Intrinsic and Extrinsic Semiconductors

Objectives

After going through this module student will be able to:

- Understand the significance of semiconductors for controlled flow of charge carriers;
- Know about charge carriers electrons and holes in semiconductors;
- Appreciate Doping and its importance;
- Distinguish between Intrinsic (or pure) semiconductors and extrinsic semiconductors;
- Explain why bulk pieces of p-type and n-type semiconductors are electrically neutral.

Content Outline

- Unit Syllabus
- Module Wise Distribution of Syllabus
- Words You Must Know
- Introduction
- Uniqueness of Semiconductors
- Charge Carriers in Semiconductors
- Intrinsic or Pure Semiconductors
- Doping
- Extrinsic or Doped Semiconductors
- Net Charge on *p*-type and *n*-type Semiconductors
- Examples
- Questions for Practice
- Summary

Unit Syllabus

Unit-09: Electronic Devices

Chapter 14: Semiconductor electronic material, devices and simple circuits.

- Energy bands in conductors, semiconductors and insulators (qualitative only) semiconductors intrinsic and extrinsic

- Semiconductor diode- I-V characteristics in forward and reverse bias, application of diode as a rectifier
- Special purpose p-n diodes: LED, photodiode, solar cell, Zener diode and their characteristics, Zener diode as a voltage regulator
- Junction transistor: Transistor action, characteristics of a transistor and transistor as amplifier common emitter configuration

Basic idea of analog and digital signal, logic gates OR, AND, NOR, NOT, NAND

Keeping the needs of state boards in mind we have not changed the content

Module Wise Distribution of Unit Syllabus - 10 Modules

Module 1	● Energy bands in solids ● Forbidden gap ● Fermi level ● Energy bands in conductors, semiconductors and insulators
Module 2	● Uniqueness of semiconductors ● Charge carriers in semiconductors electrons and holes ● Intrinsic semiconductors ● Extrinsic semiconductors p and n type ● Why are *p* and *n* type semiconductors neutral?
Module 3	● p-n junction diode ● Potential barrier ● Depletion layer ● Characteristics of *p-n* junction diode ● forward and reverse bias, knee voltage, magnitude of bias voltages ● To draw the IV characteristics curve for a *p-n* junction in forward bias and reverse bias

Module 4	● Application of diode ● Rectifier meaning and need of such a devise ● Half wave and full wave rectifier ● Rectifier in our homes ● Special purpose diode ○ LED ○ Photodiode ○ Solar cells ● Solar panels and future of energy
Module 5	● To identify a diode, an LED, a resistor and a capacitor use a multimeter to ○ See the unidirectional flow of current in case of a diode and an LED ○ Check whether a given diode is in working order
Module 6	● Zener diode ● Characteristics of Zener diode ● To draw the characteristic curve of a Zener diode and to determine its reverse breakdown voltage ● How is a Zener diode different from other diodes? ● Zener diode as a voltage regulator ● Working of a Zener diode ● Zener diodes in our homes
Module 7	● Junction transistor ● design of the transistor ● *n-p-n* and *p-n-p* ● use a multimeter to ○ Identify base of transistor ○ Distinguish between n-p-n and p-n-p type transistor ○ Check whether a given electronic component (e.g. diode, transistor, or IC) is in working order ● Transistor action ● Characteristics of a transistor, n-p-n -common emitter

Module 8	- Understanding transistor characteristics and its applications - To study the characteristics of a common emitter *n-p-n* and *p-n-p* transistor and to find the values of current and voltage gains. - Transistor as switch - Transistor as amplifier - Transistor as an oscillator
Module 9	- Transistor as an amplifier - Circuit diagram and understanding bias - Input and output waveforms - Phase change
Module 10	- Analog signals - Logic gates - Truth tables - OR gate - AND gate - NOT gate - NAND gate - NOR gate

Words You Should Know

- **Conductors:** These are the materials which conduct electricity easily. They have a very large number of free electrons.
- **Insulators:** These are the materials which do not conduct electricity because they do not have free electrons.
- **Semiconductors:** These are the materials for which electrical conductivity values are less than conductors but more than that of insulators. The conductivities of semiconductors are highly temperature sensitive.
- **Energy Level:** As per Bohr's theory electrons revolve around the nucleus only in some specific orbits called stationary orbits. Energy of electrons in these orbits is constant, are termed as energy levels.

- **Valence Bands:** This band comprises energy of valence electrons. Electrons of this band do not contribute to conduction of electric current.
- **Conduction Band:** This band corresponds to energy of free electrons. Electrons of this band are responsible for the conduction of electric current.
- **Forbidden Energy Gap (E_g):** It is the minimum energy required to take an electron from valence band to conduction band. Insulators have highest E_g and conductors have least E_g.

Introduction

In module 1 of this unit we understood how energy bands are formed in bulk solid matter. The band theory is a useful way to visualize the difference between conductors, insulators and semiconductors. Instead of having discrete energies as in the case of free atoms, the available energy states for the electrons form almost a continuum bands. Crucial to the conduction process is whether or not there are electrons in the conduction band. In insulators the electrons in the valence band are separated by a large gap from the conduction band. In conductors, like metals the valence band overlaps the conduction band, and in semiconductors there is a small energy gap between the valence and conduction bands that can be bridged by thermal or other excitations. An important parameter in the band theory is the Fermi level, the top of the available electron energy levels at low temperatures. The position of the Fermi level in relation to the conduction band is a crucial factor in determining electrical properties.

In this module we will learn special features of semiconductors.

Unique of Semiconductors

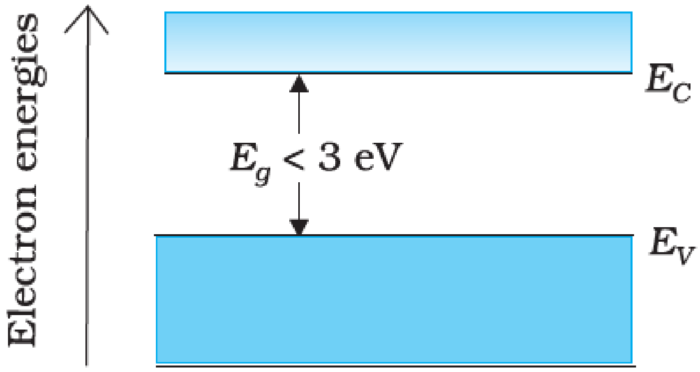
We all are familiar with electronic devices like TV, radio, cell phones etc. One may wonder how they work. A semiconductor is a material whose electrical conductivity has a value between metal conductors and insulators. They are highly temperature sensitive. At zero kelvins they behave like perfect insulators.

One may also wonder what is the difference between the flow of electric current through conductors and that through semiconductors?

The basic difference lies in magnitudes of the current and voltages used and type of charge carriers.

- In normal flow of electricity through conductors, large magnitude of current and voltages are used, while in semiconductors these are very small, of the order few volts while the currents are in milli or micro amperes.
- Charge carriers in metal conductors have a very large number of free electrons. In semiconductors these are free electrons and holes.
- You may also think that if semiconductors have very low conducting performance at low temperatures then how they work in coldest places like poles where temperature is of the order -50ºC. It is because -50ºC is much "warmer" than -273.15ºC.
- The advantage of semiconductors over metallic conductors is that semiconductors do not have ohmic resistance like metallic conductors. The motion of electrons in semiconductors is much faster than metallic conductors.

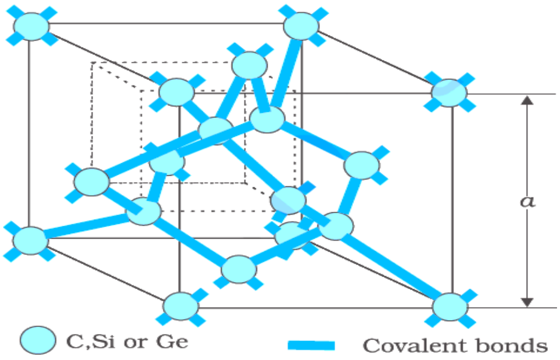
You will recall the energy band diagram for a semiconductor.



(c)

Charge Carriers in Semiconductors

Commonly used semiconductors are Germanium and Silicon, both of which have four valence electrons each.



Three-dimensional diamond-like crystal structure for Carbon, Silicon or Germanium with respective lattice spacing equal to 3.56, 5.43 and 5.66 Å

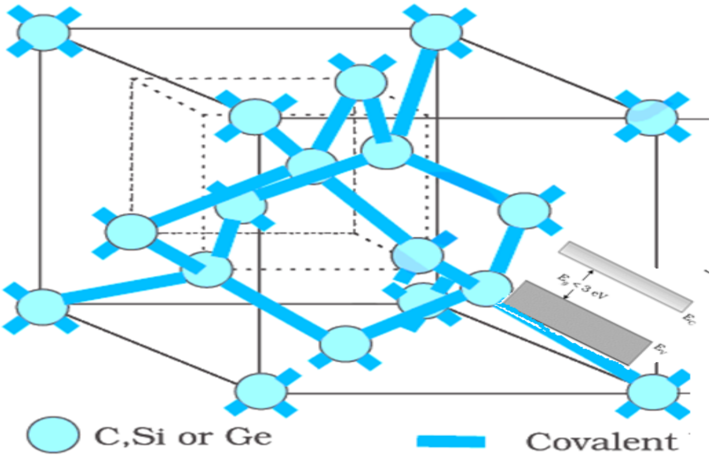
These structures are called d**iamond-like structures**. Each atom is surrounded by four nearest neighbors. We know that Si and Ge have four valence electrons.

In its crystalline structure, every Si or Ge atom tends *to* share one of its four valence electrons with each of its four nearest neighbor atoms, and also to take share of one electron from each such neighbor. These shared electron pairs are referred to as forming a covalent bond or simply a valence bond.

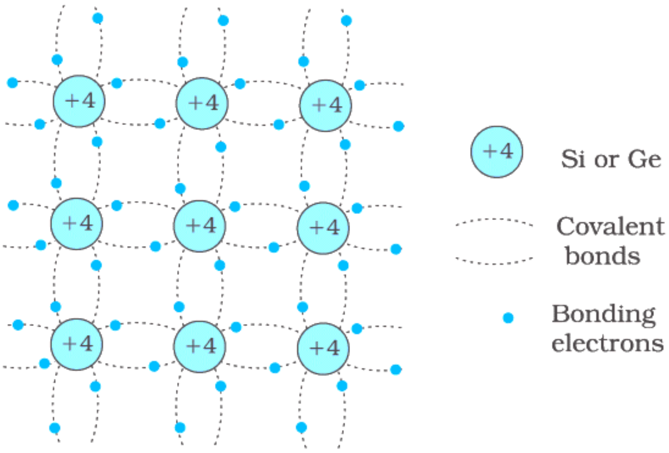
Just to Understand

How are the covalent bonds in the 3 dimensional spaces linked to the band theory?

See the figure, for a set of covalent bonds the valence band and the conduction bands are drawn. Notice for a semiconductor the additional energy required per electron to leave the valence band and acquire a position in the conduction band should be greater than 3 e V.



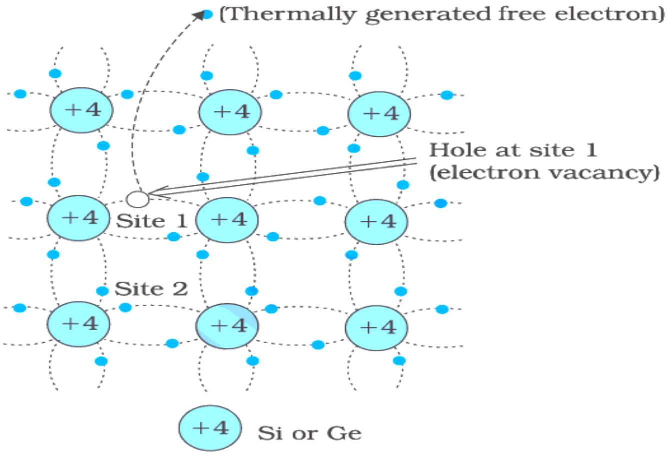
The two shared electrons can be assumed to shuttle back-and- forth between the associated atoms holding them together strongly.



Schematic two-dimensional representation of Si or Ge structure showing covalent bonds at low temperature (all bonds intact) +4 indicates inner cores of Si or Ge.Figure schematically shows the 2-dimensional representation of Si or Ge structure. This is the figure you usually draw in your notebooks to show covalent bonds.

It shows an idealised picture in which no bonds are broken (all bonds are intact). Such a situation arises at low temperatures. **As the temperature increases, more thermal energy becomes available to these electrons and some of these electrons may break away (becoming *free* electrons contributing to conduction).**

The thermal energy effectively ionises only a few atoms in the crystalline lattice and creates a ***vacancy*** in the bond as shown in the Figure



Schematic model of generation of hole at site 1 and conduction electron due to thermal energy at moderate temperatures

The neighborhood, from which the free electron (with charge –*q*) has come out leaves a vacancy with an effective charge (+*q*). This *vacancy* with the effective positive electric charge is called a hole.

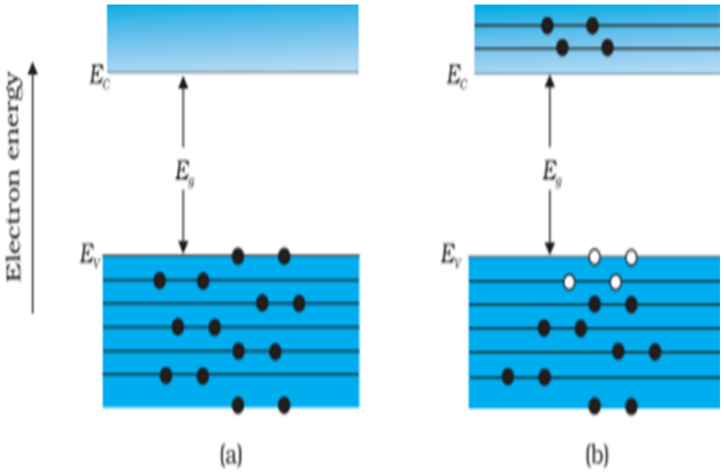
The hole behaves as an apparent free particle with effective positive charge.In intrinsic semiconductors,

The number of free electrons, n_e is equal to the number of holes, n_h.

That is

$$n_e = n_h = n_i$$

where n_i is called intrinsic carrier concentration.



(a) (b)

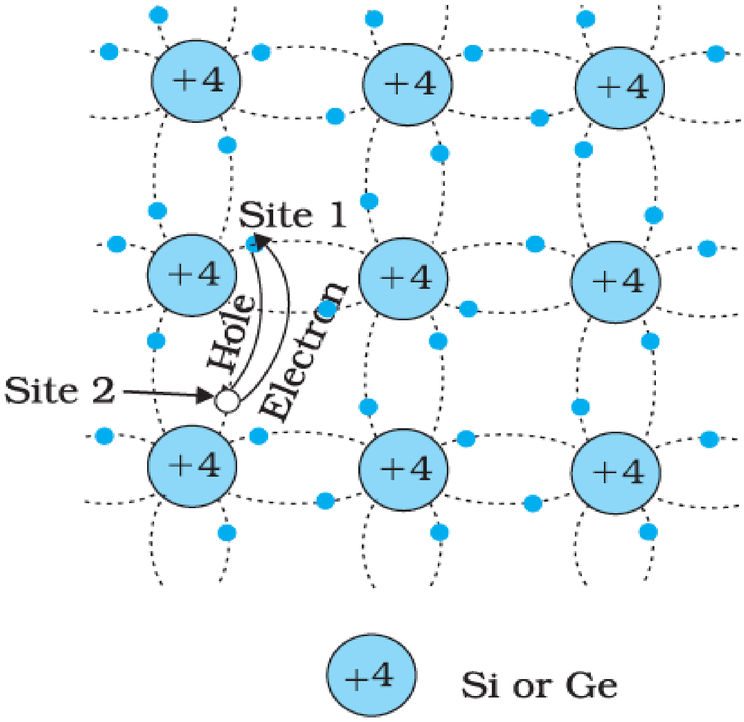
Fig (a) shows an intrinsic semiconductor at 0K and since there are no electrons in the conduction band it behaves like an insulator

Figure (b) shows an intrinsic semiconductor at temperature greater than 0 K some thermally generated electrons move from valence band to conduction band, they generate vacancies in the valence band called holes.

○ **Hole**

● **electron**

Semiconductors possess the unique property in which, apart from electrons, the holes also move and contribute to electrical conduction



Simplified representation of possible thermal motion of a hole

The electron from the lower left hand covalent bond (site 2) goes to the earlier hole site1, leaving a hole at its site indicating an apparent movement of the hole from site 1 to site 2.

If we were to place an electrical potential difference across a semiconductor crystal

We would have current flowing in two directions ;

- The electron current in the conduction bands flows from the negative terminal towards the positive terminal.
- The hole-current, in the valence band is from the positive terminal towards the negative terminal.

The two currents are due to the movement of two kinds of charge carriers carrying opposite but equal charges. The currents due to the two charge carriers add up.

We Can Sum Up

- **At zero kelvin, all these covalent bonds are fully filled and there are no free electrons for conduction of electricity. That is why it behaves as an insulator at zero kelvin.**
- **At room temperature (25°C) few electrons gain thermal energy and break away from their covalent bonds. This creates a vacancy in covalent bonds called holes. So whenever a covalent bond breaks an electron-hole pair is generated.**

- **These electrons and holes are responsible for conduction of current.**
- **In intrinsic semiconductors, number of free electrons = number of holes**

  $n_e = n_h = n_i$

  Here,

  n_e is the number density of free electrons i.e. number of free electrons per unit volume.

  n_h is the number density of holes i.e. number of holes per unit volume.

  n_i is intrinsic (pure) charge density i.e. number of free charges per unit volume.

  Note:

  It should be noted that holes correspond to vacancy or deficiency of electrons in covalent bonds.Practically, holes do not move.For convenience holes are considered positive and direction of flow of holes is taken as conventional direction of current, the same concept as used in current electricity.
- **The total current in a semiconductor is the sum of electronic current and hole current. Electrons move in the conduction band and holes move in the valence band. Therefore, total current is given by**

  $I = I_e + I_h$
- **As discussed above, very few covalent bonds break away at room temperature, hence intrinsic (pure) semiconductors show very small electrical conductivity at room temperature.**

Why Silicon and Germanium?

Carbon, Si and Ge have the same lattice structure. Why is carbon an insulator while Si and Ge are intrinsic semiconductors?

Answer

The 4 bonding electrons of C, Si and Ge lie, respectively, in the second, third and fourth orbit. Hence, energy required to take out an electron from these atoms (i.e., ionisation energy E_g) will be least for Ge, followed by Si and highest for C.

Hence, the number of free electrons for conduction in Ge and Si are significant but negligibly small for C.

Making Semiconductors Better Conductors

- The conductivity of an intrinsic semiconductor depends on its temperature, but at room temperature its conductivity is very low. As such, no important electronic devices can be developed using these semiconductors. Hence there is a necessity of improving their conductivity. This can be done by making use of **suitable impurities**.
  Impurity means any material added to pure material in very small quantities.
- When a small amount, say, a few parts per million (ppm), of a suitable impurity is added to the pure semiconductor, the conductivity of the semiconductor is increased manifold. To increase the conductivity of intrinsic semiconductors some impurities are added in intrinsic semiconductors**. This process is called Doping.**

Doping

It is the deliberate and controlled addition of impurities in intrinsic semiconductors to enhance their electrical conductivity in a controlled manner. The impurities added are atoms of either pentavalent or trivalent atoms.

For doping process following requirements are considered:

- The size of a dopant atom should be of the same order as that of a semiconductor atom.
- The dopant atom should not disturb the semiconductor crystal lattice.
- The doping should normally be done in very small quantity of the order 1ppm (**parts per million)**

Methods of Doping

Doping can be done by one of the following methods;

- By bombarding high energy dopant atoms on a crystalline semiconductor.
- By adding dopant atoms in a molten semiconductor.
- By heating semiconductors in an atmosphere of dopant atoms.

Purpose of doping is to create an imbalance in the semiconductor so that more current flows in the semiconductor. By doping either we increase the number of electrons over holes or increase the number of holes over electrons.

Extrinsic Semiconductors

- Semiconductors to which impurities are added to increase conductivity are known as extrinsic semiconductors or impurity semiconductors.
- As we said above, the deliberate addition of a desirable impurity is called doping and the impurity atoms are called dopants. Such a material is also called a doped semiconductor.
- The dopant has to be such that it does not distort the original pure semiconductor lattice.
- It occupies only a very few of the original semiconductor atom sites in the crystal. A necessary condition, to attain this is that the sizes of the dopant and the semiconductor atoms should be nearly the same.

There are two types of dopants used in doping the tetravalent Si or Ge element:

- Pentavalent dopants (valency 5); like **Arsenic (As), Antimony (Sb), Phosphorous (P)**, etc.
- Trivalent dopants (valency 3); like **Indium (In), Boron (B), Aluminium (Al)**, etc.

We shall now discuss

- How doping changes, the number of charge carriers (and hence the conductivity) of semiconductors.
- Si or Ge belongs to the fourth group in the Periodic table and, therefore, we choose the dopant element from the nearby fifth or third group, expecting and taking care that the size of the dopant atom is nearly the same as that of Si or Ge.
- Interestingly, the pentavalent and trivalent dopants in Si or Ge give two entirely different types of semiconductors

Extrinsic semiconductors are of two types:

- **p-type semiconductors**, these are formed by doping elements like Si and Ge with trivalent atoms.
- **n-type semiconductors**, these are formed by doping elements like Si and Ge with pentavalent atoms.

These are the Doped semiconductors having larger conductivity as compared to an intrinsic one.

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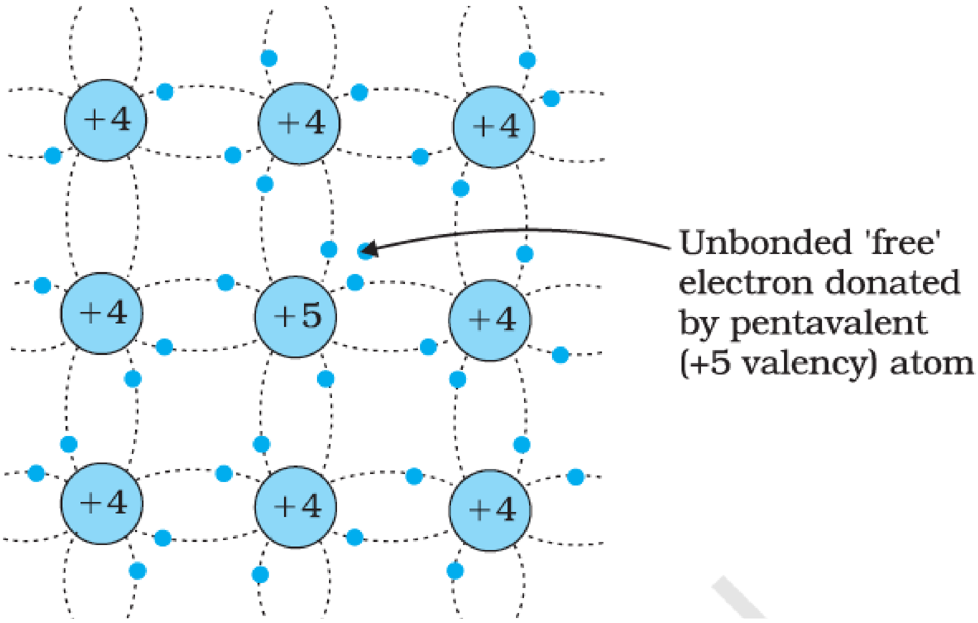
n-Type Semiconductor

Suppose we dope Si or Ge with a **pentavalent element {like Arsenic (As), Antimony (Sb), Phosphorous (P)}**, as shown in Figure



When an atom of + 5 valency element occupies the position of an atom in the crystal lattice of Si, four of its electrons bond with the four silicon neighbours while the fifth remains very weakly bound to its parent atom. This is because the four electrons participating in bonding are seen as part of the effective core of the atom by the fifth electron.

As a result, the ionisation energy required to set this electron free is very small and even at room temperature it will be free to move in the lattice of the semiconductor.

For Example

- The energy required is ~ 0.01 eV for germanium, and 0.05 eV for silicon, to separate this electron from its atom. This is in contrast to the energy required to jump the forbidden band (about 0.72 eV for germanium and about 1.1 eV for silicon) at room temperature in the intrinsic semiconductor.

Thus,

- The pentavalent dopant is donating one extra electron for conduction and hence is known as donor impurity.
- The number of electrons made available for conduction by dopant atoms depends strongly upon the doping level and
- It is independent of any increase in ambient temperature.

On the other hand, the number of free electrons (with an equal number of holes) generated by breaking of bonds in Si atoms, increases weakly with temperature.

- In a doped semiconductor the total number of conduction electrons n_e is due to the electrons contributed by donors and those generated intrinsically, while the total number of holes n_h is only due to the holes from the intrinsic source.
- Total number of conduction electrons = electrons contributed by donors + electrons generated intrinsically + holes generated intrinsically

But,

- The rate of recombination of holes would increase due to the increase in the number of electrons. As a result, the number of holes would get reduced further.

Thus,

- With the proper level of doping, the number of conduction electrons can be made much larger than the number of holes.

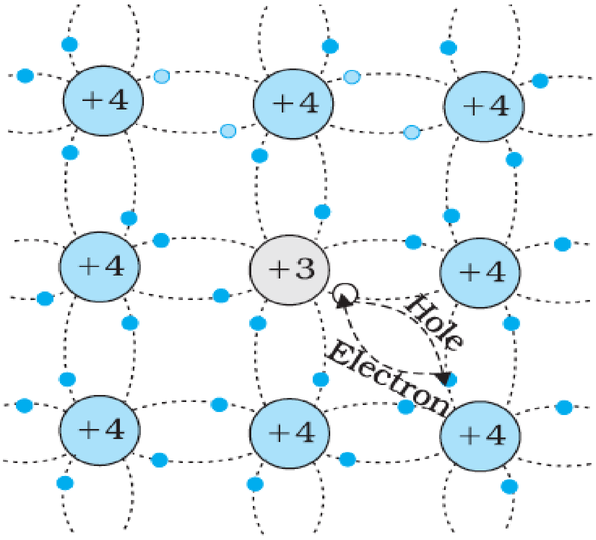
Hence in an extrinsic semiconductor doped with pentavalent impurity, electrons become the majority carriers and holes the minority carriers.

These semiconductors are, therefore, known as **n-type semiconductors**. For n-type semiconductors, we have,

$$n_e >> n_h$$

p-Type Semiconductor

This is obtained when Si or Ge is doped with a **trivalent impurity like Al, B, In** etc. The dopant has one valence electron less than Si or Ge and, therefore, this atom can form covalent bonds with neighbouring three Si atoms but does not have any electron to offer to the fourth Si atom. So the bond between the fourth neighbour and the trivalent atom has a vacancy or hole as shown in Figure



- Trivalent acceptor atom (In, Al, B etc.) doped in tetravalent Si or Ge lattice giving p-type semiconductor
- Since the neighbouring Si atom in the lattice wants an electron in place of a hole, an electron in the outer orbit of an atom in the neighbourhood may jump to fill this vacancy, leaving a vacancy or hole at its own site. Thus the hole is available for conduction.

Note that the trivalent foreign atom becomes effectively negatively charged when it shares fourth electron with neighbouring Si atom.

- Therefore, the dopant atom of p-type material can be treated as the core **of one negative charge** along with its associated hole.
- It is obvious that **one acceptor** atom gives **one hole**. These holes are in addition to the intrinsically generated holes while the source of conduction electrons is only intrinsic generation.
- Thus, for such a material, the holes are the majority carriers and electrons are minority carriers.
- Therefore, extrinsic semiconductors doped with trivalent impurity are called p-type semiconductors.

For p-type semiconductors, the recombination process will reduce the number (n_I) of intrinsically generated electrons to n_e.

We have, for p-type semiconductors

$$n_h >> n_e$$

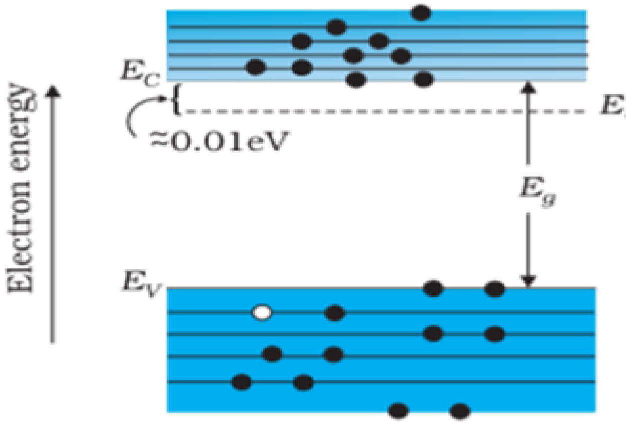
Important

- Note that the crystal maintains an overall charge neutrality as the charge of additional charge carriers is just equal and opposite to that of the ionised cores in the lattice.
- In extrinsic semiconductors, because of the abundance of majority current carriers, the minority carriers produced thermally have more chance of meeting majority carriers and thus getting annihilated.
- Hence, the dopant, by adding a large number of current carriers of one type, which become the majority carriers, indirectly helps to reduce the intrinsic concentration of minority carriers.

What Happens to the Energy Band Structure

- The semiconductor’s energy band structure is affected by doping.

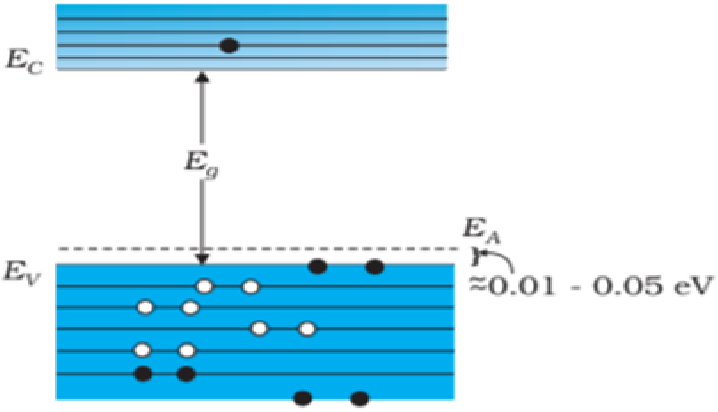
- In the case of extrinsic semiconductors, additional energy states due to donor impurities (E_D) and acceptor impurities (E_A) also exist.
- In the energy band diagram of n-type Si semiconductor, the donor energy level E_D is slightly below the bottom E_C of the conduction band ,thus electrons from this level move into the conduction band with a very small supply of energy. At room temperature, most of the donor atoms get ionised but very few ($\sim 10^{-12}$) atoms of Si get ionised. So the conduction band will have most electrons coming from the donor impurities, as shown in Figure



(a) $T > 0K$
one thermally generated electron-hole pair + 9 electrons from donor atoms

The donor energy level E_D is slightly below the lowest level E_C of the conduction band as shown in figure

Similarly, for *p* type semiconductor



(b) $T > 0K$

- The acceptor energy level E_A is slightly above the top E_V of the valence band as shown in figure.

- With a very small supply of energy an electron from the valence band can jump to the level E_A and ionise the acceptor negatively. (Alternatively, we can also say that with a very small supply of energy the hole from level sinks down into the valence band. Electrons rise up and holes fall down when they gain external energy.)
- At room temperature, most of the acceptor atoms get ionised leaving holes in the valence band. Thus at room temperature the density of holes in the valence band is predominantly due to impurity in the extrinsic semiconductor.

  The electron and hole concentration in a semiconductor **in thermal equilibrium is given by**

$$n_e n_h = n_i^2$$

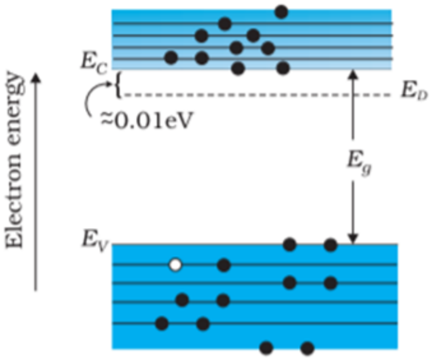
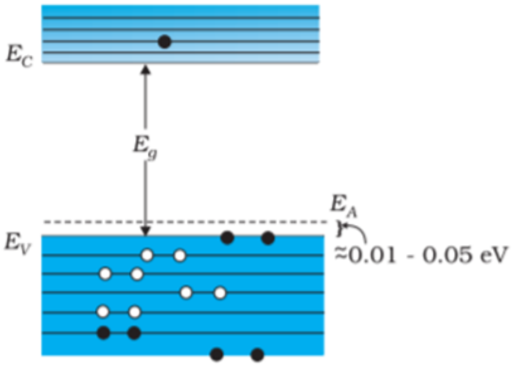
- Though the above description is grossly approximate and hypothetical, it helps in understanding the difference between metals, insulators and semiconductors (extrinsic and intrinsic) in a simple manner. The difference in the resistivity of C, Si and Ge depends upon the energy gap between their conduction and valence bands.
- For C (diamond), Si and Ge, the energy gaps are 5.4 eV, 1.1 eV and 0.7 eV, respectively.
- Sn also is a group IV element but it is a metal because the energy gap in its case is 0 eV.

Difference Between Intrinsic and Extrinsic Semiconductor

Intrinsic semiconductor	**Extrinsic semiconductor**
It is a pure natural semiconductor such as silicon and germanium.	It is obtained by adding a small quantity of nearly same size atom , Aluminium, Indium, Boron, Arsenic, phosphorous.
Conduct mildly at room temperature.	Conduct well, the conductivity can be controlled by amount of doping.
The concentration of electrons and holes are equal $n_e = n_h$ $n_e n_h = n_i^2$	The concentration is such that either $n_e >> n_h$ $n_e << n_h$ $n_e n_h = n_i^2$

Conductivity cannot be controlled much.	The conductivity can be controlled by nature and amount of doping.
Conductivity can increase exponentially with temperature.	Conductivity increases with temperature .

Difference Between n-Type and p-Type Extrinsic Semiconductors

***n*-type semiconductor**	***p*-type semiconductor**
It is obtained by adding a pentavalent impurity to a pure intrinsic semiconductor.	It is obtained by adding a trivalent impurity to a pure intrinsic semiconductor.
The impurity atoms added provide extra free electrons to the crystal lattice and are called donor atoms.	The impurity atoms added provide extra free holes to the crystal lattice and are called acceptor atoms.
Donor energy levels lie just below the conduction band  (a) $T > 0K$ one thermally generated electron-hole pair + 9 electrons from donor atoms	Acceptor energy levels lie just above the valence band  (b) $T > 0K$
The electrons are majority carriers in the conduction band and holes are minority carriers in the valence band.	The holes are majority carriers in the valence band and electrons are minority carriers in the conduction band.
The electron concentration per unit volume is higher than hole concentration.	The hole concentration per unit volume is higher than electron concentration.

Net Charge on *p*-Type and *n*-Type Semiconductors

- The p-type has holes (which are treated + ve) in majority and n-type have electrons in majority. Does that mean p-type semiconductors are positively charged and n-type semiconductors are negatively charged?

Answer to this is no, both are neutral. Amazed?

Let us see and understand this.

- We know that an atom is electrically neutral. So dopant atoms as well as semiconductor atoms both are electrically neutral.
- This means that each atom has an equal number of electrons and protons.
- Then how can charge develop on p-type and n- type?

Let's understand it with an example,

- Suppose in n-type silicon (Si) is doped with phosphorus (P)
- Atomic no. of Si is 14 and atomic no. of P is 15
- Number of electron in Si =14 and no. of electrons in P =15
- Number of protons in Si =14 and no. of protons in P = 15
- Total number of electrons in n-type (Si + P) =14 + 15 = 29
- Total number of protons in n-type (Si + P) = 14 + 15 = 29

From above example we conclude that net charge on p-type and n-type is zero because,

Total number of electrons = Total number of protons

Example

A silicon specimen is made into a p-type semiconductor by doping on an average, one indium atom per 5×10^7 silicon atoms. If the number density of silicon atoms is 5×10^{28} atoms/m^3, calculate the number of acceptor atoms in the silicon sample per cubic centimetre.

Solution

First we find the number of indium atoms per cubic meter. As rate of doping is one indium atom per 5×10^7 silicon atoms, therefore,

$$\text{Total number of indium atoms} = \frac{Total\ number\ of\ silicon\ atoms\ per\ m3}{rate\ of\ doping}$$

$$= \frac{5\times10^{28}}{5\times10^{7}} \text{ atoms per m}^3$$

$$= 10^{21} \text{ atoms per m}^3$$

$$= \mathbf{10^{15}\ indium\ atoms\ per\ cm^3}$$

Example

The number densities of holes and electrons in pure silicon are equal and are 2×10^{16} per m^3. On doping with indium, the hole density increases to $4.5\times10^{22}\ m^{-3}$.Find the electron density in doped silicon.

Solution

We know for pure semiconductor,

$$n_e = n_h = n_i = 2\times10^{16} m^{-3}$$

For doped semiconductor,

$$n_e n_h = n_i^2$$

given, $n_h = 4.5\times10^{22}\ m^{-3}$

therefore, $n_e = \frac{n_i^3}{n_h}$

$= (2\times10^{16})^2 / 4.5\times10^{22}$

$\mathbf{= 8.89\times10^9\ m^{-3}}$

Example

Suppose a pure Si crystal has 5×10^{28} atoms per cubic meter. It is doped by pentavalent atoms at the rate one atom per million of Si atoms. Find the number density of electrons and holes if, $n_i = 1.5\times10^{16}$ per cubic metre.

Solution

Number of doping atoms = number of silicon atoms (rate of doping)

$= 5\times10^{28}/10^6$

$= 5\times10^{22}$ per m^3

In n- type, n_e = number of doped atoms

$\mathbf{= 5\times10^{22}}$ **per** $\mathbf{m^3}$

In doped semiconductors,

$$n_e n_h = ni^2$$

no. density of holes $n_h = ni^2/n_e$

$$= \frac{(1.5\times10^{16})^2}{5\times10^{22}}$$

$\mathbf{= 4.5\times10^9}$ **per** $\mathbf{m^3}$

Example

Find the maximum wavelength of electromagnetic radiation, which can create electron-hole pairs in germanium. Given that The forbidden energy gap in germanium is 0.72eV, Planck's constant h = 6.62×10^{-34} J-s.

Solution

$E_g = 0.72\text{eV} = 0.72\times1.6\times10^{-19}$ J

Also, $E_g = h\nu$ or $E_g = hc/\lambda$

$\lambda = hc/E_g$

$= (6.62\times10^{-34}) \times (3\times10^{8}) / 0.72\times1.6\times10^{-19}$

$\lambda = 1.724 \times10^{-6}$ m

Questions Practice

1. **A semiconductor has equal electron and hole concentration of 6×10^{8} per m^3. On doping with certain impurity, electron concentration increases to $9\times10^{12}/m^3$.**
   (i) **Identify the new semiconductor obtained after doping.**
   (ii) **Find new hole concentration**.
   [Ans: (i) n-type (ii) 4×10^{4}/m3]

2. **In pure silicon, the number of conduction electrons is 6×10^{19} per m^3. Find the total no. of current carriers (electrons and holes) in the same semiconductor of size 1cm×1cm×1mm**.
   [Ans. 12×10^{12}]

3. **In a photodiode the conductivity increases when exposed to light. It is found the conductivity increases only if wavelength is less than 620 nm. What is the energy gap?**
   Given h = 6.6×10^{-34} J-s
   [Ans: 1.995eV]

Summary

We have learnt in this module

Intrinsic Semiconductors

- These are pure semiconductors without any impurity. They show very small electrical conductivity at room temperature.

  - Whenever a covalent bond breaks, an electron-hole pair is generated.
  - Holes are vacancies in covalent bonds.
  - Holes are treated as positively charged.
  - Actually holes do not move, it is the electrons near them that fill their vacancy, creating a hole instead. This is like a hole is moving in the solid. (think of it as musical chairs or kho-kho)
  - In intrinsic semiconductors $n_e = n_h = n_i^2$

    Where, n_e and n_h are electron and hole densities. n_i is called intrinsic charge density.

Doping

- It is the process of addition of suitable impurities in intrinsic semiconductors to increase their electrical conductivity.
  - Doping is done in very small quantities with pentavalent or trivalent atoms.
  - The dopant energy bands allow easy creation of majority carriers electrons in n type and holes in p type.
  - There are different methods adopted for doping.

Extrinsic Semiconductors

- These are pure semiconductors with suitable impurities. They have good electrical conductivity
- ***p*-type semiconductors**, these are formed by doping with trivalent atoms.

  $$\mathbf{n_h >> n_e}$$

- ***n*-type semiconductors**, these are formed by doping with pentavalent atoms.

  $$\mathbf{n_h >> n_e}$$