Introduction to Semiconductor Theory

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Semiconductor Materials

•Semiconductors, as the name implies, are a group of materials whose electrical conductivity is greater than that of insulators but less than that of metals.

Insulators **Semiconductors** **Metals**

→ Increasing conductance

- Semiconductor materials are found in Group IV and neighbouring columns of the periodic table. The ones in group IV (C, Si, Ge) are called elemental semiconductors because they are composed of the pure element.

II	III	IV	V	VI
	B	C	N P	
	Al	Si		S
Zn	Ga	Ge	As	Se
Cd	In		Sb	Te

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Elemental	IV compunds	Binary III-V compounds	Binary II-VI compunds	Ternary compounds	Quaternary compounds
Si Ge	SiC SiGe	AlP AlAs	ZnS ZnSe	GaAsP AlGaAs	InGaAsP
		AlSb	ZnTe		
		GaN	CdS		
		GaP	CdSe		
		GaAs	CdTe		
		GaSb			
		InP			
		InAs			
		InSb			

These compounds are widely used in various electronic and optical applications.

Why semiconductor device ?

- Semiconductor devices such as diodes, transistors and integrated circuits can be found everywhere in our daily lives like in televisions, automobiles, washing machines and computers.

- Semiconductor conductivity can be varied/controlled.

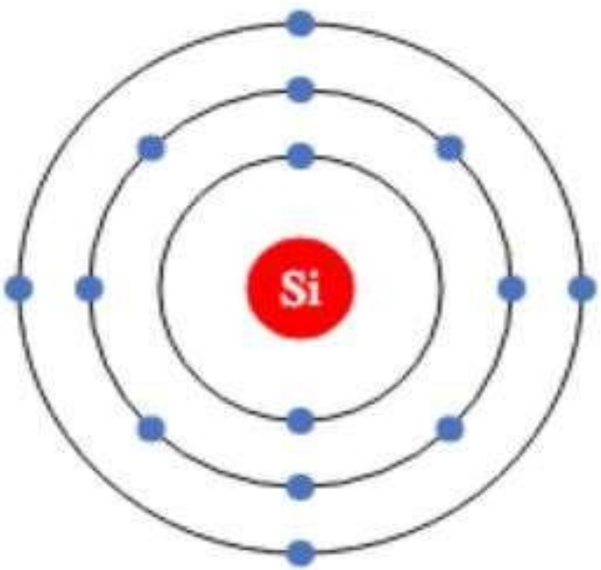
- Semiconductor is easily available.

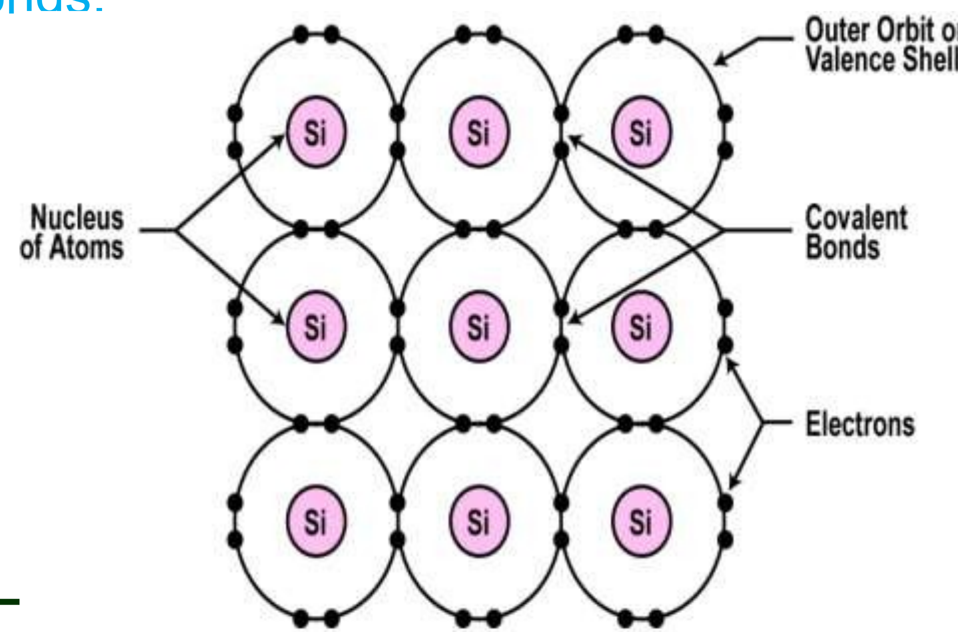
Application of semiconductor

Elemental and compound semiconductor	Applications
Si, Ge	All types of devices like diode, transistors IC, etc.
GaAs, GaP, GaN, $GaAs_{1-x}P_x$, GaTe, AlN, InGaN	LED . The x value (0–1) in $GaAs_{1-x}P_x$ decides the band gap 1.4–2.7 eV, and hence colour of the LED changes from IR to UV; other compounds are also used for different colours
GaAs, In–P	Microwave devices
ZnS	Fluorescent materials for screen, tube light, etc.
GaAs, AlGa As	Lasers
In–Sb, Cd–Sa, P Li–Te	Light detectors
GaAsP, InGaAsP	Power electronics products

Semiconductor

- Silicon : It's a Group 4 element which means it has 4 electrons in outer shell.
- However, like all other elements it would prefer to have 8 electrons in its outer shell.
- The unique capability of semiconductor atoms is their ability to link together to form a physical structure called a crystal lattice.
- The binding forces between neighboring atoms results from the fact that each of the valance electrons is shared by one of its four nearest neighbors.
- These links are called covalent bonds.





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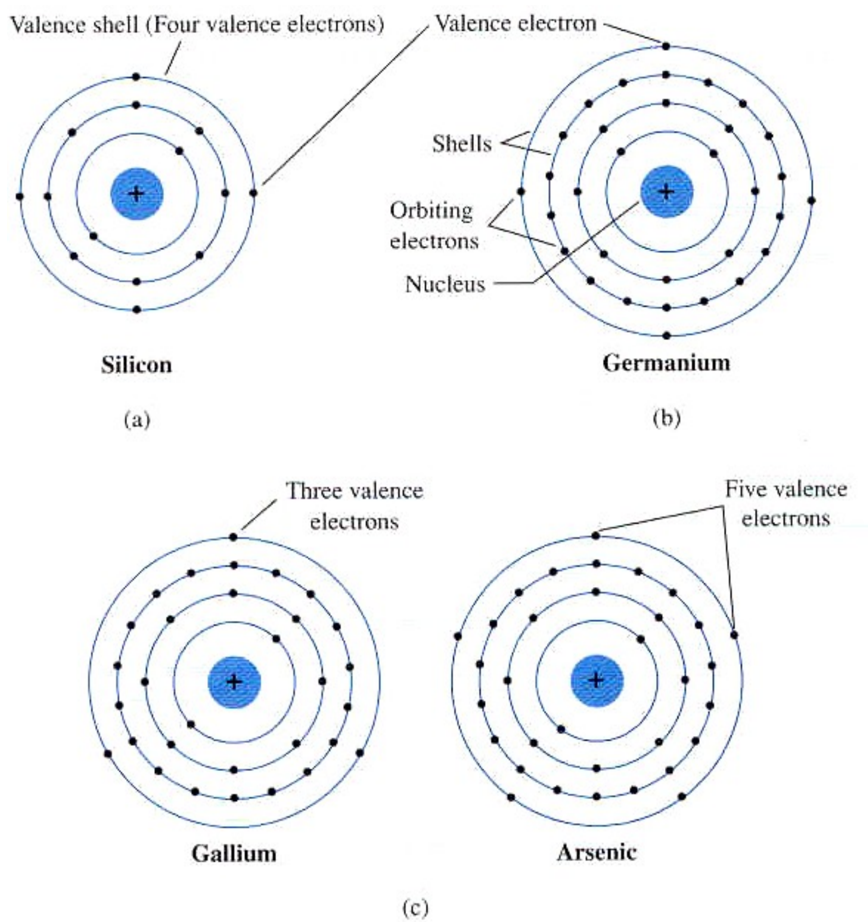
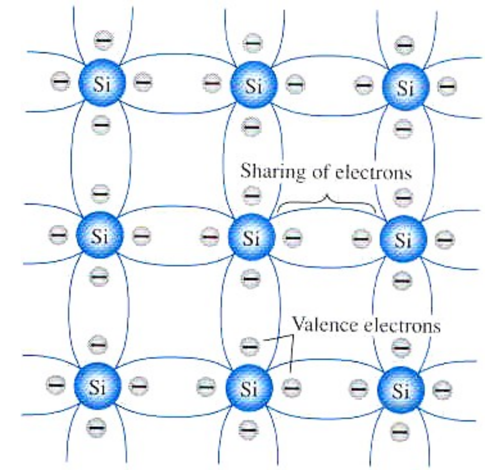
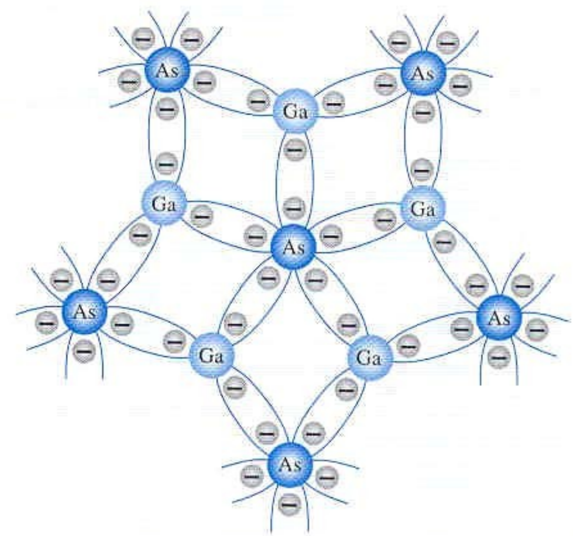
Covalent Bond Structure of Semiconductors







Intrinsic Material

A pure semiconductor crystal with no impurities or lattice defects is called an ***intrinsic*** semiconductor.

At T=0 K

Valence band is full with electrons

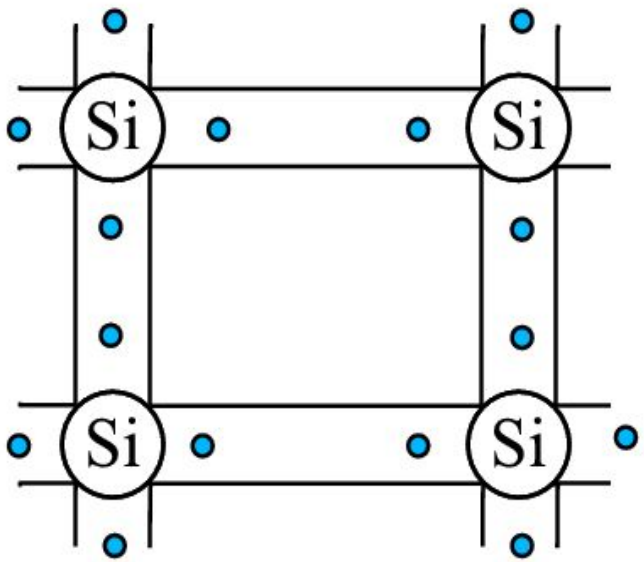
Conduction band is empty

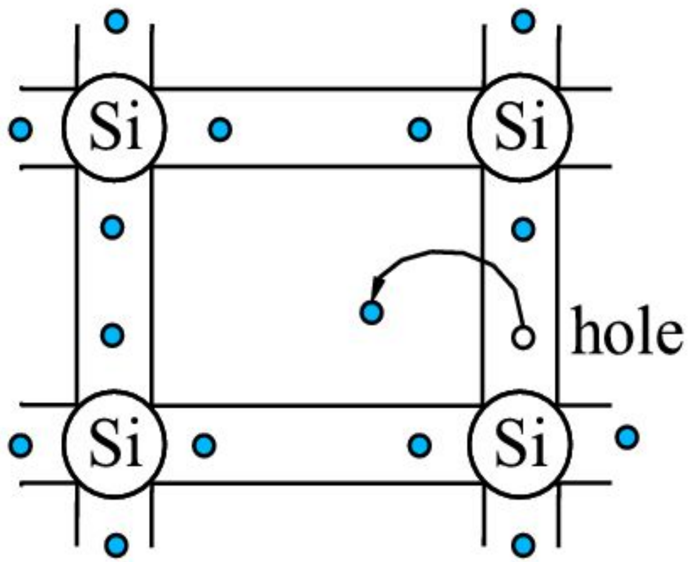
So no carriers available for conduction.

At T>0 thermal fluctuations break electrons to free creating electron-hole pairs.

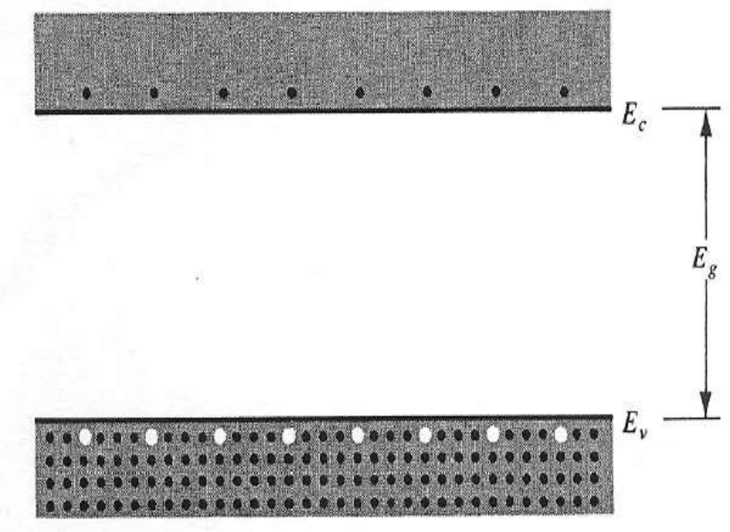
Electron-hole pairs (EHP) are generated.

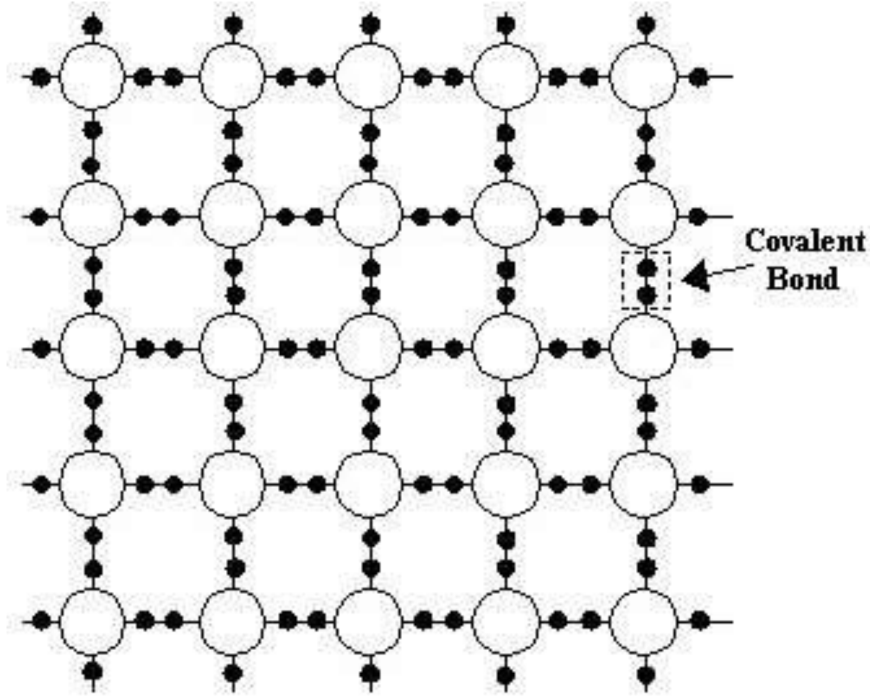
Number of electrons=No. of holes





electrons and holes





Electron-hole pairs in a semiconductor. The bottom of the conduction band denotes as E_c and the top of the valence band denotes as E_v.

For T>0

- some electrons in the valence band receive enough thermal energy to be excited across the band gap to the conduction band.
- The result is a material with some electrons in an empty conduction band and some unoccupied states in an filled valence band.
- An empty state in the valence band is referred to as a ***hole***.
- If the conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band, they are called an ***electron-hole pair*** (EHP).

- At 0 Kelvin there are no free charge carriers, but as temp increases a few electron- hole pairs (EHP) are generated due to valence electrons getting thermally excited to have enough energy to “jump” over the bandgap into the conduction band.

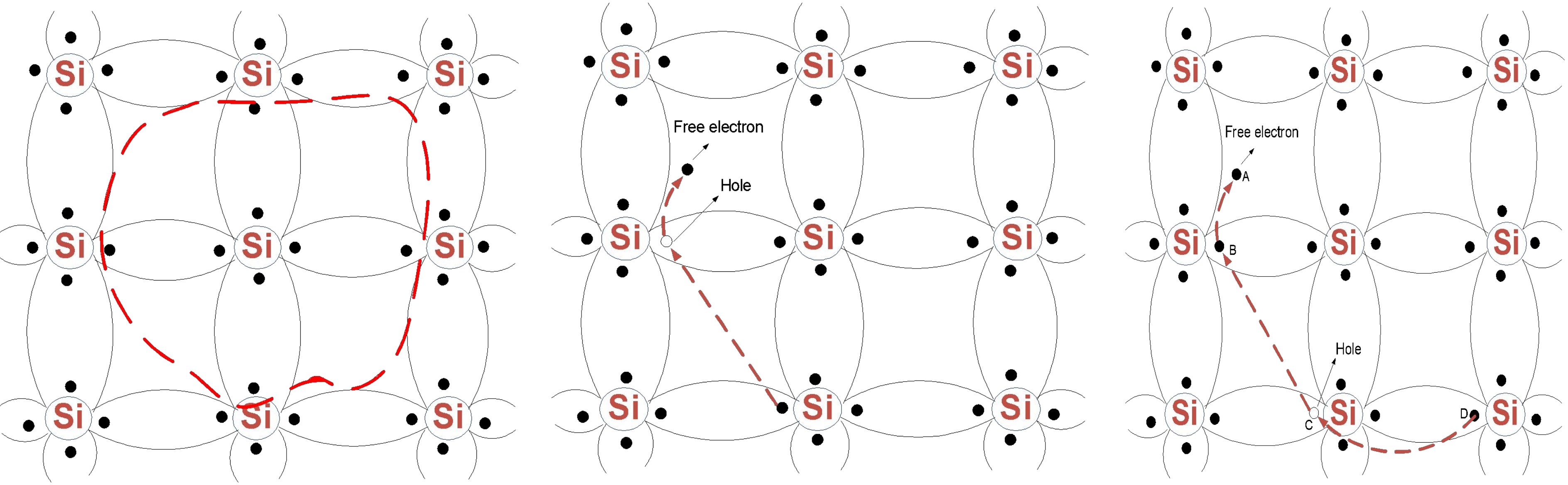
•Since electron-holes are always created in pairs, then

$$\boldsymbol{n = p = n_i}$$

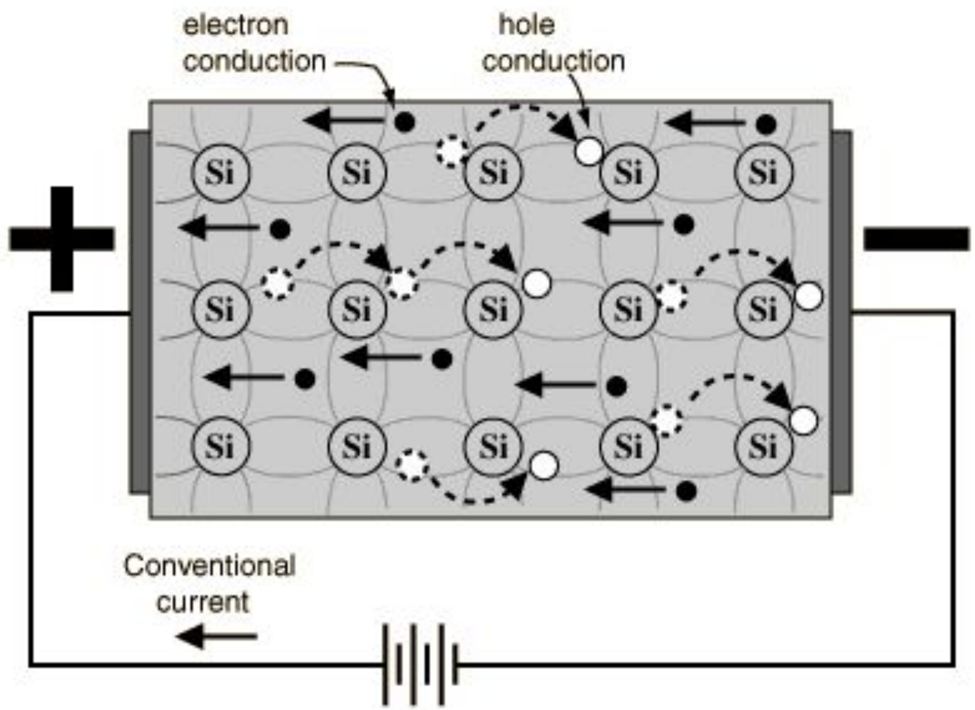
*where **n** and **p** are the electrons and holes concentration (per cm^3), respectively*

- Recombination occurs when an electron in the conduction band makes a transition to the valence band to recreate a complete covalent bond structure with the hole
- At steady state, EHPs recombine at the same rate as they are generated
- Generation and recombination of EHP are dependent on temperature

Structure of Si Semiconductor



current carrying mechanisim of hole



- If a voltage is applied, then both the electron and the hole can contribute to a small current flow.
- Current carried by valence electrons in valance band is called as hole current.
- Current carried by free electrons in conuction band is called as electron current.

How to Increase conductivity

- **Case-1**
- The conductivity of the semiconductor material increases when the temperature increases.
- This is because the application of heat makes it possible for some electrons in the valence band to move to the conduction band.
- Obviously the more heat applied the higher the number of electrons that can gain the required energy to make the conduction band transition and become available as charge carriers.
- This is how temperature affects the carrier concentration.
- **Case-2**
- Another way to increase the number of charge carriers is to add them in from an external source.
- Doping or implant is the term given to a process whereby one element is injected with atoms of another element in order to change its properties.
- Semiconductors (Si or Ge) are typically doped with elements such as Boron, Arsenic and Phosphorous to change and enhance their electrical properties.

Extrinsic semiconductor

- ***Doping is the process of adding specific impurities to a pure semiconductor in such a way that the newly formed covalent bonding creates excess charge carriers within the crystal lattice***

- When a crystal is doped such that the equilibrium carrier concentrations n_0 and p_o are different from the intrinsic carrier concentration n_i, the material is said to be *extrinsic.*

- When trivalent impurities(B, Al) are added to intrinsic semiconductor, then it is called as p-type extrinsic semiconductor.

- When pentavalent impurities(P,As) are added to intrinsic semiconductor, then it is called as n-type extrinsic semiconductor.

- When impurities or lattice defects are introduced, additional levels are created in the energy bands structure, usually within the band gap.

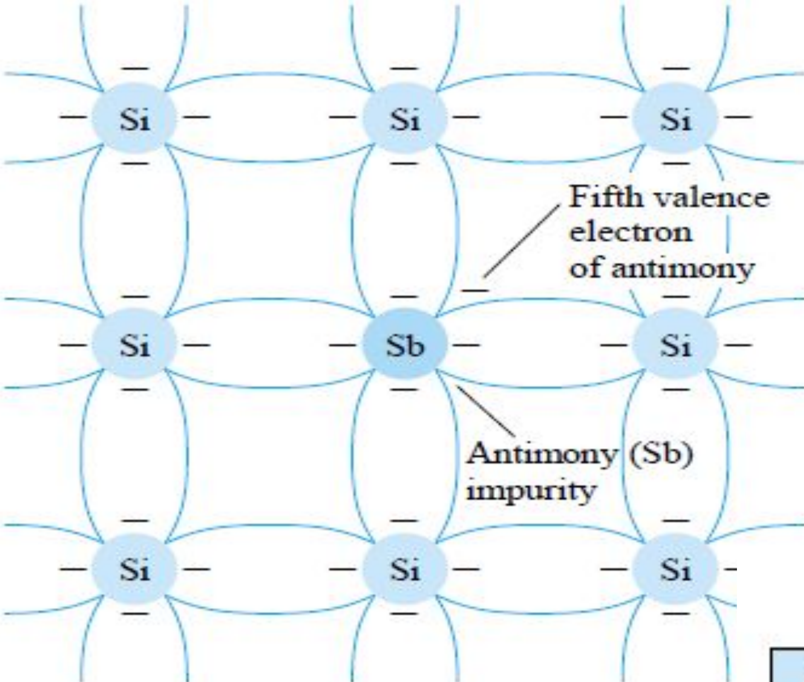
N-Type Semiconductor:

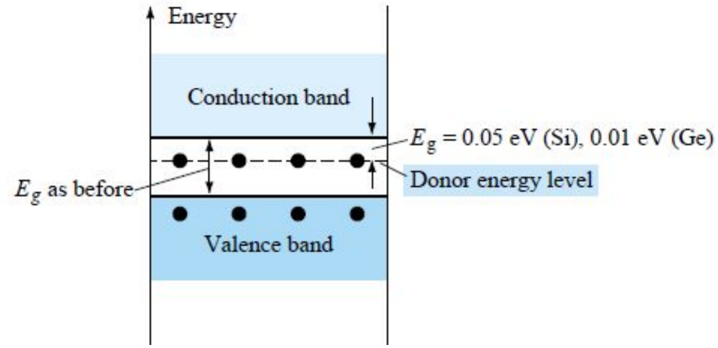
- The N-type of material is obtained by adding the impurity of five valance electrons(penta-valent) such as antimony, arsenic, and phosphorus.

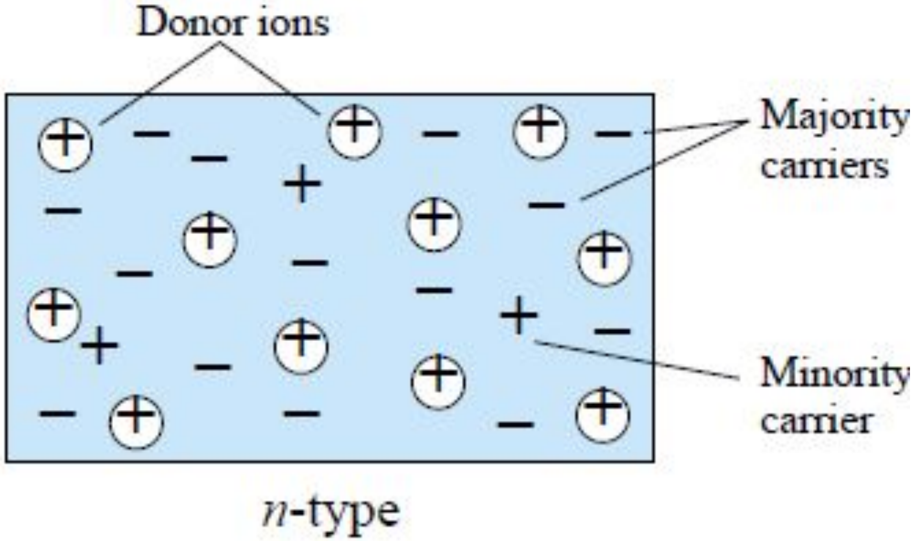
- The penta-valent elements have five electrons at their valence band. After doping, four electrons will combine with the Si material to form a covalent bond and one will be a free electron. An impurity from column V introduces an energy level very near the conduction band in Ge or Si.

- This level is filled with electrons at 0 K, and very little thermal energy is required to excite these electrons to the conduction band. Thus, at about 50-100 K nearly all of the electrons in the impurity level are "donated" to the conduction band. Due to the free electron the conductivity of the combined material increases significantly.

- Such an impurity level is called a donor level, and the column V impurities in Ge or Si are called donor impurities.
- So the material doped with donor impurities can have a considerable concentration of electrons in the conduction band.

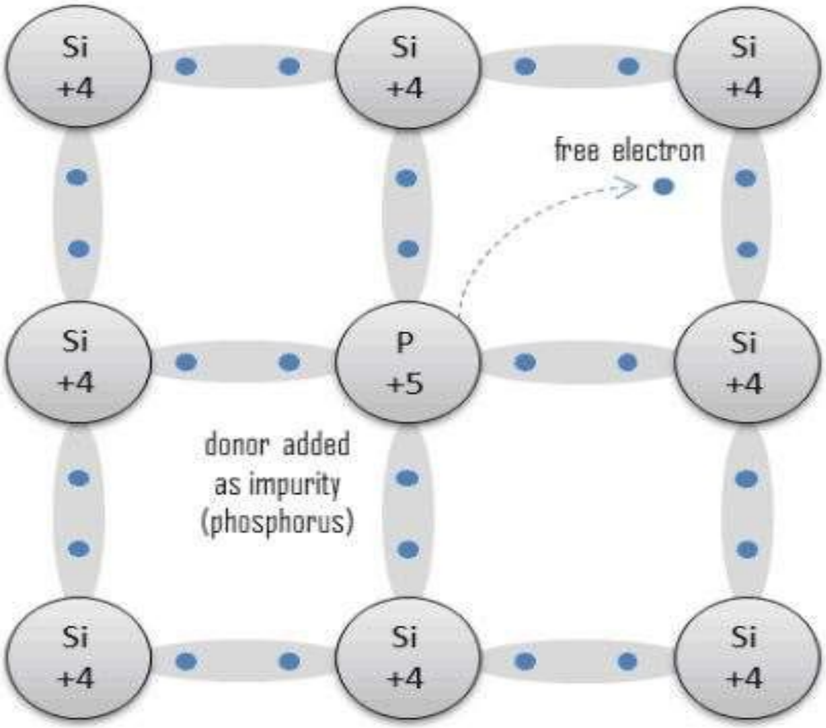


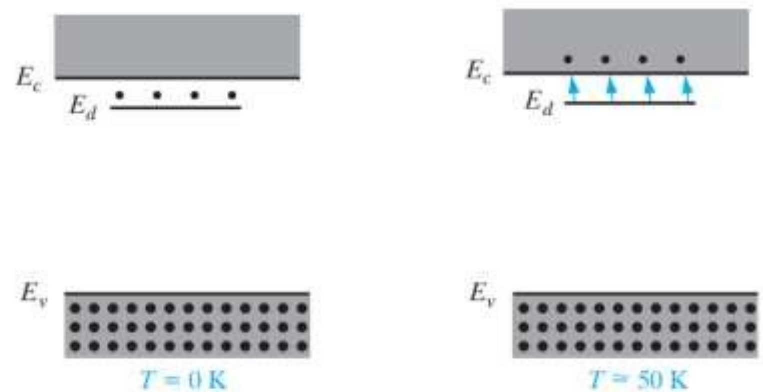




In this material, the electrons are called majority carrier and holes are called minority carrier

N-type extrinsic semiconductor



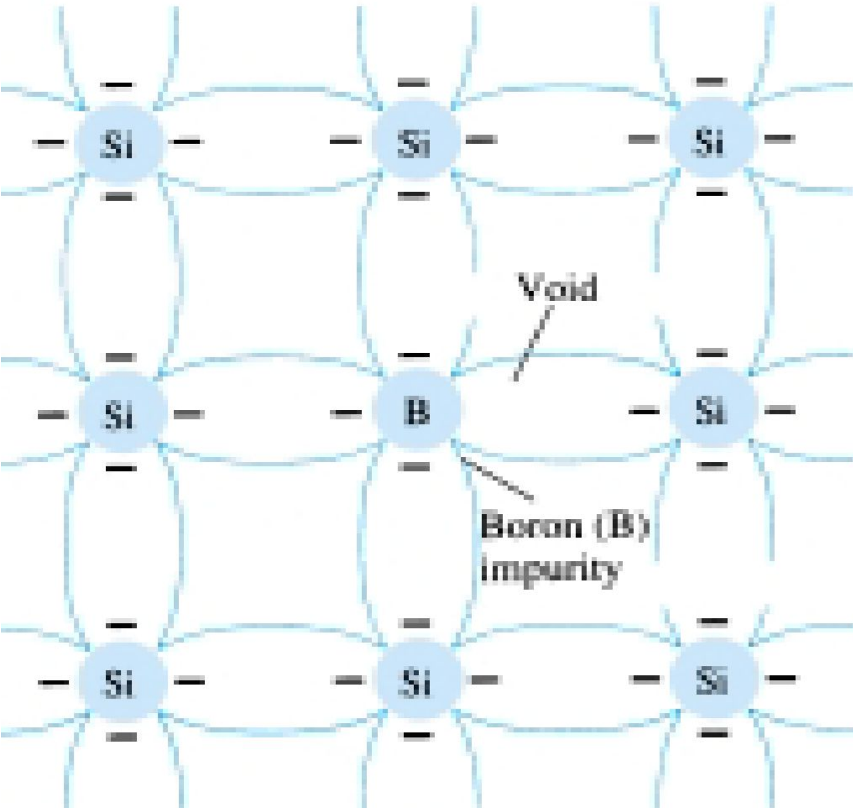


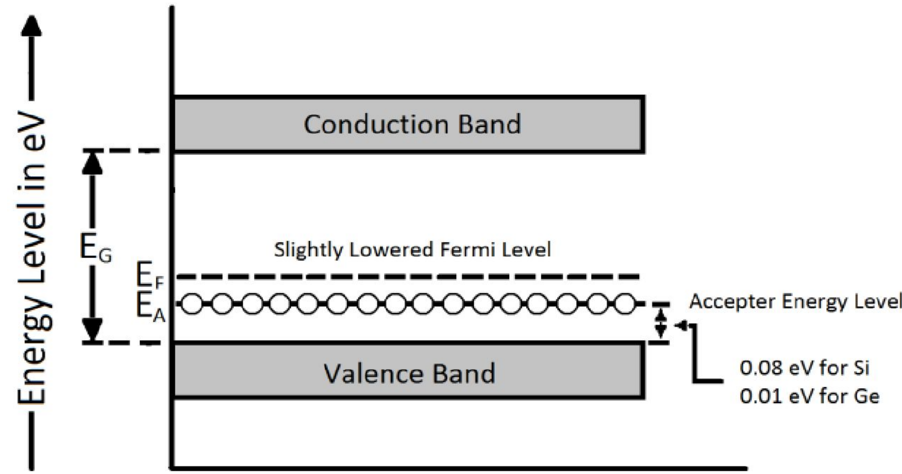
P-type Semiconductor

- The P-type of material is obtained by adding the impurity of three valance electrons(tetravalent) such as boron, gallium, and indium.
- In this combination, one electron is required to complete the covalent bonds of the newly formed lattice. The resulting vacancy is called hole which readily accept a free electron.

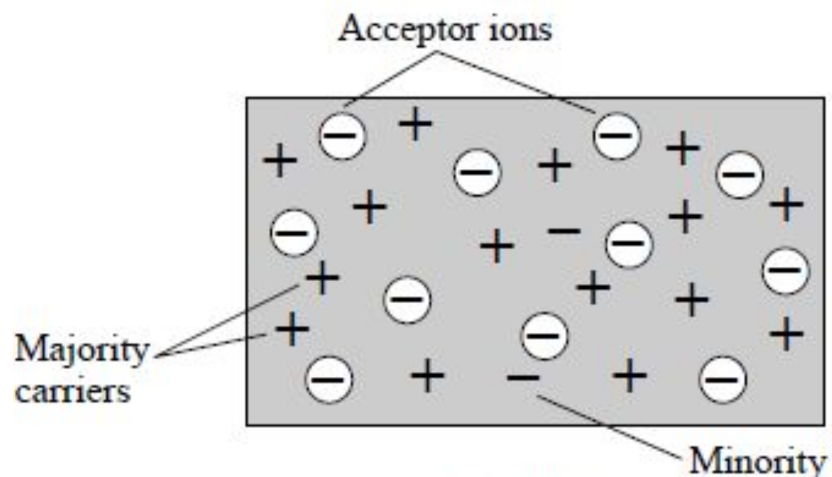
- Atoms from group III (B, Al, Ga, and In) introduce impurity levels in Ge or Si near the valence band.
- These levels are empty of electrons at 0 K.
- At Low temp enough thermal energy is available to excite electrons from the valence band into the impurity level, leaving behind holes in the valence band.

- Since this type of impurity level "accepts" electrons from the valence band, it is called an *acceptor* level, and the column III impurities are acceptor impurities in Ge and Si.





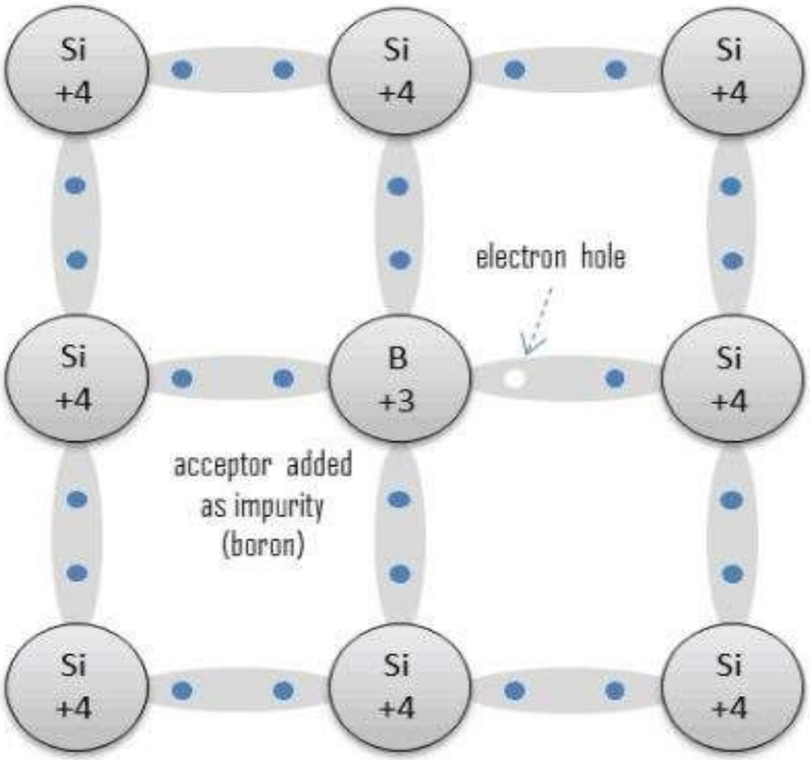
Energy Band Diagram for P-Type Semiconductor

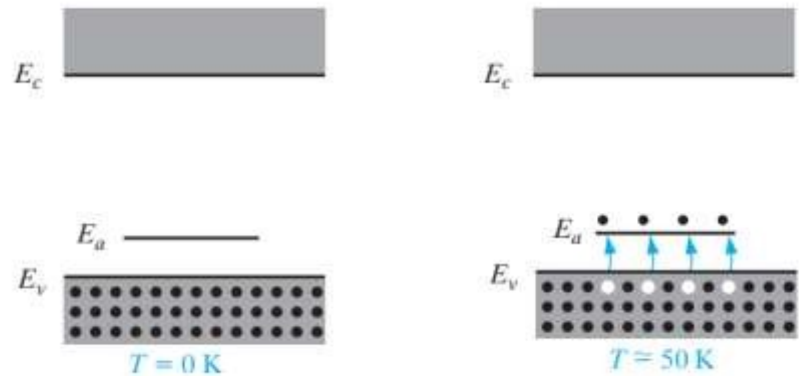


p-type

In this material, the holes are called majority carrier and electrons are called minority carrier

P-type extrinsic semiconductor



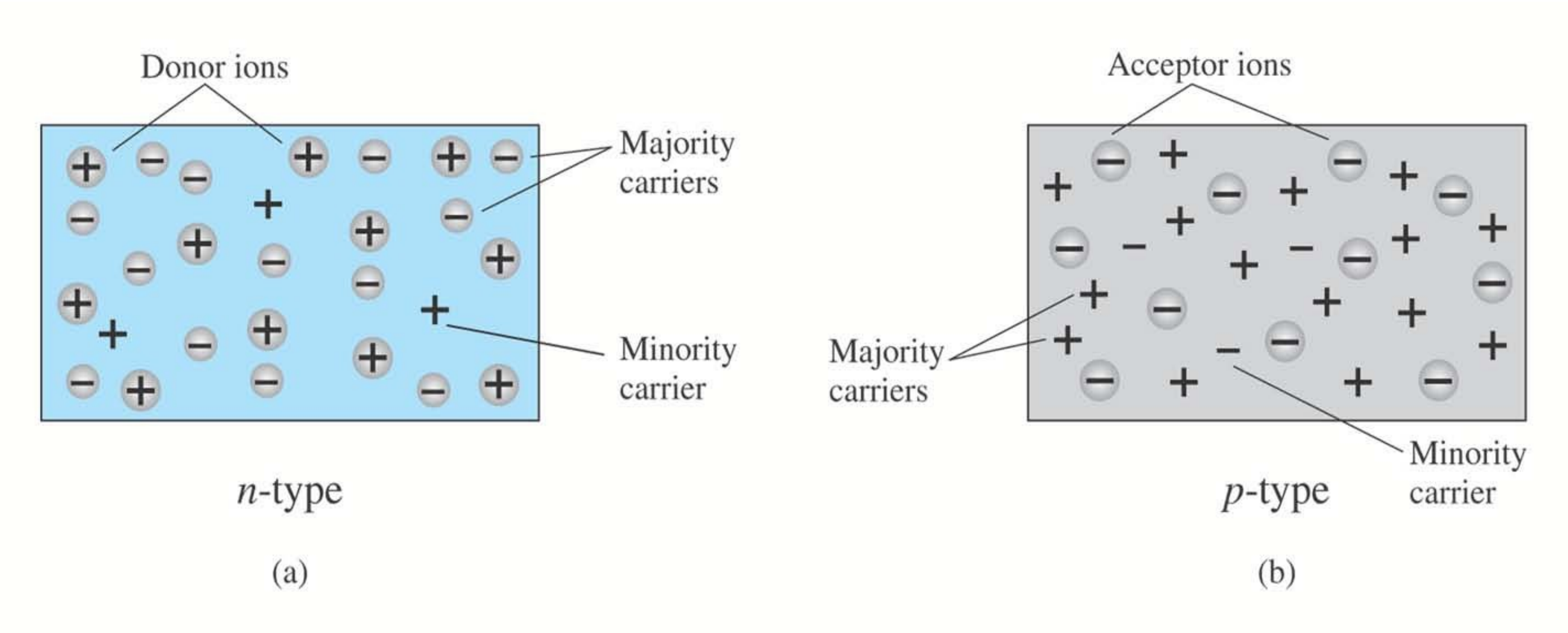


- **In n-type material, the electron is the majority charge carrier and holes are minority.**
- **In p-type material, the holes are the majority charge carrier and electrons are minority**

Majority and Minority carriers:

N-Type: electrons- Majority
holes-Minority

P-Type: holes- Majority
Electrons-Minority



Difference between extrinsic and intrinsic semiconductor

	Intrinsic Semiconductors	Extrinsic Semiconductors
1	It is pure semi-conducting material and no impurity atoms are added to it.	It is prepared by doping a small quantity of impurity atoms to the pure semi-conducting material.
2	Examples: crystalline forms of pure silicon and germanium.	Examples: silicon "Si" and germanium "Ge" crystals with impurity atoms of As, Sb, P etc. or In B, Aℓ etc.
3	The number of free electrons in the conduction band and the no. of holes in valence band is exactly equal and very small indeed.	The number of free electrons and holes is never equal. There is excess of electrons in n-type semi-conductors and excess of holes in p-type semi-conductors.
4	Its electrical conductivity is low.	Its electrical conductivity is high.
5	Its electrical conductivity is a function of temperature alone.	Its electrical conductivity depends upon the temperature as well as on the quantity of impurity atoms doped the structure.