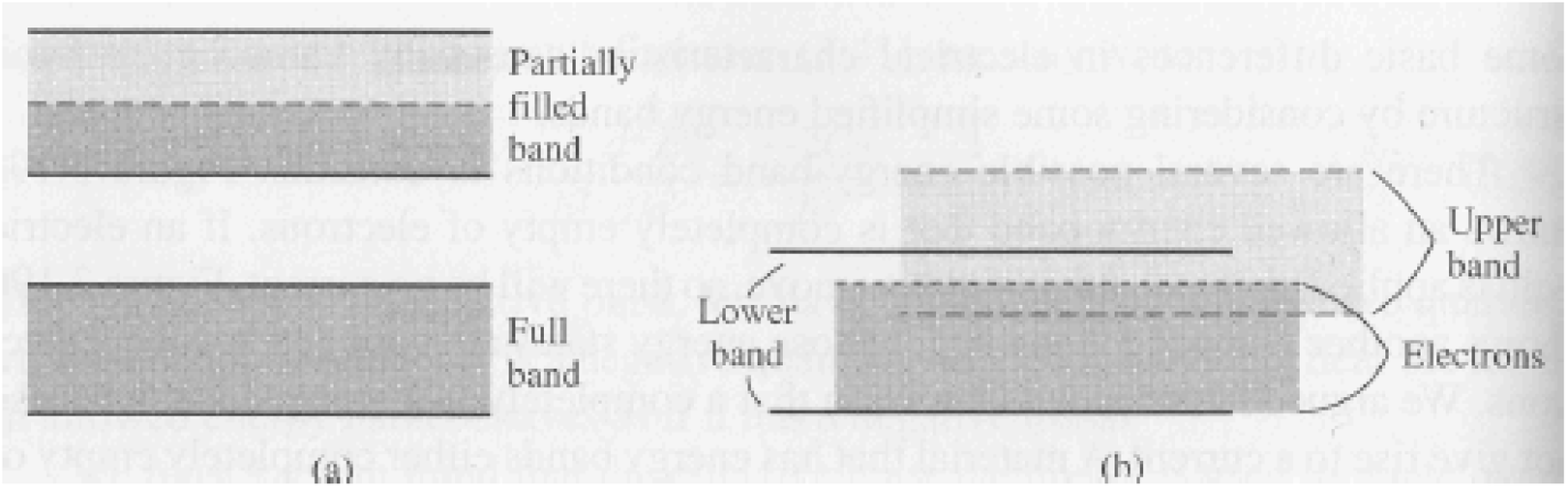
Semiconductors:



- E_g in semiconductors is small. E_g ~ 1eV
- At T>0K, there will be some electrons in conduction band and holes in valence band, which can contribute to current.
- resistivity can be varied over many orders of magnitude by doping



Metals:



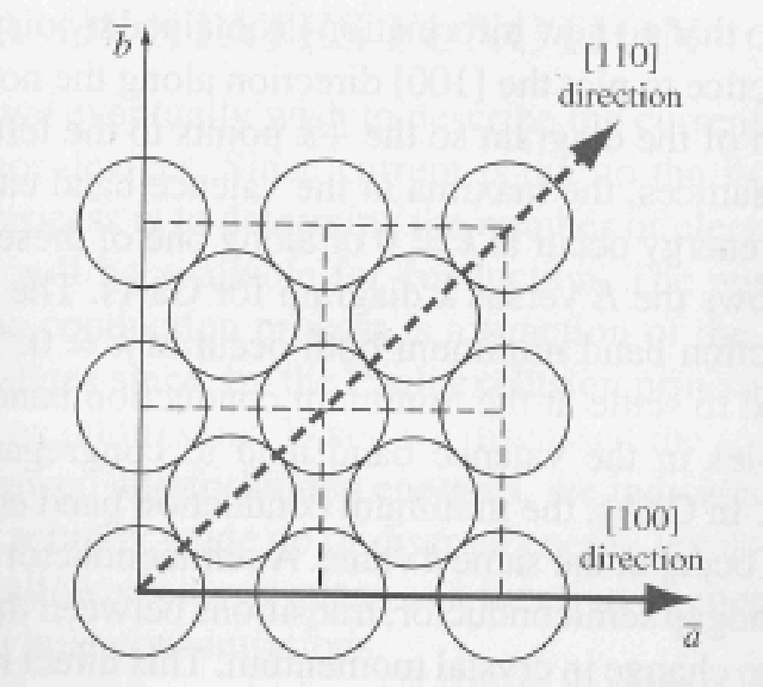
- Two possibilities - half filled conduction band or conduction and valence bands overlap.

- plenty of electrons and empty energy states that these electrons can move into.

- Very high electrical conductivity.

Extending energy band theory to three dimensions

- Extend concepts of energy band and effective mass to 3-dimensions



Different potentials in different directions

- distance between atoms not the same in different directions

- E vs. k diagram → as seen before depends on 'a' and 'a' varies with direction.

Density of states function

- we want to know the number of charge carriers and their temperature dependence

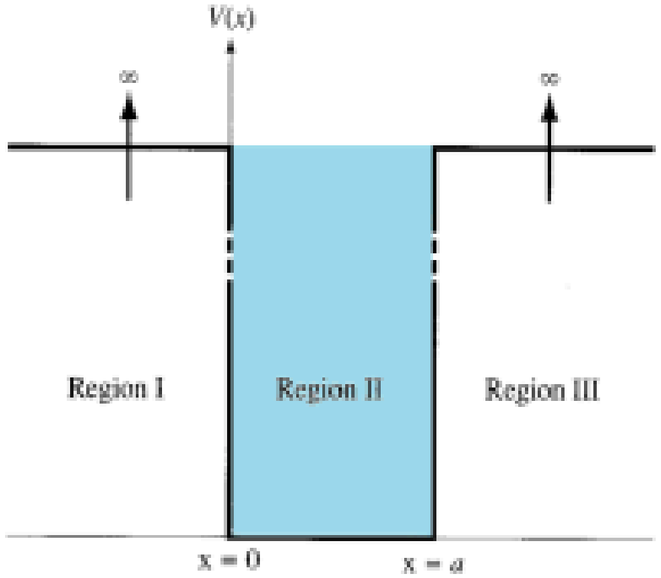
- hence the question is: how many energy levels do we hav and what is the chance that they are populated in dependence of the temperature.

Mathematical model for density of states

- we consider a free electron confined to an 3-dimensional cubical infinite potential well of side 'a'.

$$V(x,y,z) = 0 \quad \text{for} \quad 0 < x < a,\ 0 < y < a,\ 0 < z < a$$

$$V(x,y,z) = \infty \quad elsewhere$$



One dimensional potential well $\longrightarrow$ $K = \frac{n\pi}{a}$ and $K = \sqrt{\frac{2mE}{\hbar^2}}$

Extension to semiconductors.

We have derived expression for density of allowed electron quantum states using model of free electron in an infinite potential well.

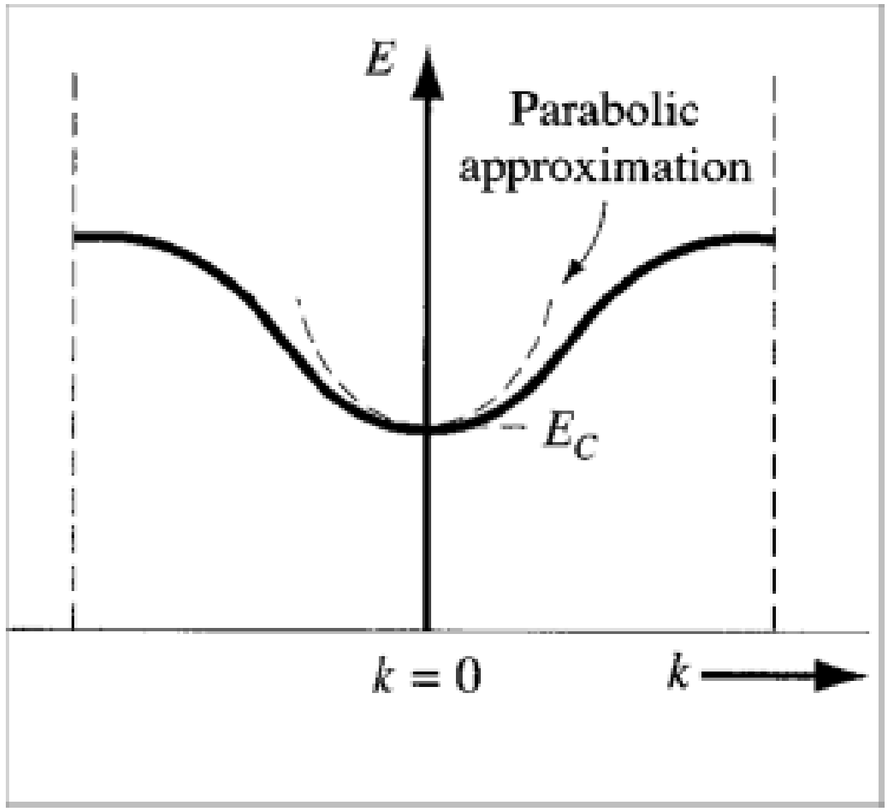
Electrons and holes are also confined within a semiconductor crystal

So we can extend this model to derive density of quantum states in conduction and valence bands.

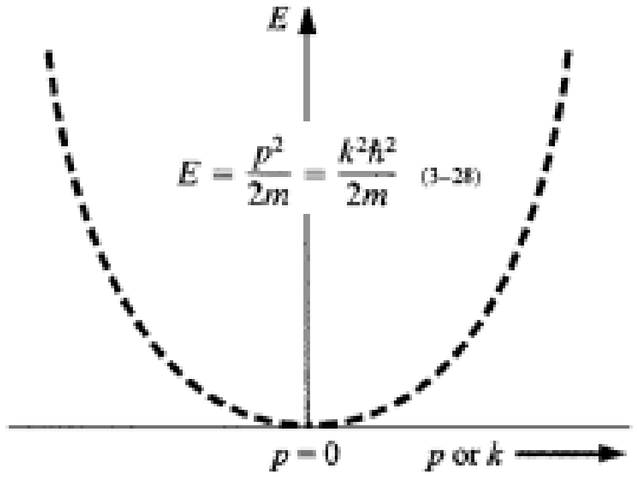
Extension to semiconductors.

Conduction band:

$$E = E_c + \frac{\hbar^2 k^2}{2m_n^*}$$

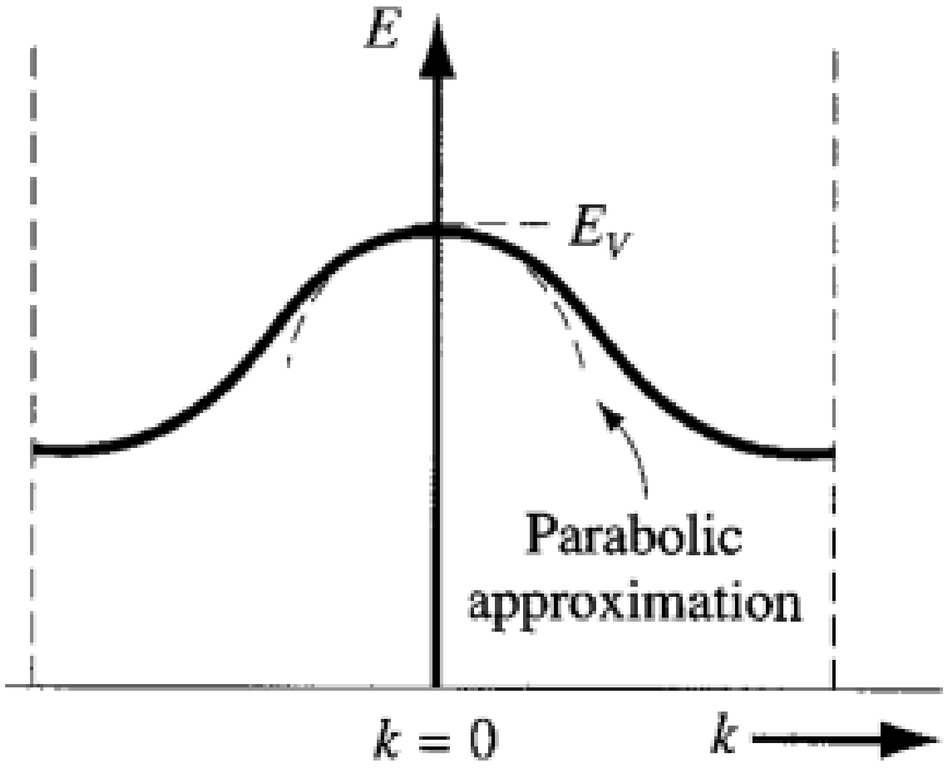


$$E - E_c = \frac{\hbar^2 k^2}{2m_n^*}$$



Parabolic E vs. k for free electron

Valence band:



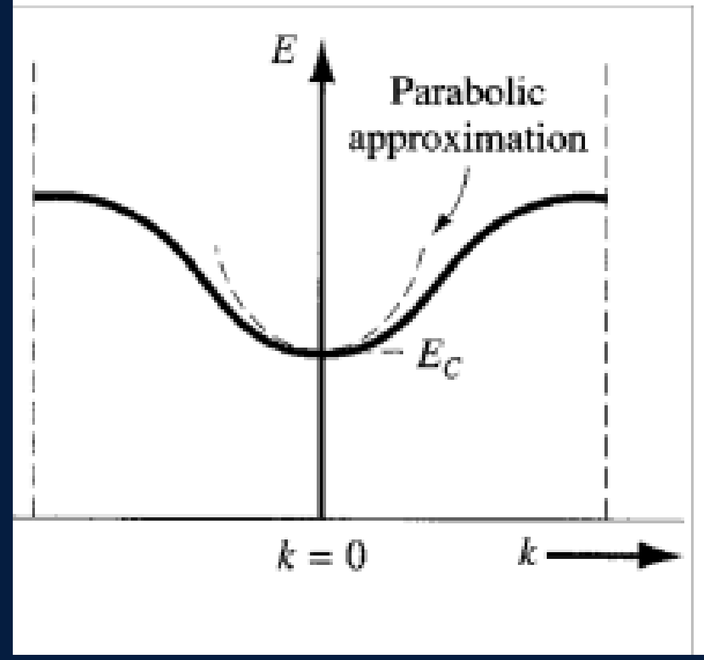
$$E = E_v - \frac{\hbar^2 k^2}{2m_p^*}$$

$$E_v - E = \frac{\hbar^2 k^2}{2m_p^*}$$

Density of states in the conduction band

For free electron, $E = \frac{\hbar^2 k^2}{2m}$ and $g(E) = \frac{4\pi(2m)^{3/2}}{h^3}\sqrt{E}$

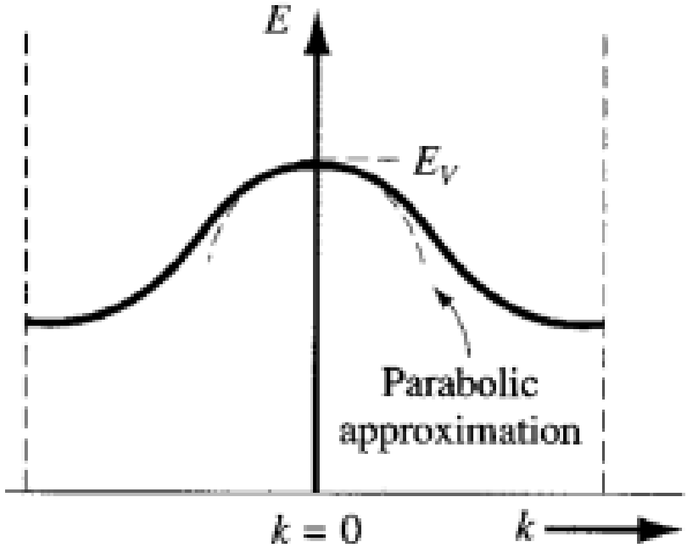
For conduction band, $E - E_c = \frac{\hbar^2 k^2}{2m_n^*}$



$$g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}$$

Density of states in the valence band

for $E \leq E_v$



$$E_v - E = \frac{\hbar^2 k^2}{2m_p^*}$$

$$g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_v - E}$$

Density of states function

In general: $$g(E) = \frac{4\pi(2m)^{3/2}}{h^3}\sqrt{E}$$

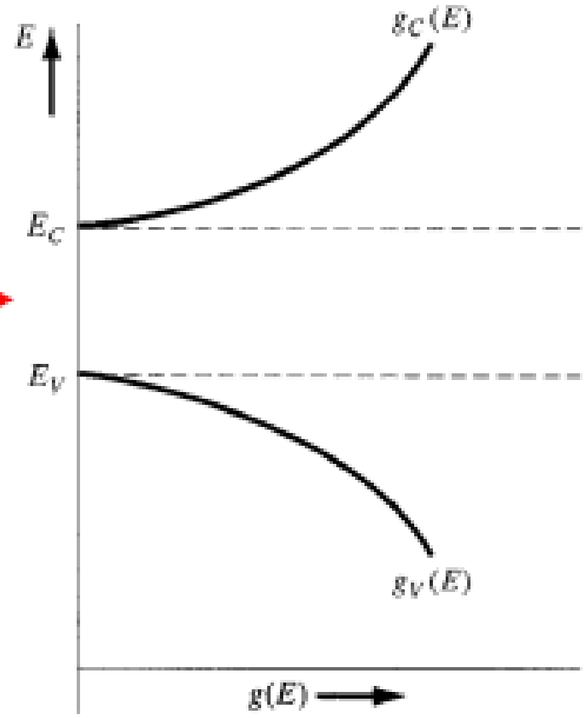
for $E \geq E_c$

$$g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}$$

$g(E) = 0$ for $E_v < E < E_c$

for $E \leq E_v$

$$g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_v - E}$$



Statistical Mechanics.

- While studying, large number of particles, we are interested only in statistical behavior of the group as a whole.

- In a semiconductor crystal, we are not interested in the behavior of each individual electron.

- The electrical characteristics will be determined by statistical behavior of large number of electrons.

- While studying statistical behavior, we must consider the laws that the particles obey.

Distribution Laws:

Distribution of particles among energy states → 3 laws.

	Particles distinguishable	Particles Identical
Unlimited number of particles allowed in each energy state	Maxwell-Boltzmann probability function. E.g. Behavior of gas at low pressure.	Bose-Einstein function. E.g. Behavior of photons or black body radiation.
Limited number of particles allowed in each energy state		Fermi-Dirac probability function E.g. Electrons is a semiconductor crystal.

Fermi-Dirac distribution function:

$$\frac{N(E)}{g(E)} = f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

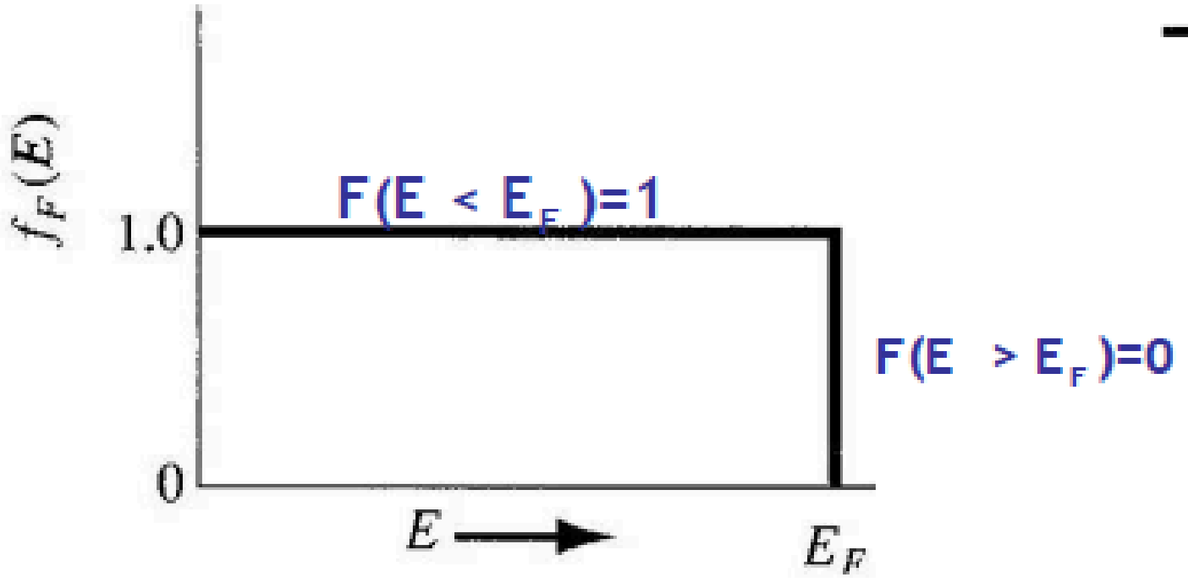
N(E) → number of electrons per unit volume per unit energy.

g(E) → number of quantum states per unit vol per unit energy.

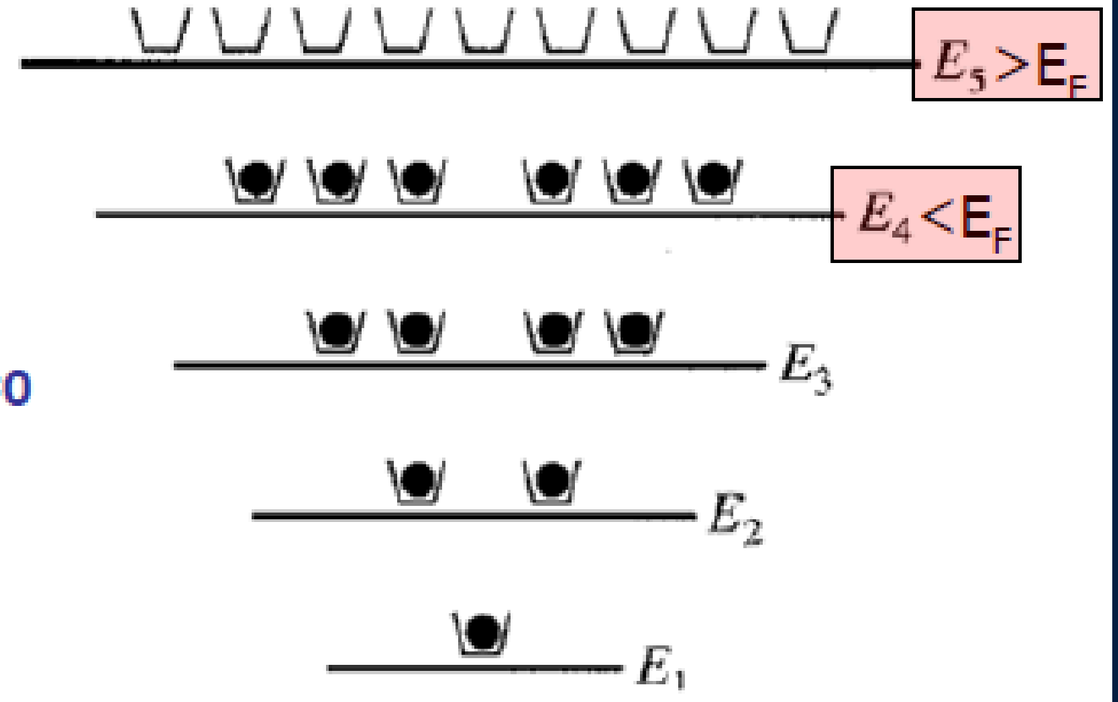
E_F → Fermi energy (explained in more detail later)

At T = 0K

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$



The Fermi probability function versus energy for T=0K

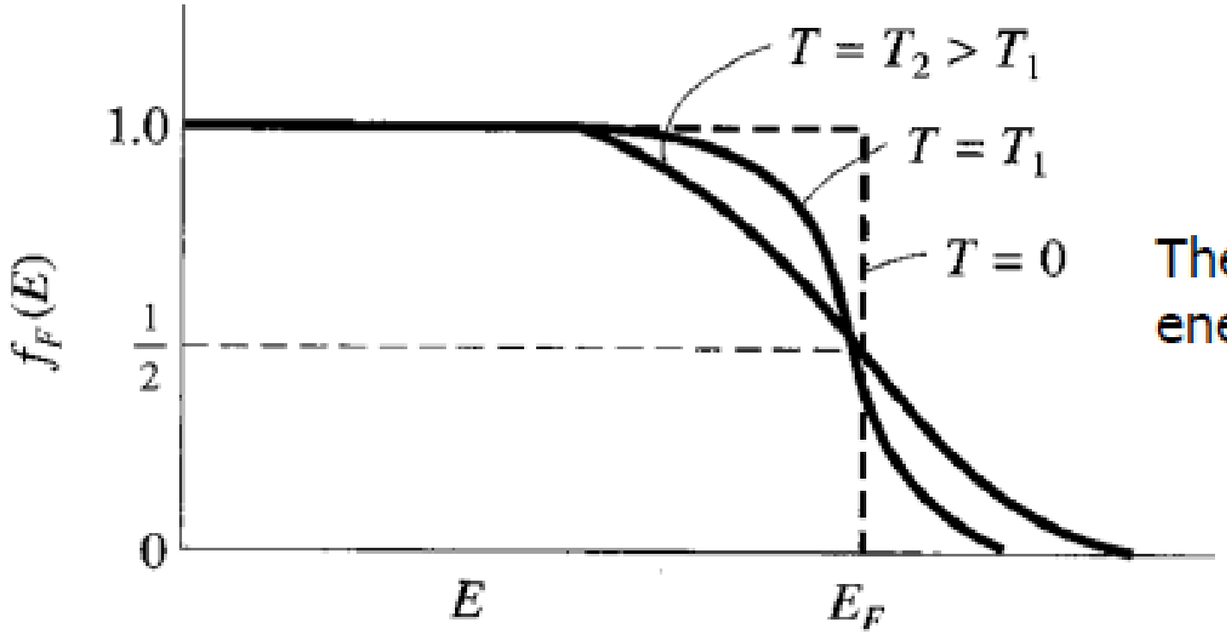


Discrete energy states and quantum states for a particular system.

At $E=E_F$

$$f_F(E = E_F) = \frac{1}{1 + \exp(0)} = \frac{1}{1+1} = \frac{1}{2}$$

So Fermi Energy is the energy level where probability is ½.
At T>0

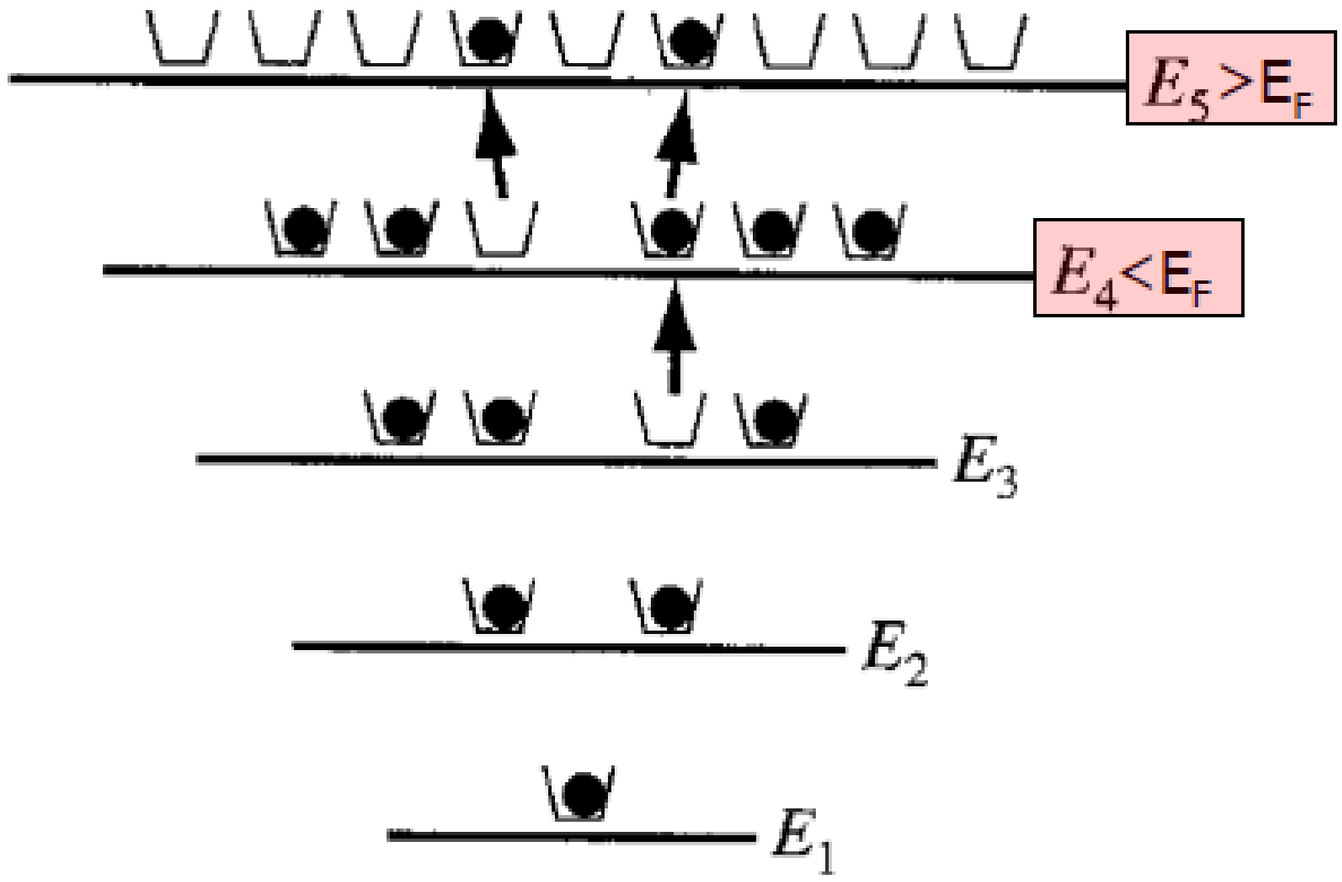


The fermi probability function versus energy for different temperatures.

Applet

At T>0K, there is non-zero probability that some states above EF are occupied and some states below are empty → some electrons have jumped to higher energy levels with increasing thermal energy.

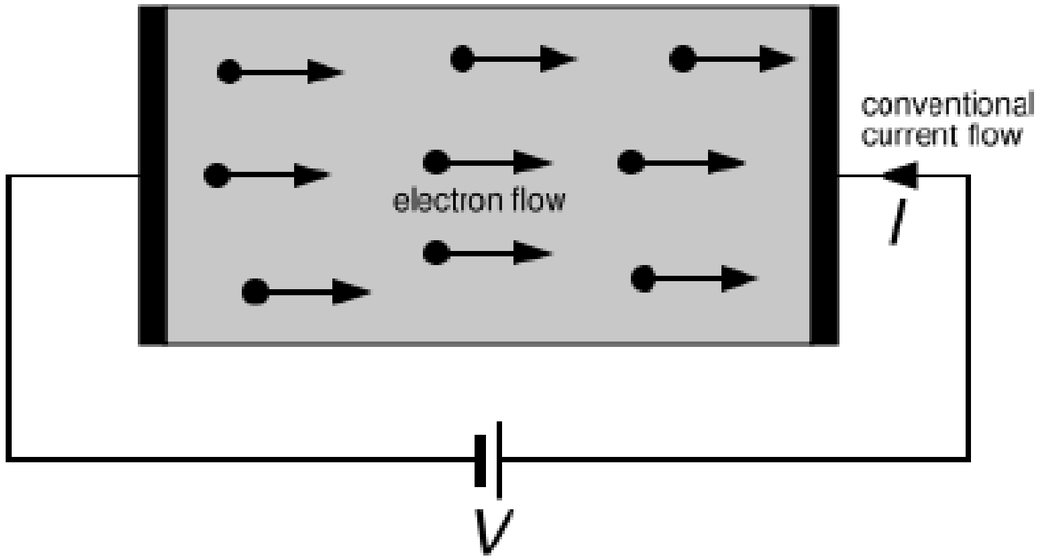
At T > 0 K

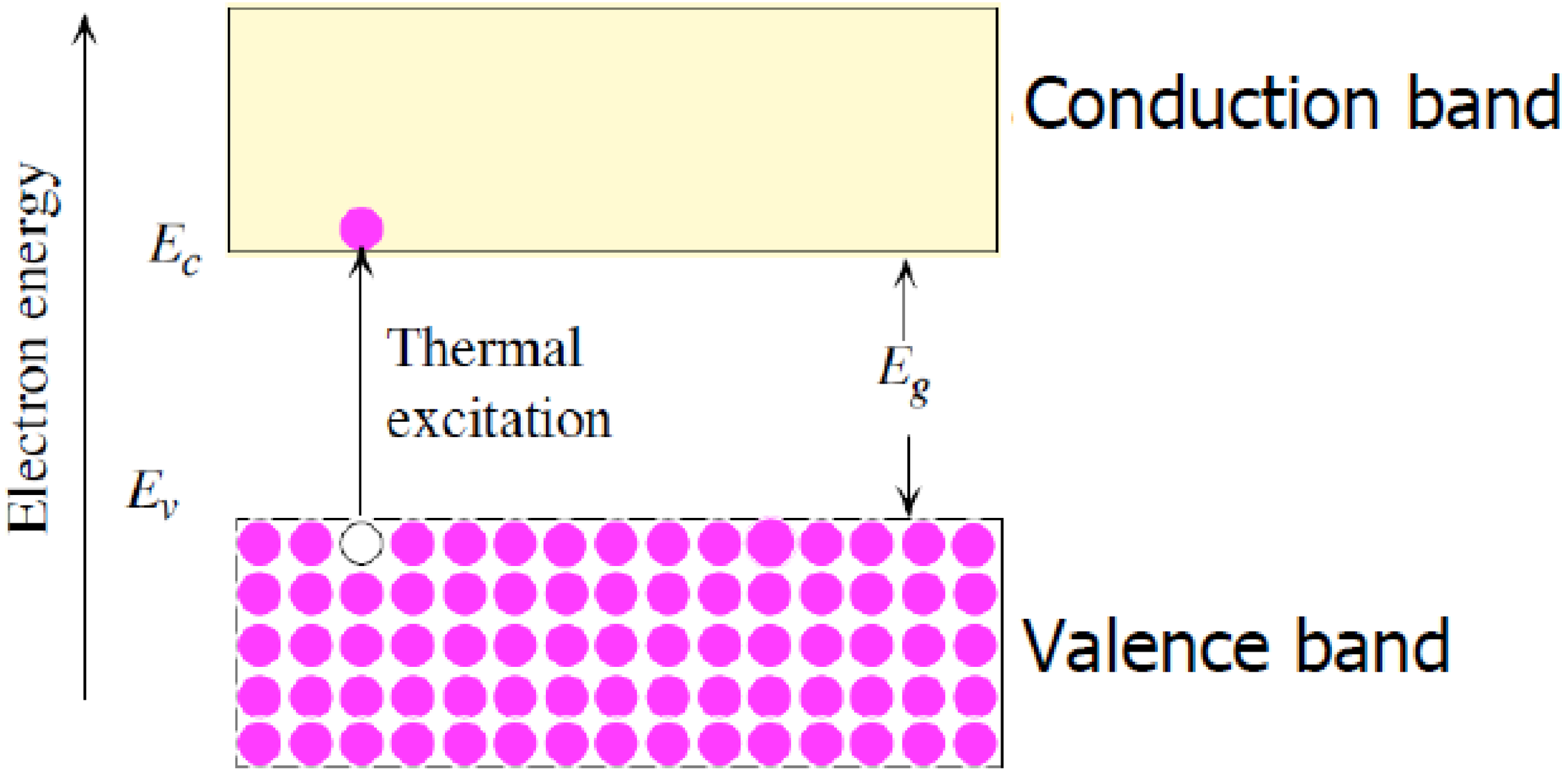


Discrete energy states and quantum states for the same system at T>0K

Why?

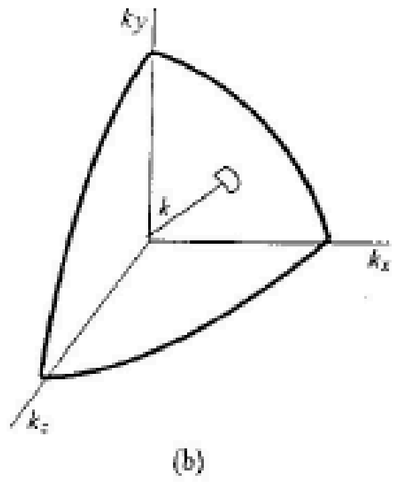
- Current is determined by flow rate and density of charge carriers.
- The density of electron and holes are related to the density of states function and the Fermi distribution (or probability) function.

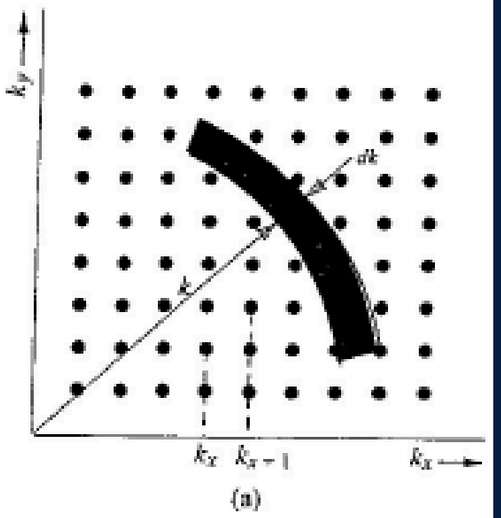



Electron energy
E_c
E_v
Thermal
excitation
E_g
Conduction band
Valence band

Density of states

$$g(E) = \frac{4\pi(2m^*)^{\frac{3}{2}}}{h^3}\sqrt{E}$$





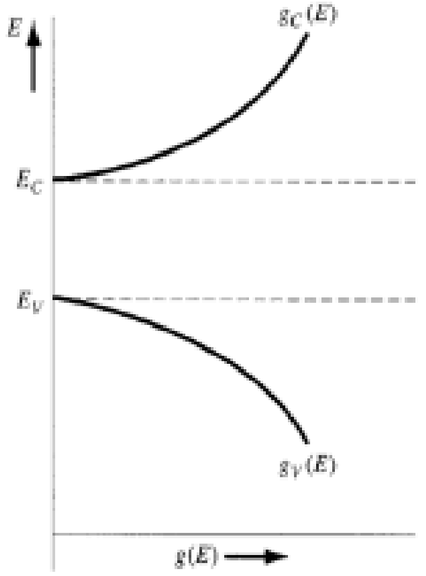
Density of quantum states per unit volume at energy E

For conduction band

$$g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}$$

For valence band

$$g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_v - E}$$



Fermi-Dirac distribution (or probability) function

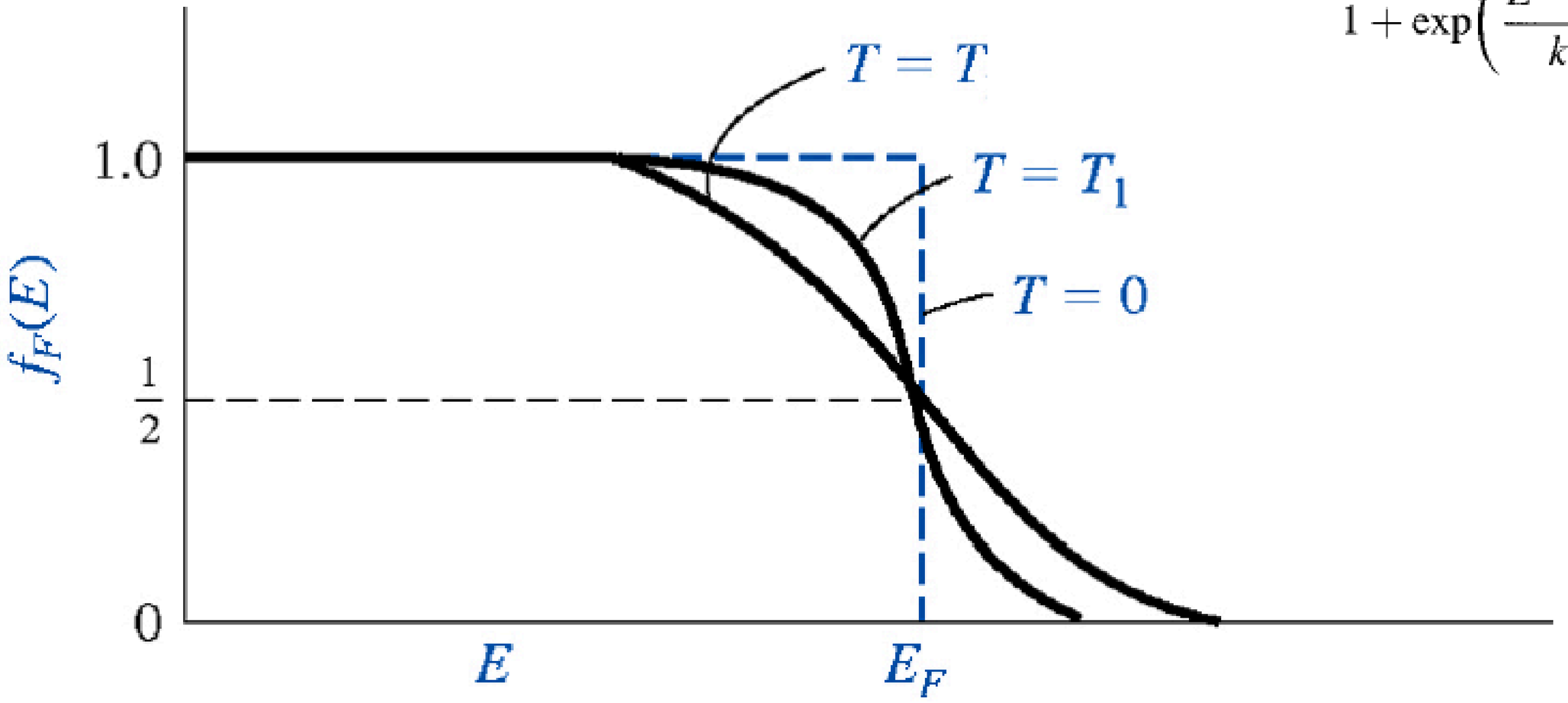
$$\frac{N(E)}{g(E)} = f(E) = \frac{1}{1 + exp\left\{\frac{(E - E_F)}{kT}\right\}}$$

The probability that a quantum state at an energy E will be occupied by an electron

The ratio between filled and total quantum states at any energy E

Fermi-Dirac distribution (or probability) function

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$



Distribution of electron and holes

Number of electrons at E
(in conduction band)

$$n(E) = g_c(E)\, f_F(E)$$

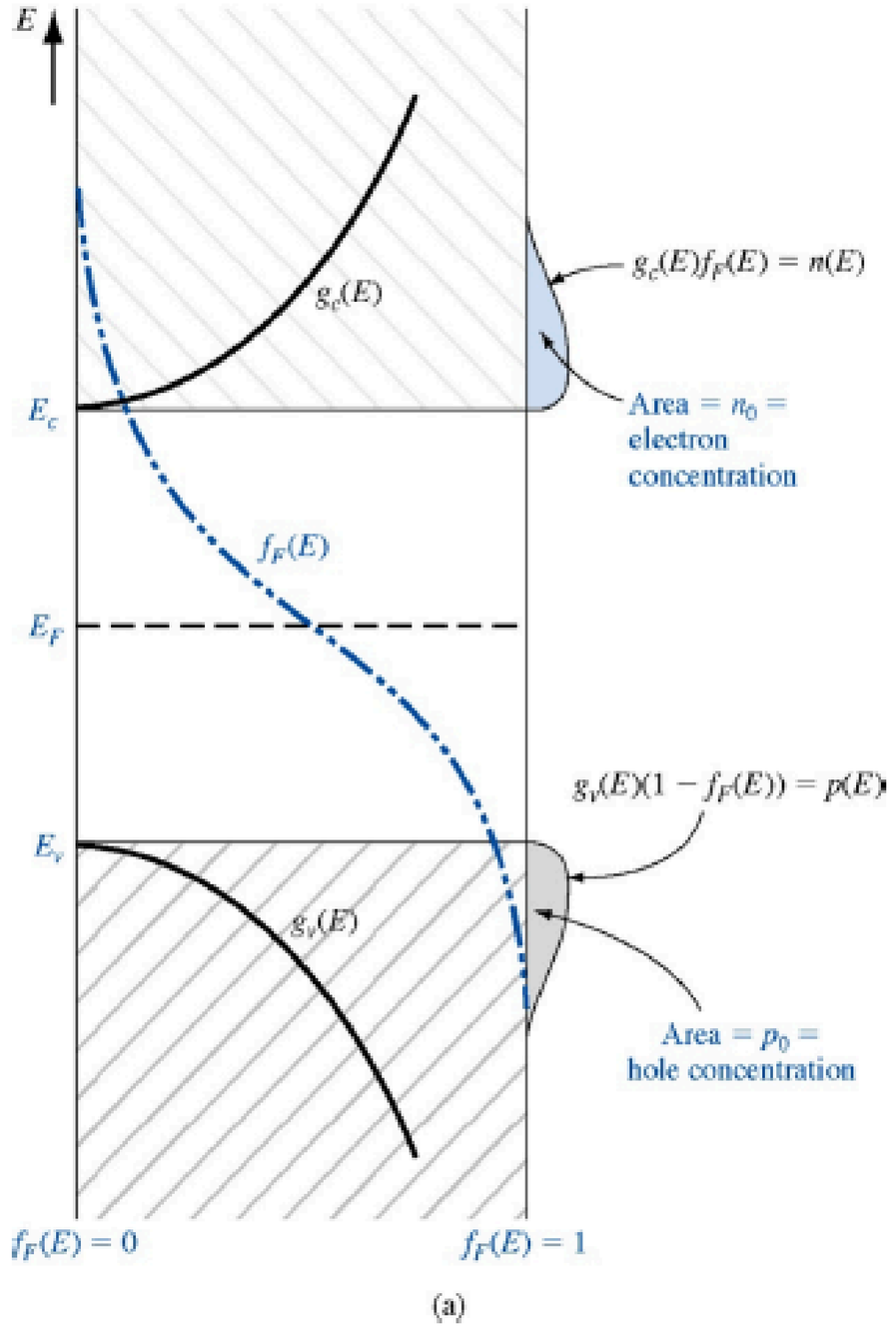
Density of states at E

Fermi-Dirac probability function

Number of holes at E
(in valence band)

$$p(E) = g_v(E)\left[1 - f_F(E)\right]$$

conduction band



(a)

valence band

Electron concentration

$$n_0 = \int_{\text{Bottom of conduction band}}^{\text{Top of conduction band}} \text{Density of states} * \text{Probability function } dE$$

$$n_0 = \int_{E_C}^{\infty} g_c(E) f_F(E)\, dE$$

The equation is valid for both intrinsic and extrinsic semiconductors

$$n_0 = \int g_c(E) f_F(E)\, dE$$

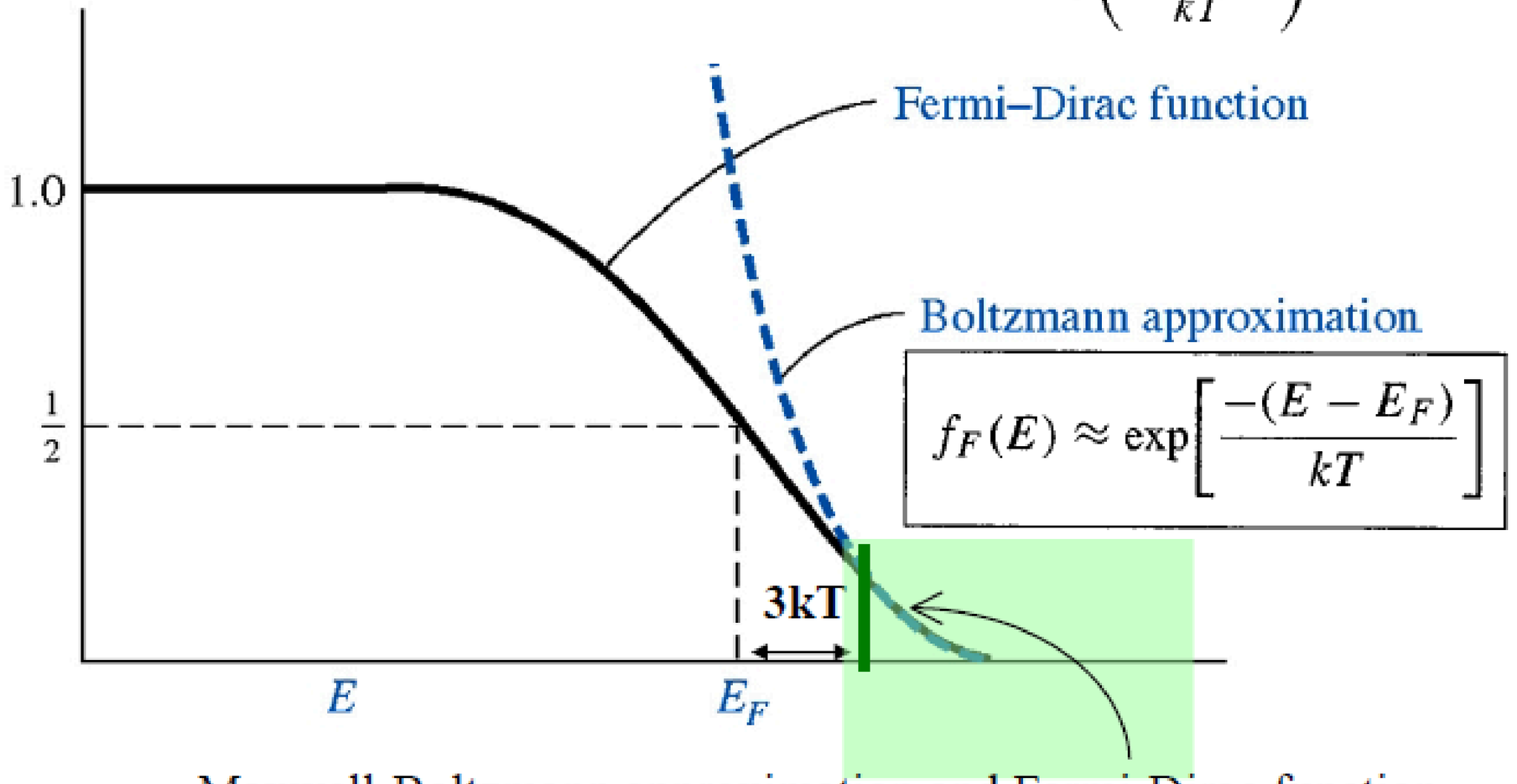
$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

Condition:
$E - E_F >> kT$

$$f_F(E) \approx \exp\left[\frac{-(E - E_F)}{kT}\right]$$

Comparison of Fermi-Dirac probability function and Maxwell-Boltzmann approximation

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$



Maxwell-Boltzmann approximation and Fermi-Dirac function are within 5% of each other when $E\text{-}E_F \geq 3KT$

$$n_0 = \int_{E_c}^{\infty} \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}\exp\left[\frac{-(E - E_F)}{kT}\right] dE$$

$$\eta = \frac{E - E_c}{kT}$$

$$n_0 = \frac{4\pi(2m_n^* kT)^{3/2}}{h^3}\exp\left[\frac{-(E_c - E_F)}{kT}\right]\int_0^{\infty} \eta^{1/2}\exp(-\eta)\, d\eta$$

Gamma function:

$$\frac{1}{2}\sqrt{\pi}$$

$$n_0 = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

N_c= effective density of states function in the conduction band

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

The equation is valid for both intrinsic and extrinsic semiconductors

Hole concentration

$$p_0 = \int g_v(E)[1 - f_F(E)]\, dE$$

$$1 - f_F(E) = \frac{1}{1 + \exp\left(\dfrac{E_F - E}{kT}\right)}$$

$$1 - f_F(E) = \frac{1}{1 + \exp\left(\dfrac{E_F - E}{kT}\right)} \approx \exp\left[\frac{-(E_F - E)}{kT}\right]$$

$$p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E} \exp\left[\frac{-(E_F - E)}{kT}\right] dE$$

$$p_0 = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2} \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

$$N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

N_v= effective density of states function in the valence band

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

Effective density of states function and effective mass values

	$N_c(cm^{-3})$	$N_v(cm^{-3})$	m_n^*/m_0	m_p^*/m_0
Si	2.8×10^{19}	1.04×10^{19}	1.08	0.56
Gallium Arsenide	4.7×10^{17}	7.0×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.0×10^{18}	0.55	0.37

Intrinsic semiconductor

Intrinsic electron concentration = Intrinsic hole concentration

$$n_i = p_i$$

Intrinsic carrier concentration

Why?

- charge carriers due to thermal excitation
- thermally generated electrons and holes always created in pairs.

INTRINSIC Semiconductor

Intrinsic Fermi level

$$n_0 = n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right]$$

$$p_0 = p_i = n_i = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

Intrinsic carrier concentration

$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \cdot \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

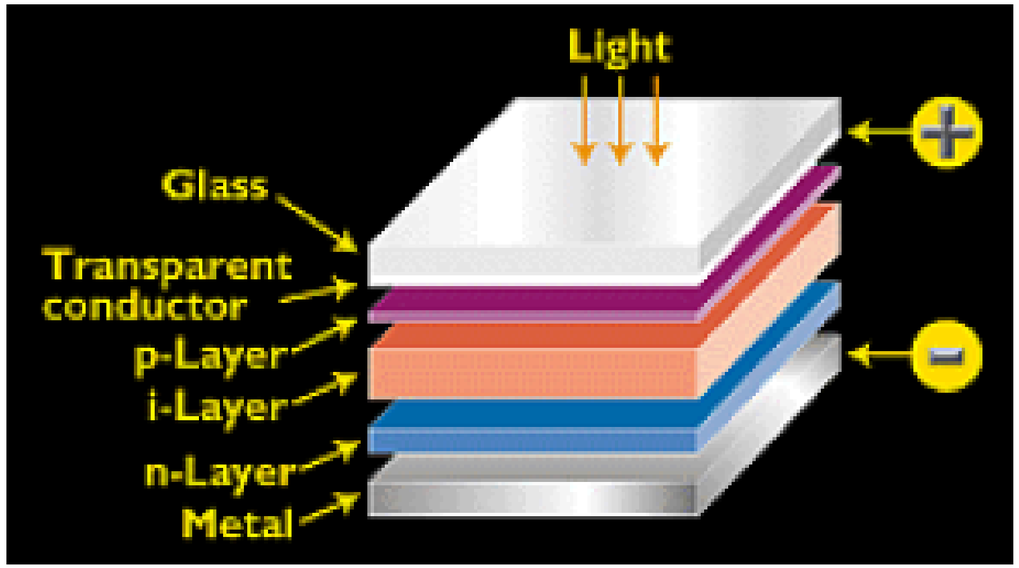
$$n_i^2 = N_c N_v \exp\left[\frac{-(E_c - E_v)}{kT}\right] = N_c N_v \exp\left[\frac{-E_g}{kT}\right]$$

Commonly accepted values of n_i at T=300K

Semiconductor	N_i
Silicon	1.5×10^{10} cm^{-3}
Gallium Arsenide	1.8×10^{6} cm^{-3}
Germanium	2.4×10^{13} cm^{-3}

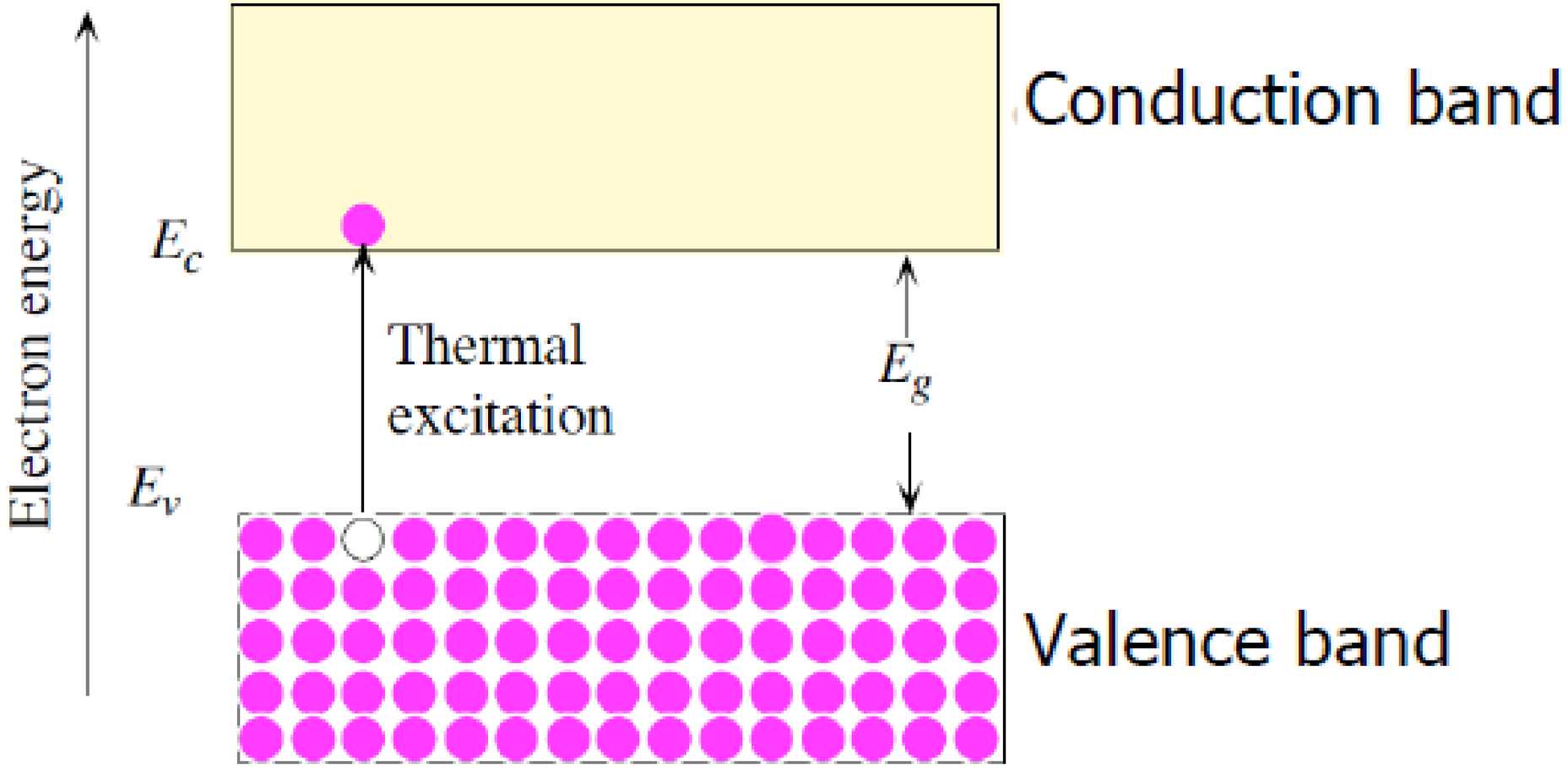
Application of the intrinsic semiconductors

- High Electron Mobility Transistor
- High resistivity substrate for RF circuits
- amorphous-Si Solar Cells



Structure of solar cell

Where is the intrinsic Fermi level?



E_{Fi} (Intrinsic Fermi level): E_F at which electron and hole concentration becomes equal

Electron concentration Hole concentration

$$N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] = N_v \exp\left[\frac{-(E_{Fi} - E_v)}{kT}\right]$$

$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{1}{2} kT \ln\left(\frac{N_v}{N_c}\right)$$

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

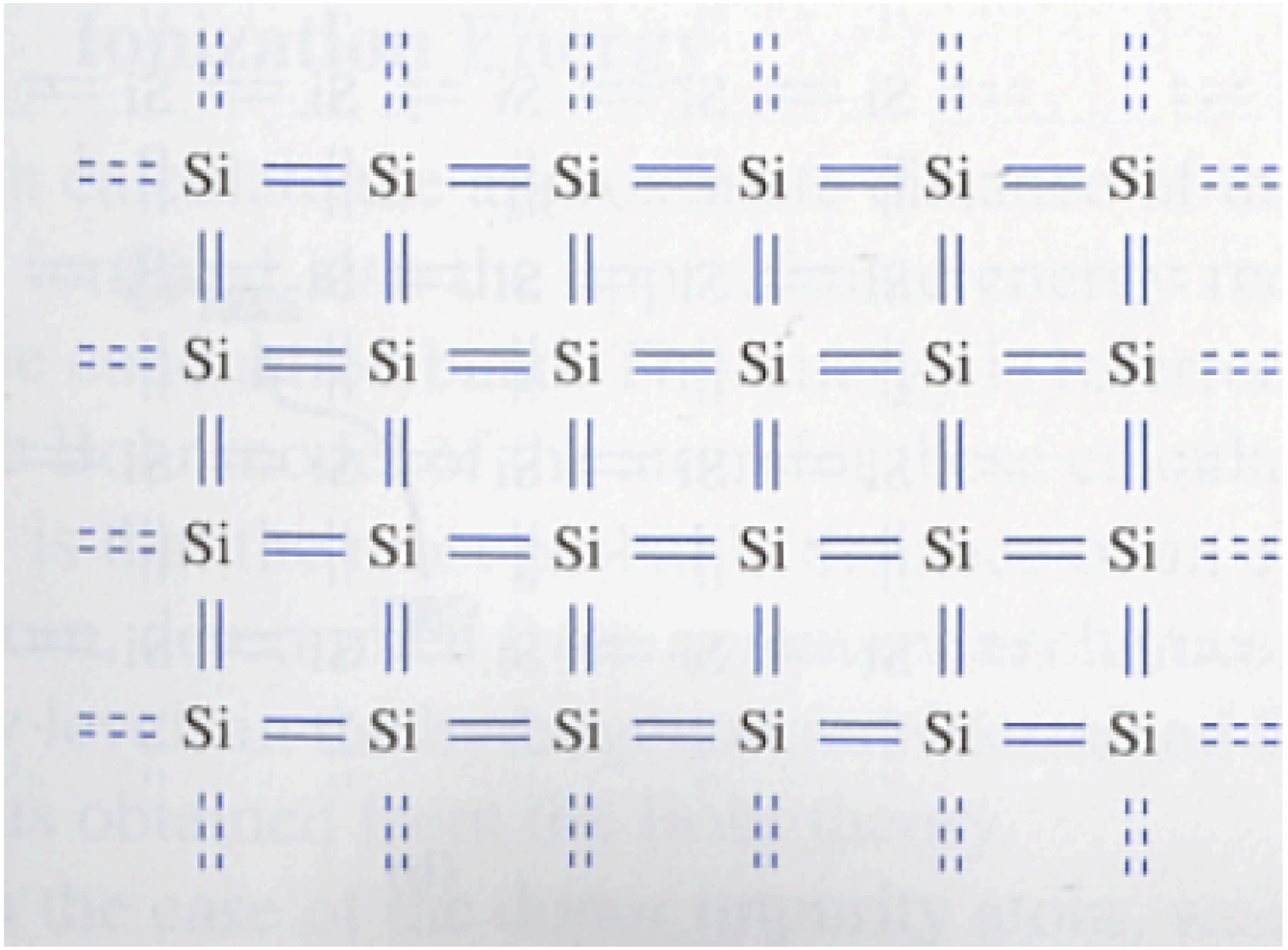
$$E_{Fi} = \frac{1}{2}(E_c + E_v) + \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

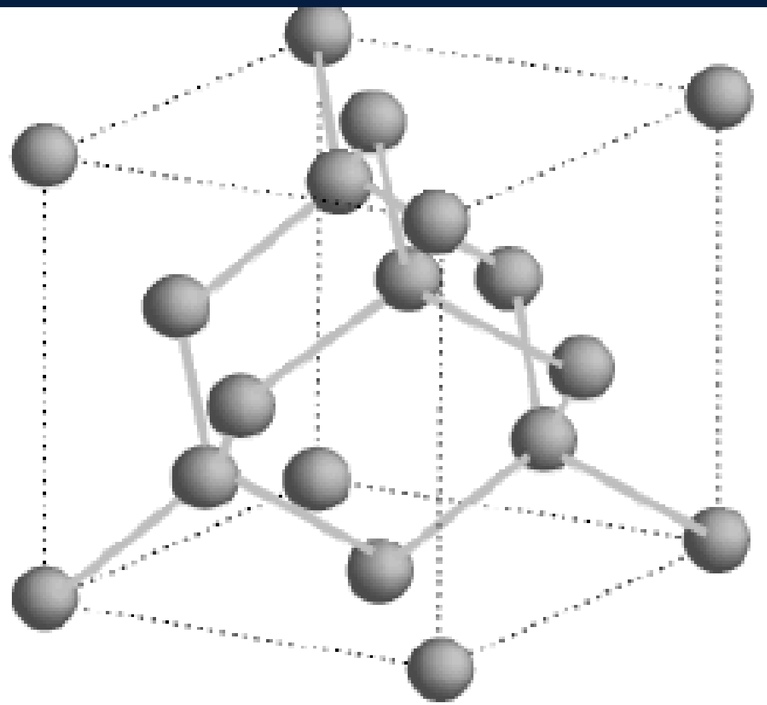
$$\frac{1}{2}(E_c + E_v) = E_{\text{midgap}} \longrightarrow$$

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right)$$

Even in intrinsic semiconductor, Fermi level is not exactly at centre between conduction and valence bands.

The Extrinsic Semiconductor



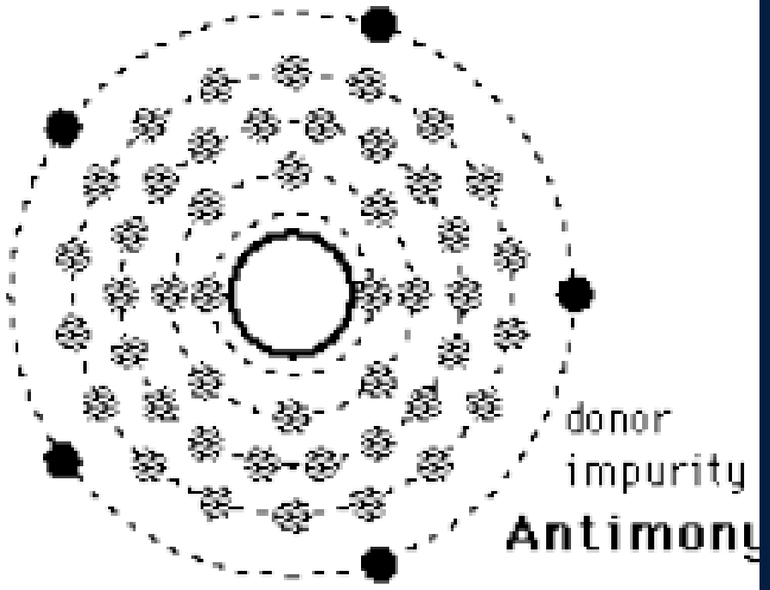


Intrinsic silicon lattice

Acceptor and Donor Impurities:

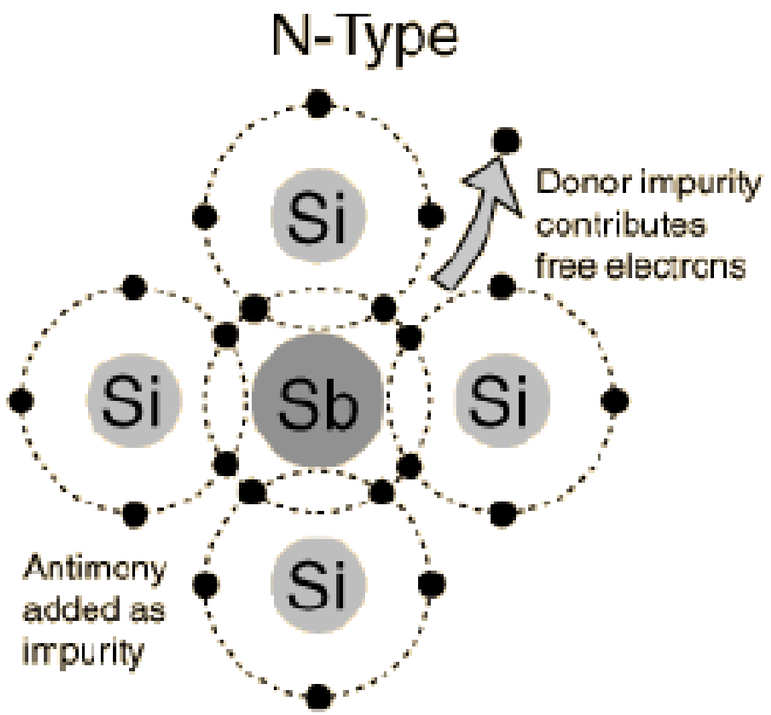
- In Si four electrons in the valence shell participate in bonding.
- atom with more than 4 valence electrons → donor impurity
- less than 4 → acceptor impurity.

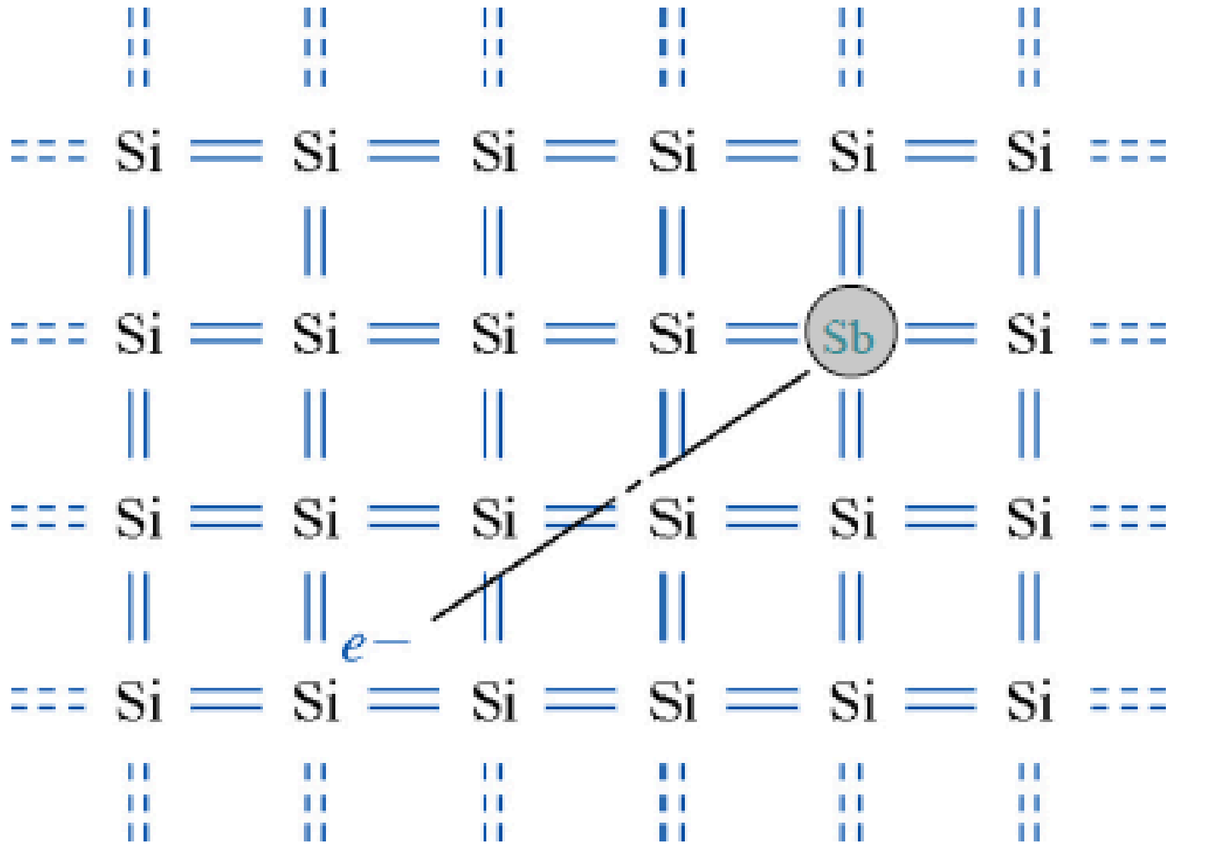
Antimony
Arsenic
Phosphorous



Boron
Aluminum
Gallium

Donor Impurity:

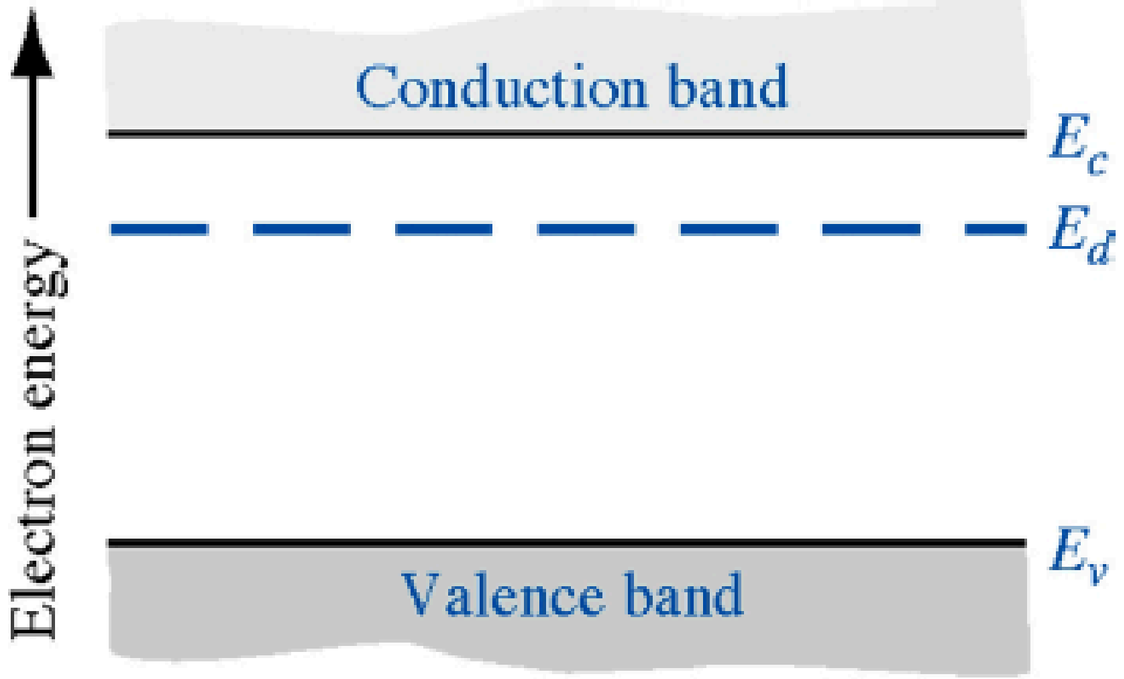




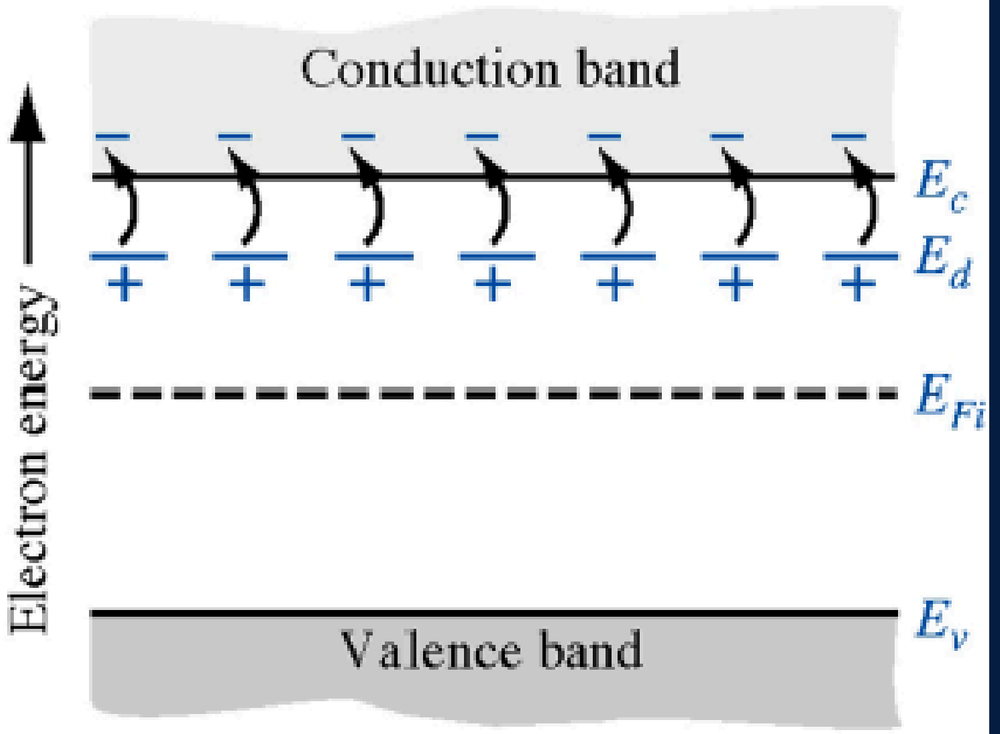
Silicon lattice doped with donor impurity

- At very low temperature, the donor (excess) electron is still bound to the impurity atom.
- However, the donor electron is loosely bound to the impurity atom and can become free with small amount of thermal energy. Impurity atom is then ionized and positively charged.

Donor electron energy level:



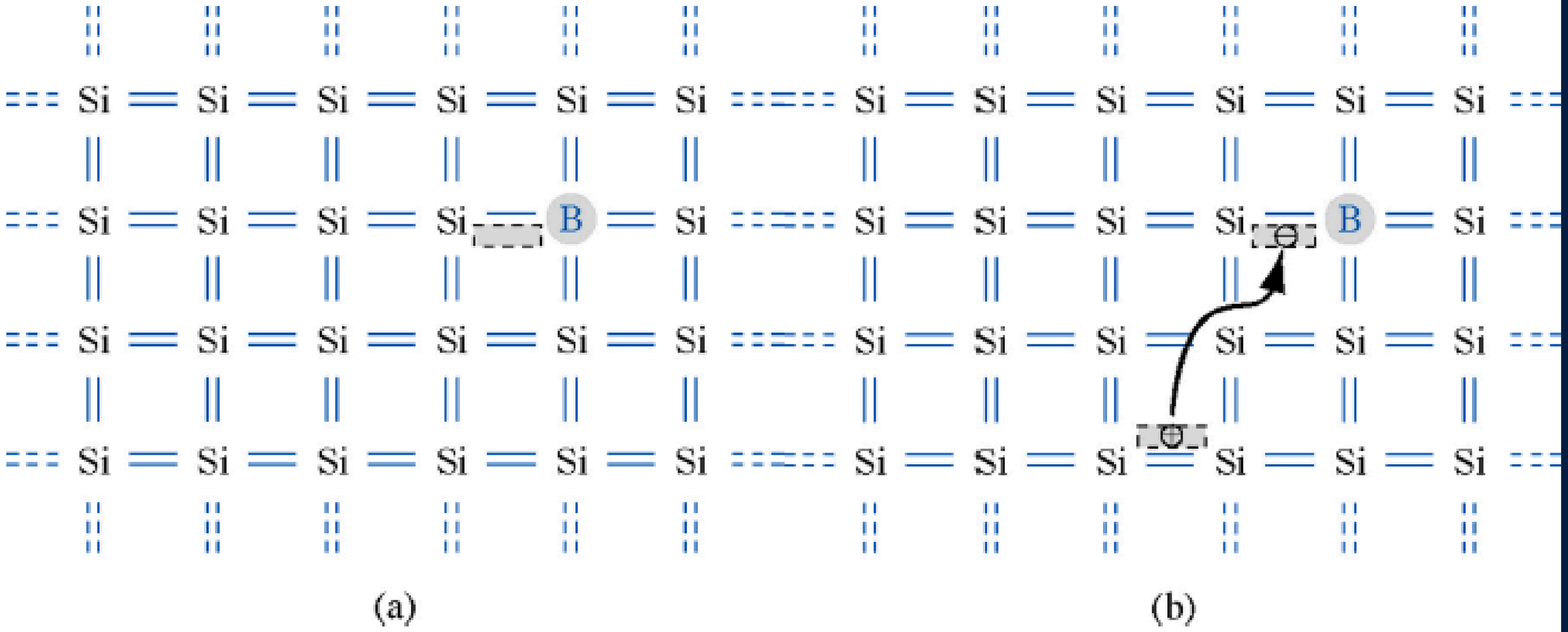
(a)



(a)

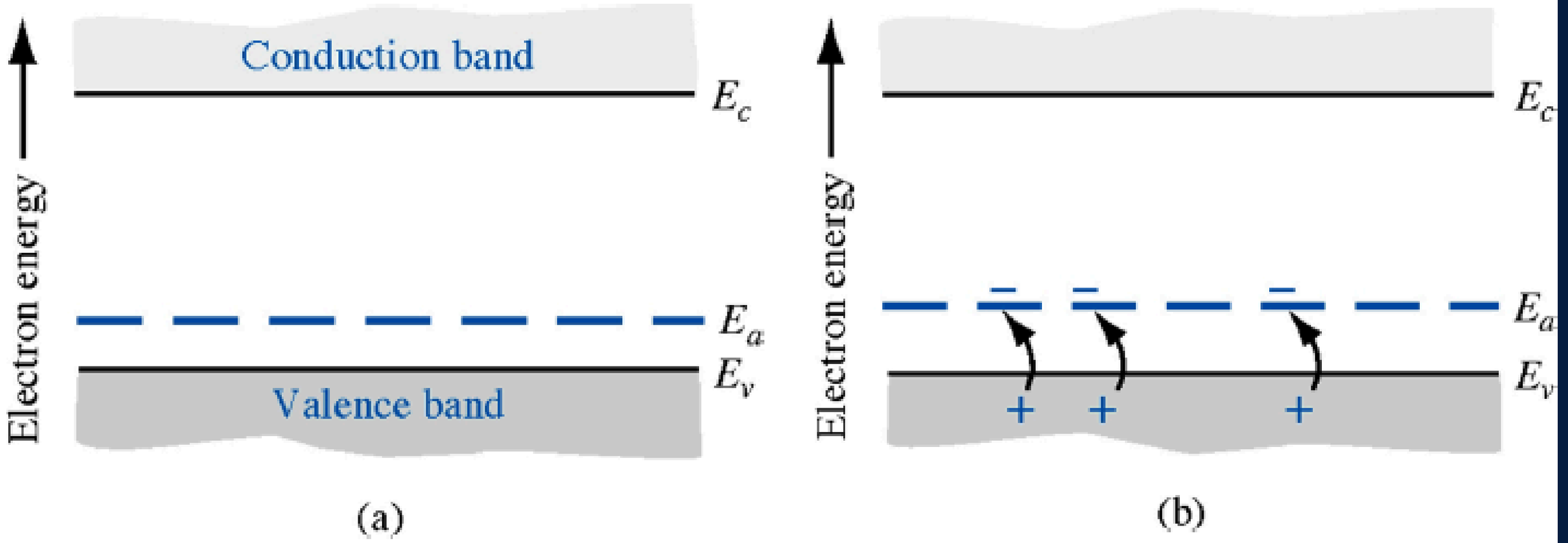
- little energy required to move donor electrons from donor states to conduction band.
- positively charged donor ions are fixed but donor electrons in the conduction band can move through the crystal.

Acceptor Impurity:



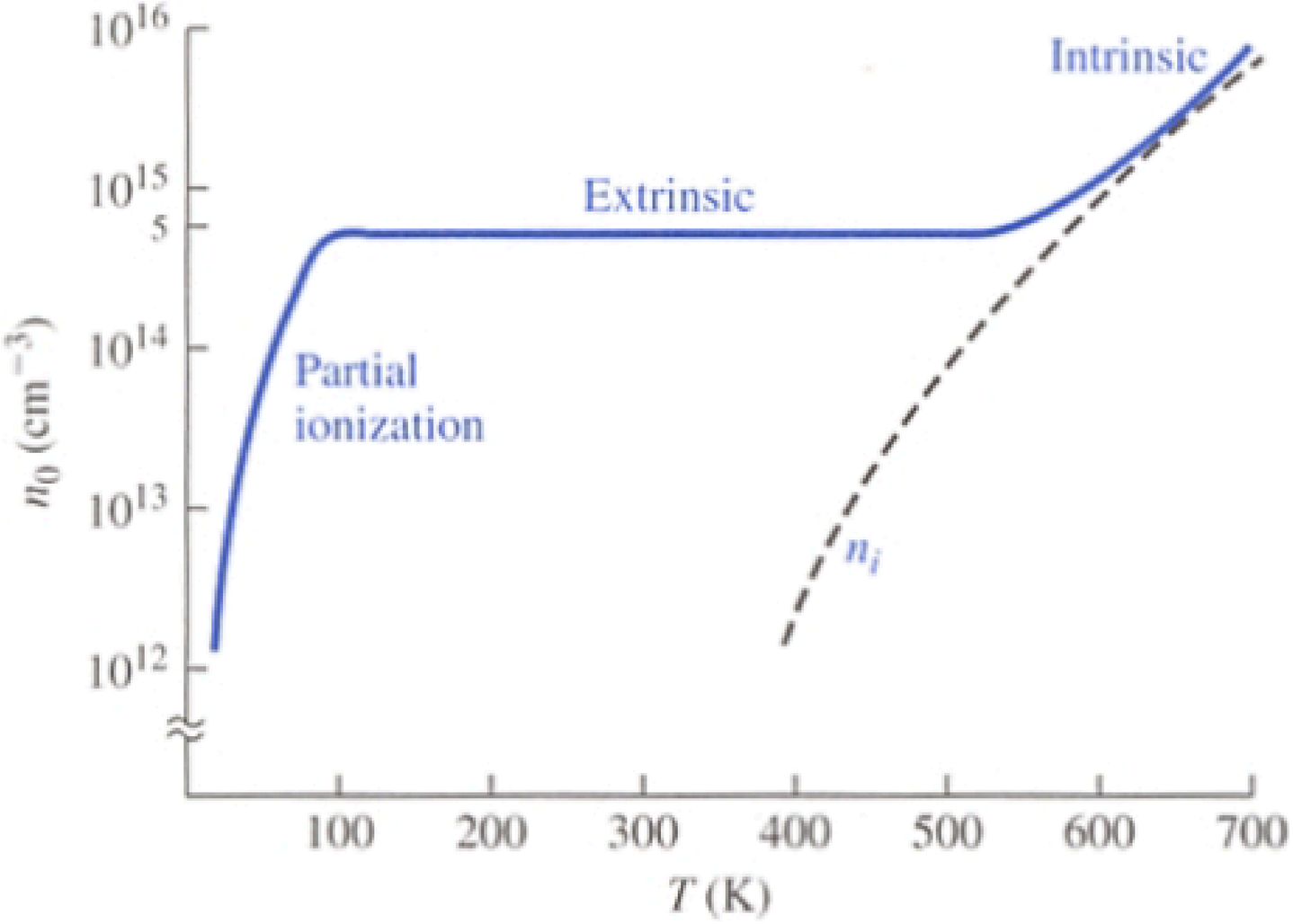
- One covalent bond is incomplete for Si.
- With little thermal energy, a valence electron can break from another covalent bond and can occupy this position, thus creating a hole at the location of the broken covalent bond.
- The acceptor impurity is then ionized and negatively charged.

Acceptor Energy Level:



- little energy required to move valence electrons to acceptor levels.
- negatively charged acceptor ions are fixed but holes in the valence band can move through the crystal.

Electron concentration vs. temperature in n-type semiconductor



Electron concentration vs. temperature showing partial ionization, extrinsic and intrinsic regions.

Electron concentration vs. temperature in extrinsic semiconductor

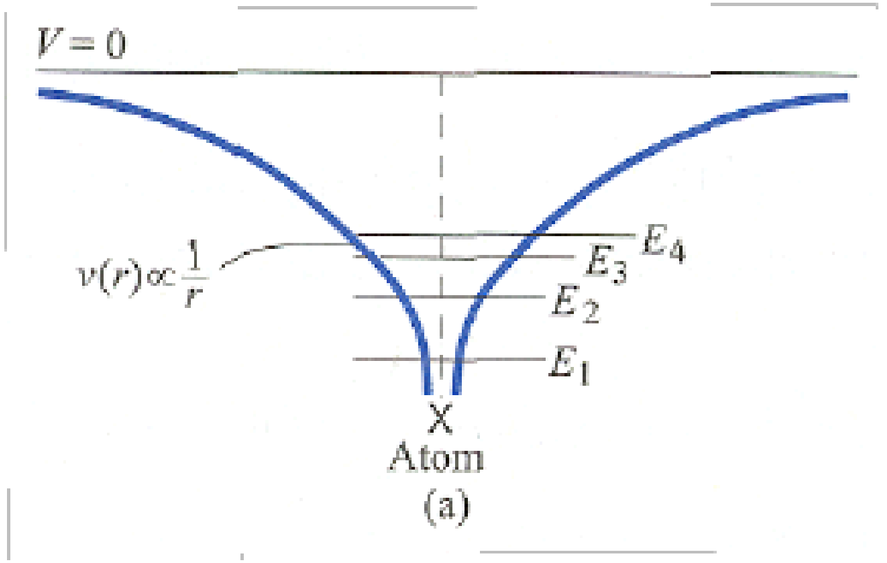
- At low temperatures, donor impurities are partially ionized. As temperature increases the percentage of ionized donor impurities also increases

- Once all donor impurities are ionized, there is no increase in carrier concentration. Even though intrinsic carrier concentration continues to increase, it is still small compared to extrinsic concentration.

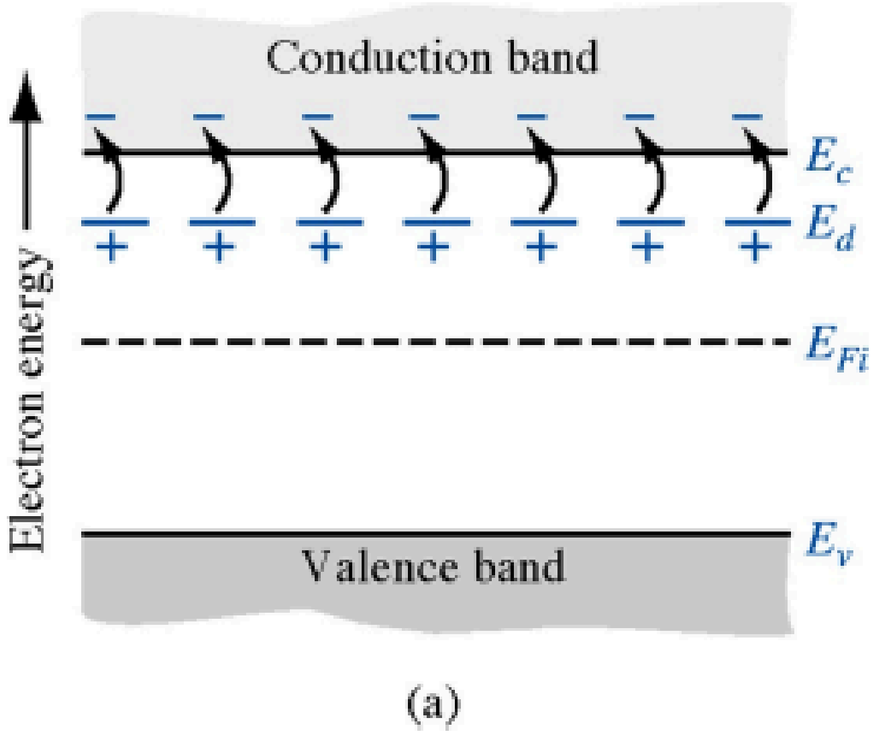
- At high temperatures, intrinsic carrier concentration dominates and electron concentration continues to increase again.

Ionization energy:

The ionization energy is the energy necessary to remove an electron from the neutral atom.



In case of donor atoms, the ionization energy is the energy necessary to elevate an electron from the donor level to conduction band.



Ionization energy:

- In the next few slides, we will calculate the approximate ionization energy for donor atoms.

- We use Bohr atomic model for these calculations. For hydrogen atom, Bohr model and quantum mechanics give similar results.

- Donor impurity atom can be visualized as one donor electron orbiting the positively charged donor ion. This condition is similar to that in a hydrogen atom.

- However we have to consider permittivity of silicon instead of permittivity of free space.

Angular Momentum Quantization

Bohr proposed that circumference of electron orbit = integer number of wavelengths → $2\pi r = n\lambda_n$

Then angular momentum, $$L = mvr = \frac{hr}{\lambda} = \frac{hr}{\left[\frac{2\pi r}{n}\right]} = \frac{nh}{2\pi}$$

angular momentum of electron is quantized.

Ionization energy calculation:

Coulomb attraction force Centripetal force

$$\frac{e^2}{4\pi\epsilon r_n^2} = \frac{m^* v^2}{r_n}$$

Angular momentum quantization $\Longrightarrow$ $m^* r_n v = n\hbar$

$$r_n = \frac{n^2\hbar^2 4\pi\epsilon}{m^* e^2}$$

As defined in Chapter 2,

Bohr radius = $a_0 = \dfrac{4\pi\epsilon_0\hbar^2}{m_0 e^2} = 0.53\ \text{Å}$

$$\frac{\text{orbiting electron radius}}{\text{Bohr radius}} = \frac{r_n}{a_0} = n^2\epsilon_r\left(\frac{m_0}{m^*}\right)$$

For silicon,

$\varepsilon_r = 11.7$ and $\dfrac{m^*}{m_0} = 0.26$

For n=1, $\dfrac{r_1}{a_0} = 45$

- $r_1/a_0=45$ or $r_1=23.9A^0$
- This radius ~ 4 lattice constants of Si.
- Each unit cell contains 8 silicon atoms.
- Donor electron thus loosely bound to the donor atom.
- We will next find the approximate ionization energy.

Total energy $E = T + V$

Kinetic energy

Potential energy

$$T = \frac{1}{2} m^* v^2 \longrightarrow T = \frac{m^* e^4}{2(n\hbar)^2 (4\pi\epsilon)^2}$$ (refer slide 37)

$$V = \frac{-e^2}{4\pi\epsilon r_n} = \frac{-m^* e^4}{(n\hbar)^2 (4\pi\epsilon)^2}$$

$$E = T + V = \frac{-m^* e^4}{2(n\hbar)^2 (4\pi\epsilon)^2}$$

- Ionisation energy of Hydrogen in lowest energy state = -13.6eV
- For Si, it is -25.8meV << band gap.
- Calculations using Bohr model give only the order of magnitude of the ionisation energy. Actual values differ.

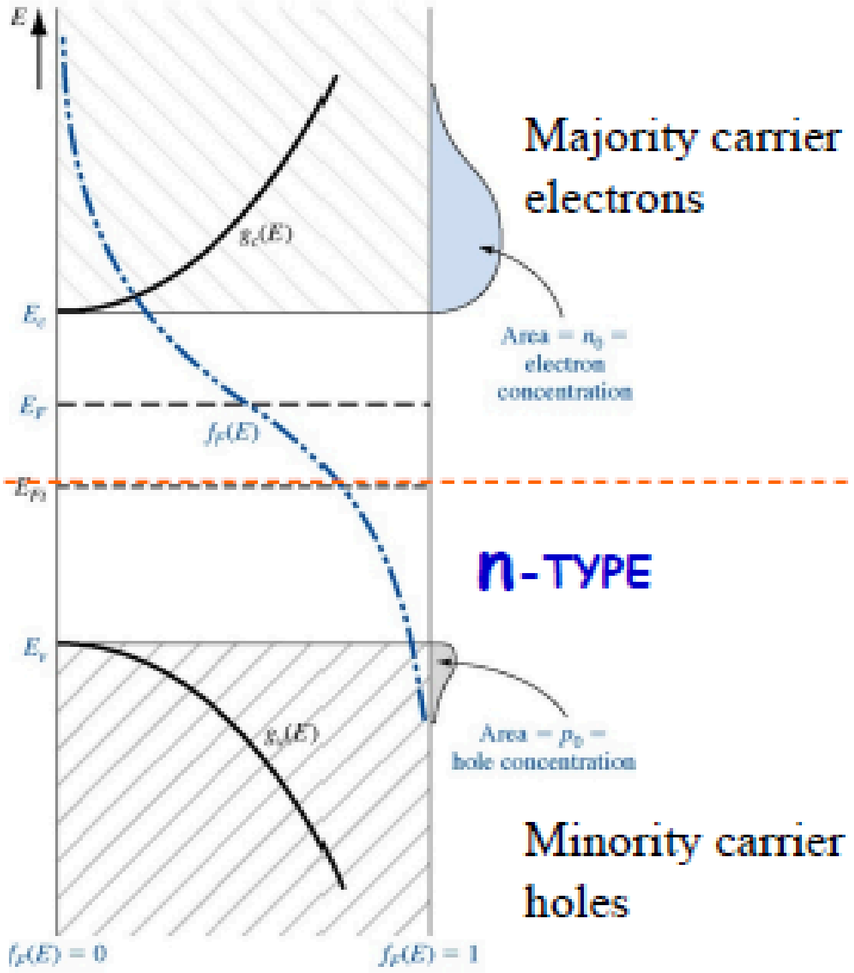
Impurity ionization energies in Silicon and Germanium

Impurity	Ionization energy (eV)	
	Si	Ge
Donors		
Phosphorus	0.045	0.012
Arsenic	0.05	0.0127
Acceptors		
Boron	0.045	0.0104
Aluminum	0.06	0.0102

Impurity ionization energies in gallium arsenide

Impurity	Ionization energy (eV)
Donors	
Selenium	0.0059
Tellurium	0.0058
Silicon	0.0058
Germanium	0.0061
Acceptors	
Beryllium	0.028
Zinc	0.0307
Cadmium	0.0347
Silicon	0.0345
Germanium	0.0404

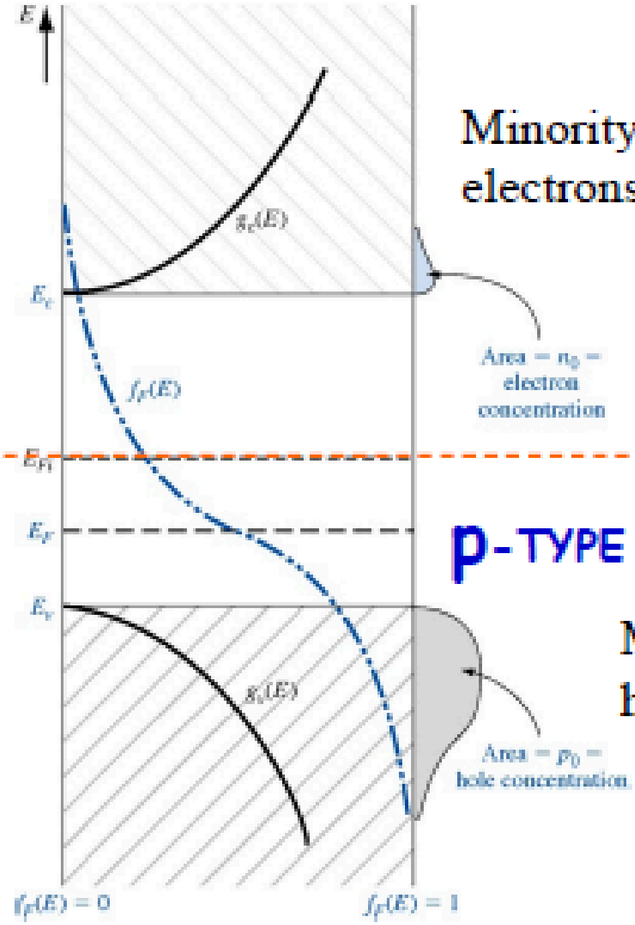
EXTRINSIC Semiconductor



Majority carrier electrons

n-TYPE

Minority carrier holes



Minority carrier electrons

p-TYPE

Majority carrier holes

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

The equation is valid for both intrinsic and extrinsic semiconductors

Another form (relation between E_F and E_{Fi})

Intrinsic carrier concentration

$$n_0 = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right] \exp\left[\frac{(E_F - E_{Fi})}{kT}\right]$$

$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$p_0 = n_i \exp\left[\frac{-(E_F - E_{Fi})}{kT}\right]$$

$$n_0 p_0 = n_i^2$$

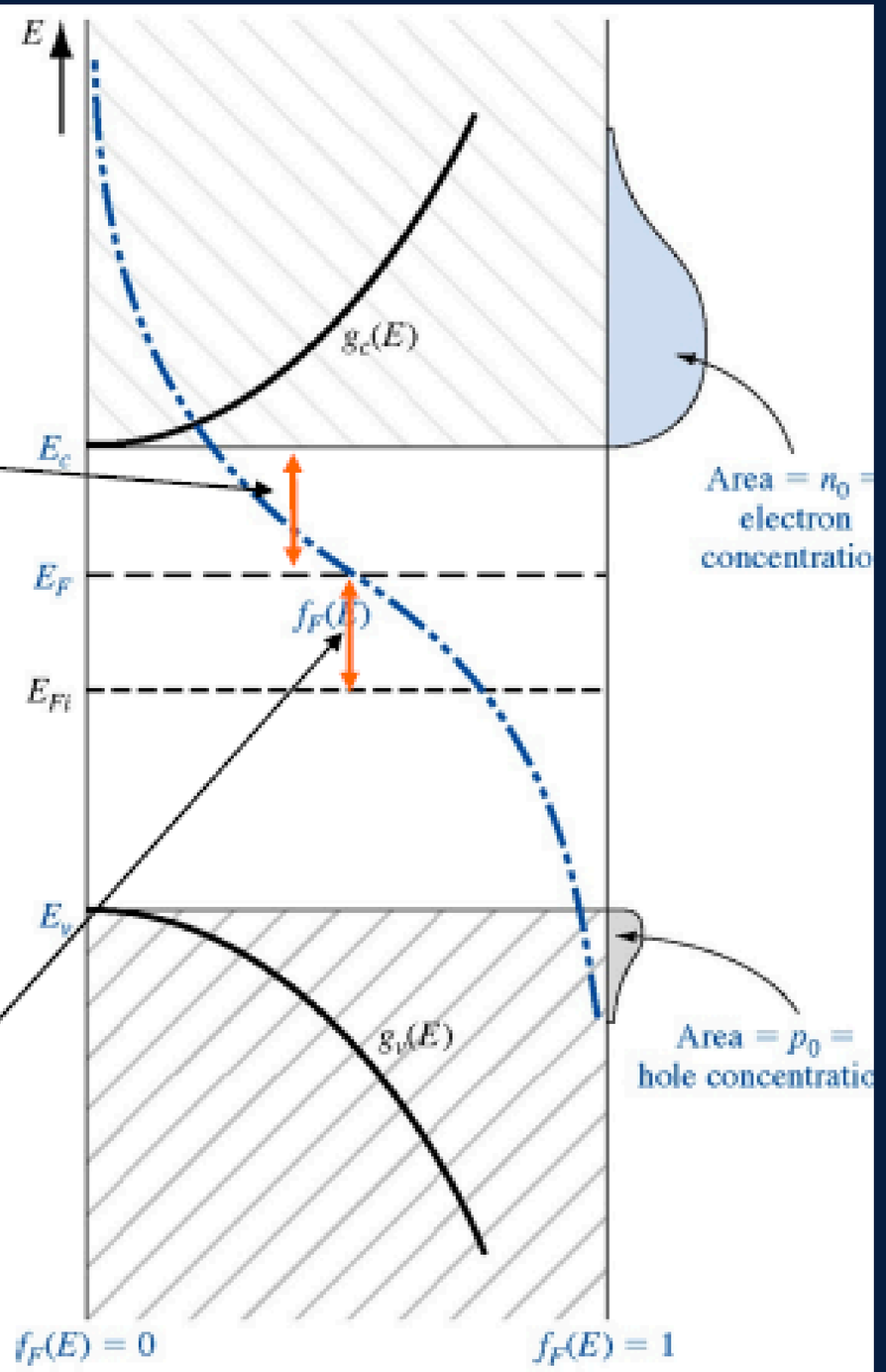
Where is the Fermi level?

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)$$

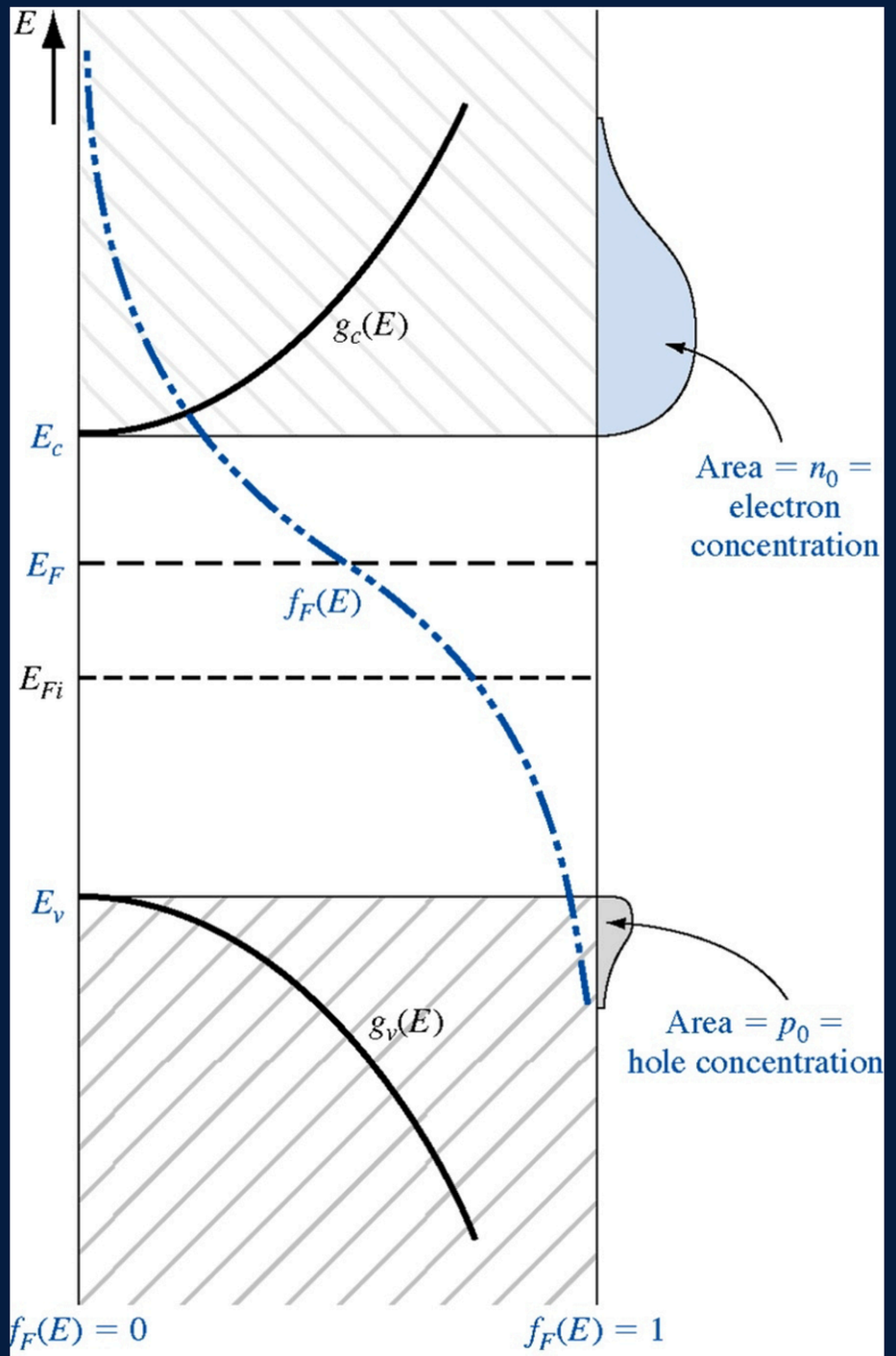
$$n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$$

$$E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right)$$



Condition for the Boltzmann approximation

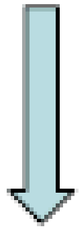
EC-EF > 3KT



If the impurity concentration is very high....

Fermi level will be very close to conduction band or valence band.

No Boltzmann approximation



Use The Fermi-Dirac Integral

$$f_F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

Boltzman approximation

$$f_F(E) \approx \exp\left[\frac{-(E - E_F)}{kT}\right]$$

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

Only if E_C-E_F > 3KT

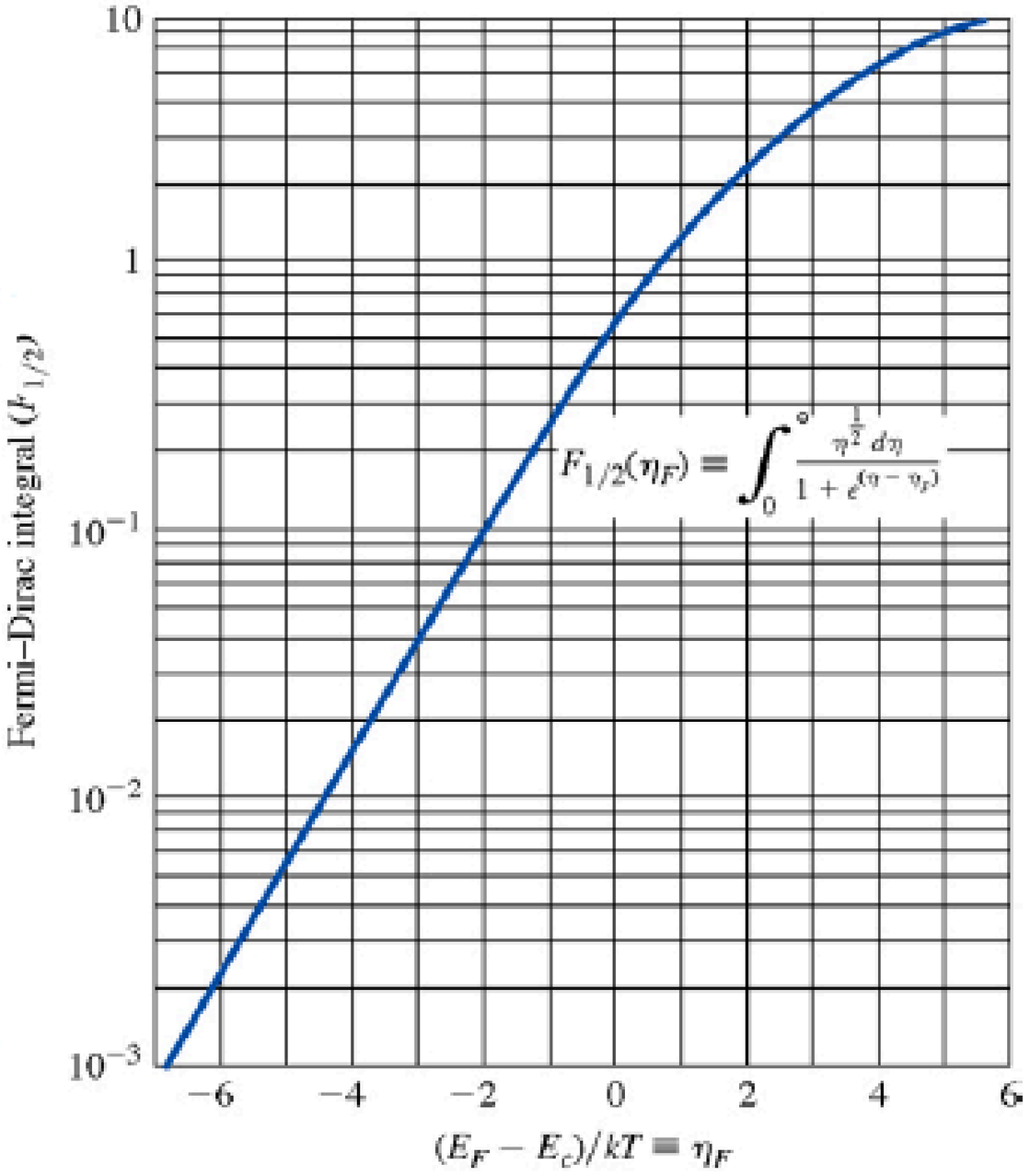
Fermi-Dirac Integral

$$n_0 = \frac{4\pi}{h^3}(2m_n^*)^{3/2}\int_{E_c}^{\infty}\frac{(E-E_c)^{1/2}\,dE}{1+\exp\left(\frac{E-E_F}{kT}\right)}$$

$$\eta = \frac{E-E_c}{kT} \qquad \eta_F = \frac{E_F-E_c}{kT}$$

$$n_0 = 4\pi\left(\frac{2m_n^*kT}{h^2}\right)^{3/2}\int_0^{\infty}\frac{\eta^{1/2}\,d\eta}{1+\exp(\eta-\eta_F)}$$

$$F_{1/2}(\eta_F) = \int_0^{\infty}\frac{\eta^{1/2}\,d\eta}{1+\exp(\eta-\eta_F)}$$



If $\eta_F > 1$, then $E_F > E_C$

Degenerate Semiconductors

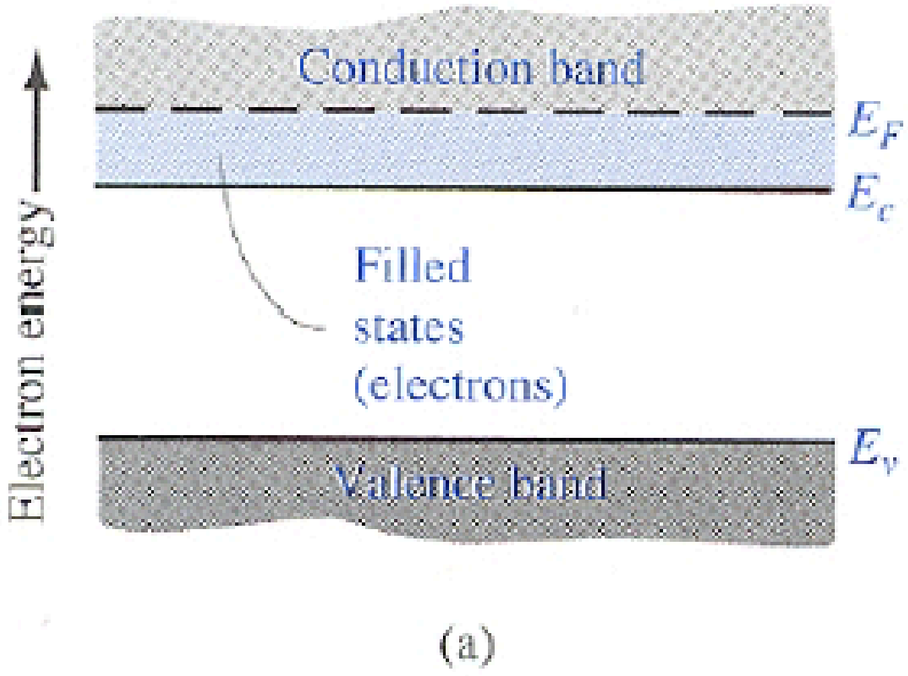
If the impurity atoms are very close each other…

- Donor electrons interact with each other
- The single discrete donor energy will split into a band
- The band may overlap the conduction band
- If the concentration exceed N_c, E_F lies within the conduction band

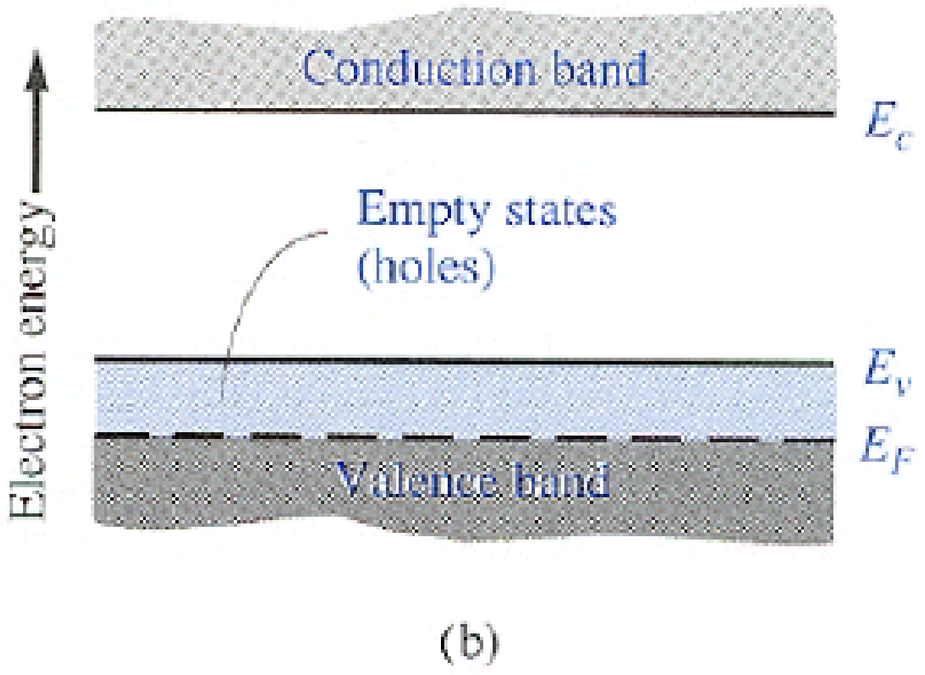
Degenerated Semiconductor

$N_d > N_c$

$N_a > N_v$



(a)



(b)

Fermi level in the conduction band: Metallic conduction

Statistics of donors and acceptors

How many electrons still in the donor levels compared to the total number of electrons? depends on the temperature and the Fermi level....

Probability function for donor & acceptor levels

Density of electrons occupying donor states / Density of donor atoms

$$\frac{n_d}{N_d} = \frac{1}{1 + \frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)}$$

This same as the Fermi-Dirac probability function except the pre-exponential coefficient of ½.

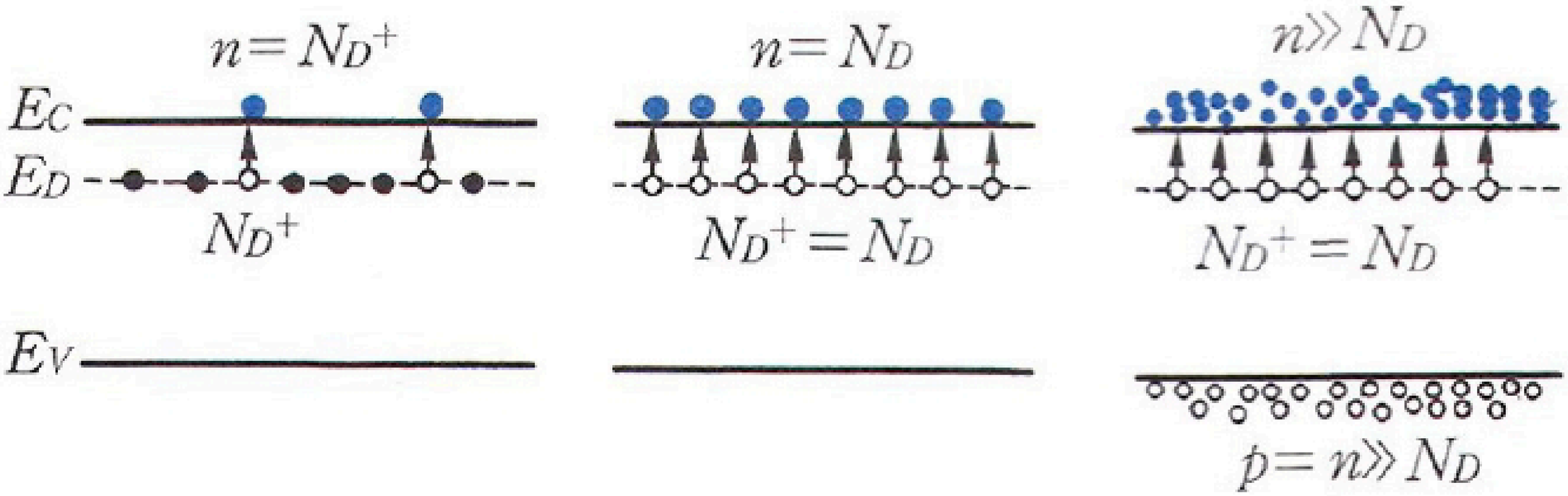
$$n_d = N_d - N_d^+$$

N_d^+: Concentration of ionized donors

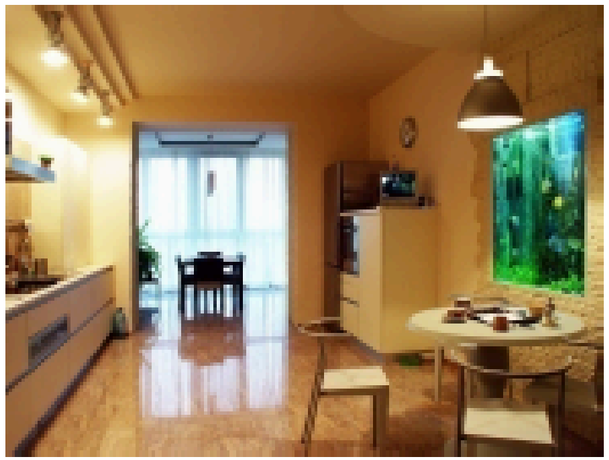
similar for holes:

$$p_a = \frac{N_a}{1 + \frac{1}{g}\exp\left(\frac{E_F - E_a}{kT}\right)} = N_a - N_a^-$$

g=degeneration factor; 4 for GaAs and Si acceptor levels



Low temperature



Moderate temperature

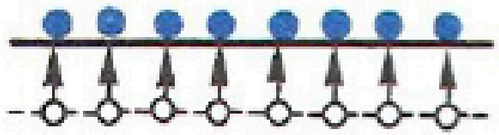
High temperature

Moderate temperature

$E_d - E_F >> kT$

$$\frac{n_d}{N_d} = \frac{1}{1 + \frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)}$$

$n = N_D$



$N_D^+ = N_D$

$$n_d \approx \frac{N_d}{\frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)} = 2N_d \exp\left[\frac{-(E_d - E_F)}{kT}\right]$$

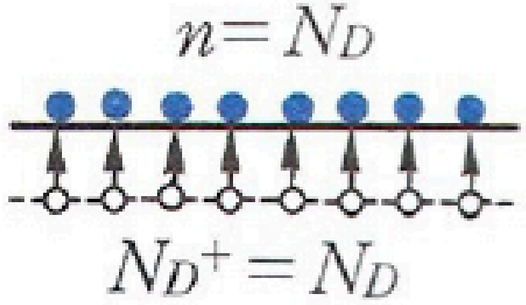
If $E_d - E_F >> kT$, then even $E_c - E_F >> KT$

Then, $n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$

Fraction of electrons still in the donor states

$$\frac{n_d}{n_d + n_0} = \frac{2N_d \exp\left[\frac{-(E_d - E_F)}{kT}\right]}{2N_d \exp\left[\frac{-(E_d - E_F)}{kT}\right] + N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]}$$

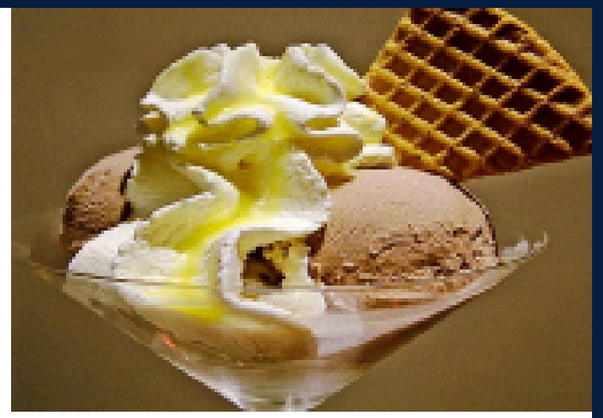
$$\frac{n_d}{n_d + n_0} = \frac{1}{1 + \frac{N_c}{2N_d} \exp\left[\frac{-(E_c - E_d)}{kT}\right]}$$



With Phosphorus doping of $N_d = 10^{16} cm^{-3}$, at T=300K, $n_d/(n_d+n_0) = 0.41\%$

Almost complete ionization at Room Temp!

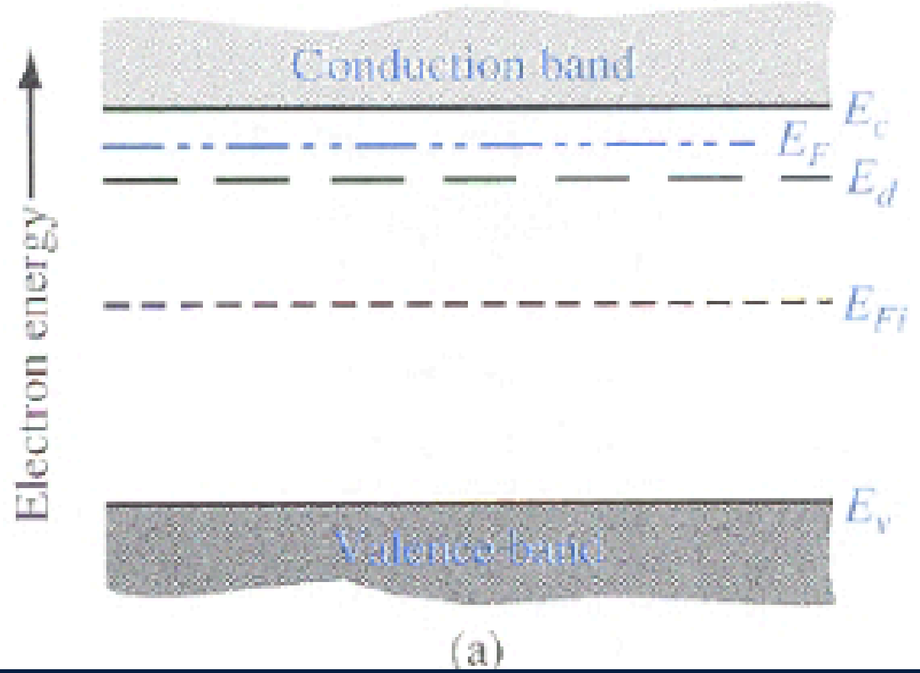
Extremely low temperature (T=0K)



$n_d = N_d$ **Freeze-out**

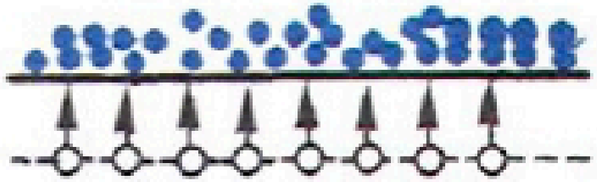
$$n_d = \frac{N_d}{1 + \frac{1}{2}\exp\left(\frac{E_d - E_F}{kT}\right)}$$

$E_F > E_d$



High temperature

$n \gg N_D$ (because of thermally generated electrons)

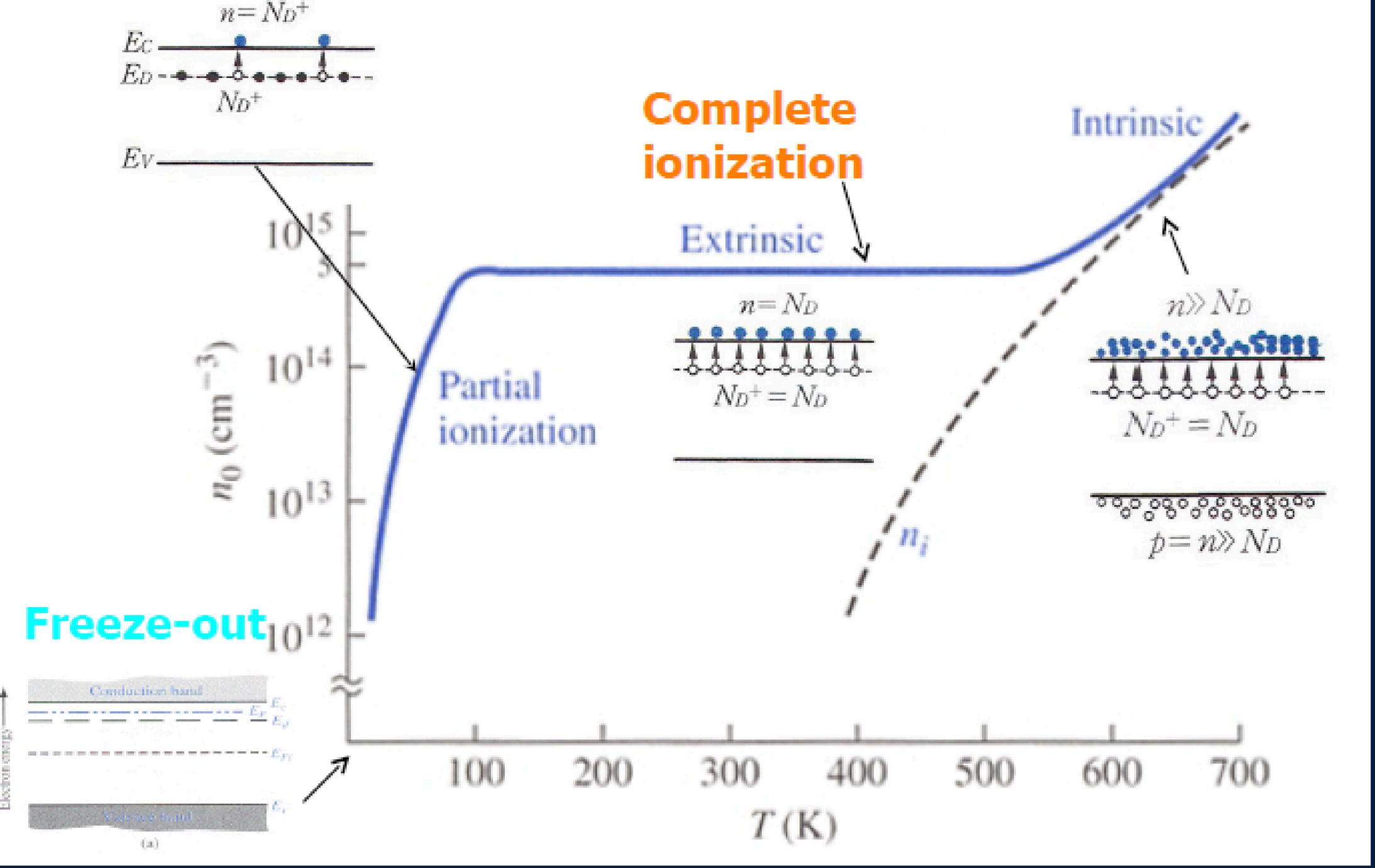


$N_D^+ = N_D$

$$n_0 = n_i = N_c \exp\left[\frac{-(E_c - E_{Fi})}{kT}\right]$$

$p = n \gg N_D$ (because of thermally generated holes)

- At very high temperature behavior is just like the intrinsic semiconductor


$n = N_D^+$
E_C
E_D
N_D^+
E_V
Complete ionization
Intrinsic
Extrinsic
$n = N_D$
$N_D^+ = N_D$
$n \gg N_D$
$N_D^+ = N_D$
$p = n \gg N_D$
Partial ionization
n_i
n_0 (cm^{-3})
10^{15}
10^{14}
10^{13}
10^{12}
Freeze-out
100
200
300
400
500
600
700
T (K)

Compensated semiconductor

- Both donor and acceptor impurities in the same region
- If $N_d > N_a \rightarrow$ n-type compensated semiconductor
- If $N_d < N_a \rightarrow$ p-type compensated semiconductor
- If $N_d = N_a \rightarrow$ completely compensated (will behave like intrinsic material)
- Practical semiconductor is always compensated semiconductor.

Eg. Substrate is predoped usually p-type. All other dopings are done on to of this.

Charge neutrality :

Ionized acceptors

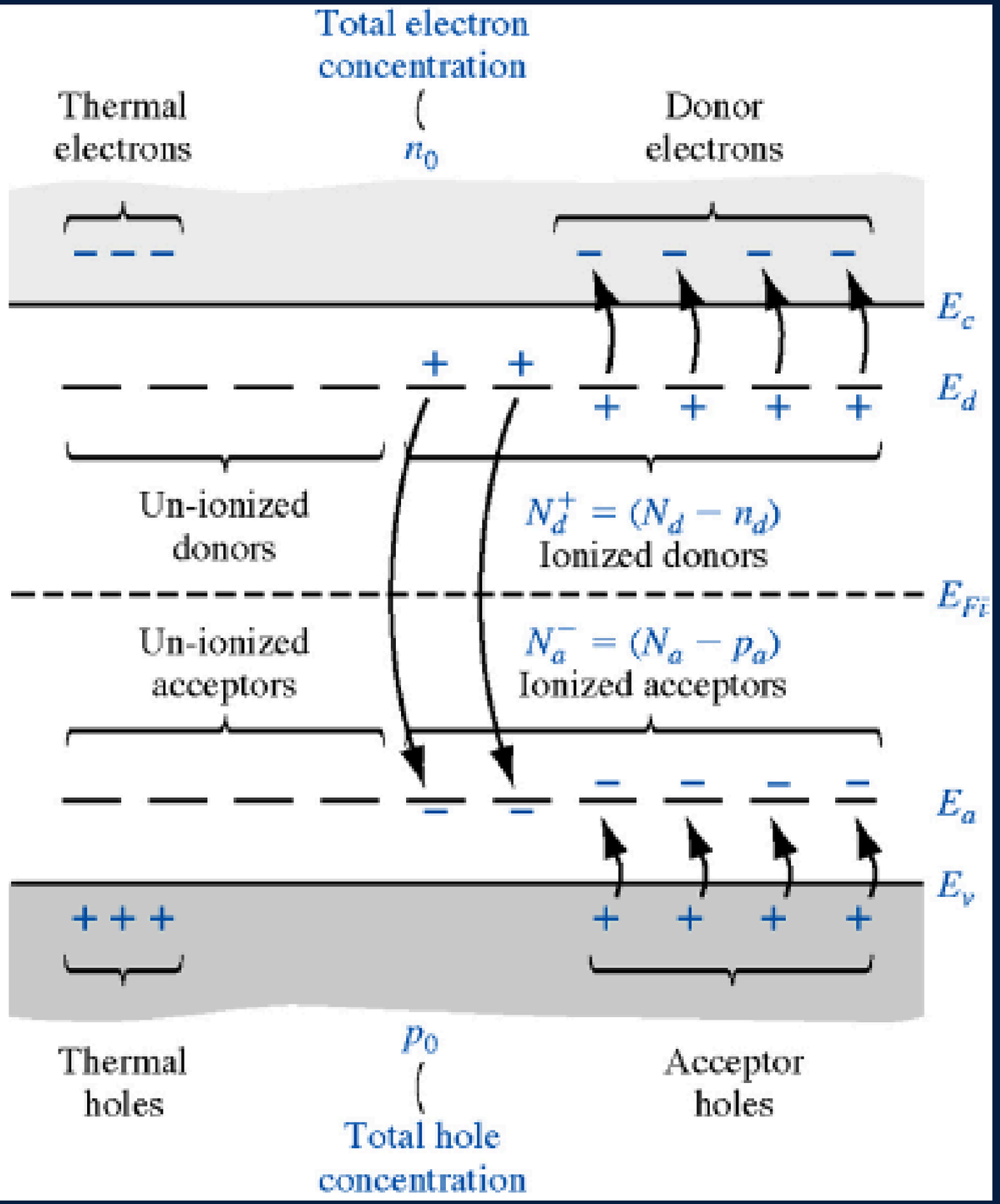
$$n_0 + (N_a - p_a) = p_0 + (N_d - n_d)$$

Ionized donors

complete ionization

n_d and p_a are both zero

$$n_0 + N_a = p_0 + N_d$$



Recall $n_0 + N_a = p_0 + N_d$

Using the relation $n_i^2 = n_0 p_0$

$$n_0 + N_a = \frac{n_i^2}{n_0} + N_d$$

$$n_0 = \frac{(N_d - N_a)}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

n_o is not simply N_d

Similarly in p-type semiconductor,

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

Minority carrier concentration

$$p_0 = \frac{n_i^2}{n_0}$$

(n-type material)

$$n_0 = \frac{n_i^2}{p_o}$$

(p-type material)

Position of Fermi Energy Level

Where is the Fermi level of an extrinsic semiconductor?

$$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$$

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)$$

N-type: $N_d >> n_i$ then $n_0 \approx N_d$

$$E_c - E_F = kT \ln\left(\frac{N_c}{N_d}\right)$$

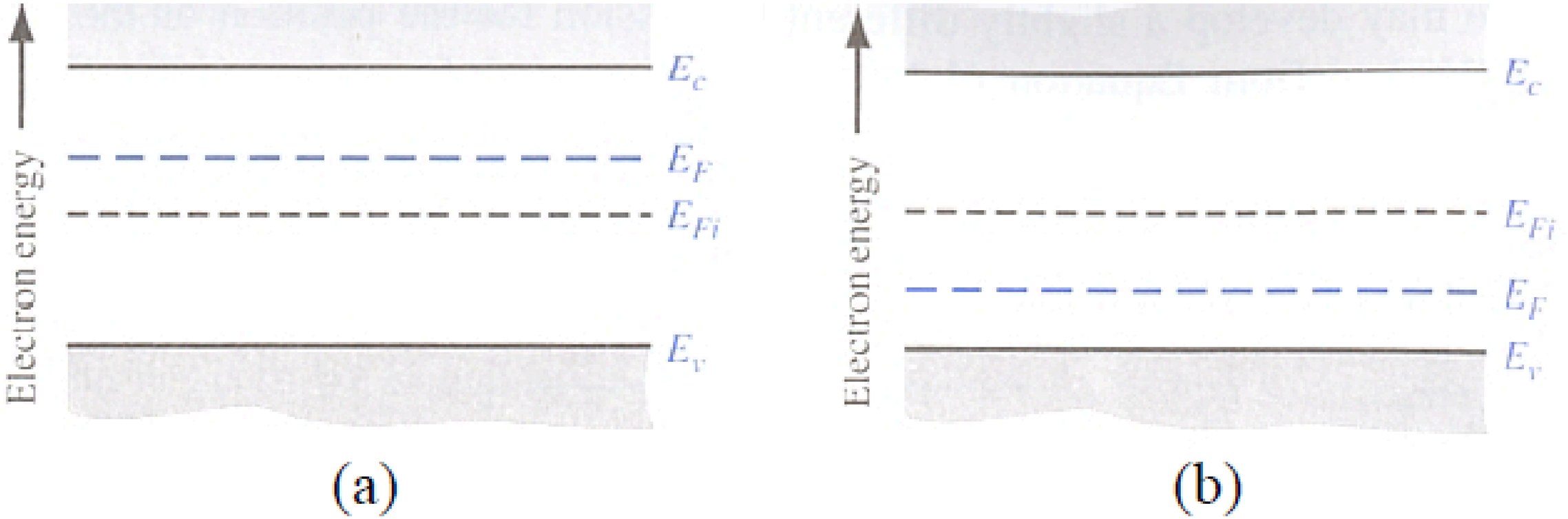
Where is the Fermi level of a p-type extrinsic semiconductor?

$$p_0 = N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right]$$

$$E_F - E_v = kT \ln\left(\frac{N_v}{p_0}\right)$$

P-type: $N_a >> n_i$ then $p_0 \approx N_a$

$$E_F - E_v = kT \ln\left(\frac{N_v}{N_a}\right)$$



Position of Fermi level for an (a) n-type and (b) p-type semicondcutor.

Different expression for the n-type...

$$E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right)$$

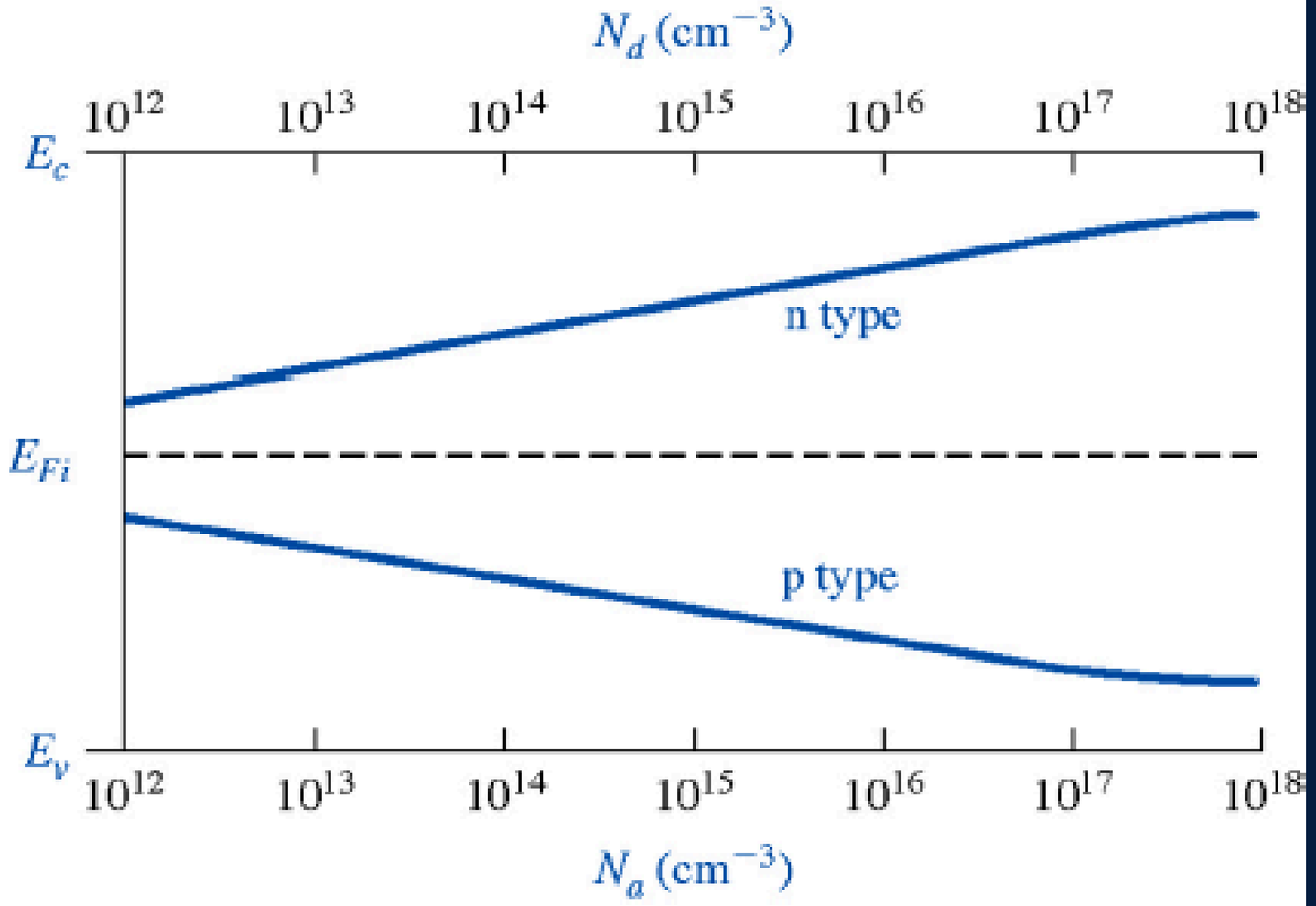
Another expression for the p-type

$$E_{Fi} - E_F = kT \ln\left(\frac{p_0}{n_i}\right)$$

Variation of E_F with doping concentration:

$$E_F = E_c - kT \ln\left(\frac{N_c}{N_d}\right)$$

$$E_F = E_v + kT \ln\left(\frac{N_v}{N_a}\right)$$



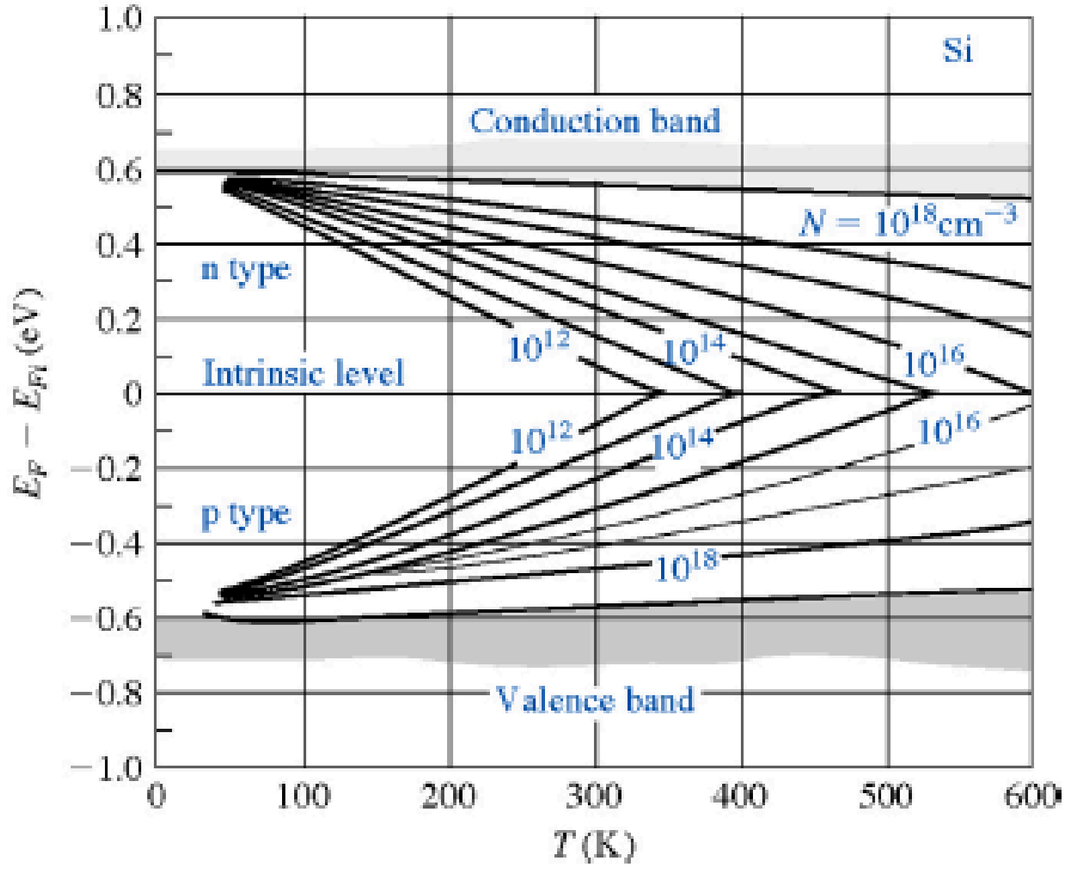
Variation of E_F with temperature T

$$E_F - E_{Fi} = kT \ln\left(\frac{n_0}{n_i}\right)$$

$$E_{Fi} - E_F = kT \ln\left(\frac{p_0}{n_i}\right)$$

• At higher temperatures, the semiconductor becomes more intrinsic. n_i increases and Fermi level moves towards mid-gap

•At T=0, Fermi level is above E_d in n-type and below E_a in p-type semiconductor



Variation of Fermi level with temperature for different doping concentrations

Summary

- Electron concentration $n_0 = N_c \exp\left[\frac{(E_c - E_F)}{kT} \right]$
- Hole concentration $p_0 = N_v \exp\left[\frac{(E_F - E_v)}{kT} \right]$

Holds for both intrinsic as well as extrinsic semiconductor

- Intrinsic carrier concentration :

$$n_i^2 = n_0 p_0 \quad N_c N_v \exp\left[\frac{(E_c - E_v)}{kT} \right] \quad - N_c N_v \exp\left[\frac{E_g}{kT} \right] \quad =$$

-

- In intrinsic semiconductor, Fermi level is close to but not exactly in the centre between conduction and valence bands.

$$E_{Fi} - E_{midgap} \quad \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*} \right)$$

Summary

- In extrinsic semiconductor, Fermi level is close to conduction band (n-type) or valence band (p-type)

- Position of Fermi level in extrinsic semiconductor

$$E_F - E_{Fi} \quad kT \ln\left(\frac{n_0}{n_i}\right)$$

- In compensated n-type semiconductor electron concentration is given by

$$n_0 = \frac{N_d - N_a}{2} \quad \sqrt{\left(\frac{N_d \quad N_a}{2}^2 \quad - n_i^2\right)} \quad +$$

- When two different systems are in contact and in thermal equilibrium, E_F must be the same in both systems.