Total current = electron current + hole current

or, $I_t = I_e + I_h$

Extrinsic Semiconductors/Doped Semiconductors/Impure Semiconductor

As we know, intrinsic or pure semiconductors have small conductivity at room temperature. Therefore, they are not of much use.

By adding some amount of impurity atoms to a pure or intrinsic semiconductor, we can change its conductivity or characteristics.

Doping:- Doping is a process where impurity atoms are added to pure or intrinsic semiconductor in order to increase the conductivity.

Doping is done at a rate such that only one atom of impurity is added per 10^6 to 10^{10} semiconductor atoms i.e., in the ratio $\frac{1}{10^6}$ or $\frac{1}{10^{10}}$

We add impurities to increase the number of electrons or holes in a semiconductor.

The impurity materials that are added can be of two types:-

ⓐ Donor Impurity or Pentavalent Impurity

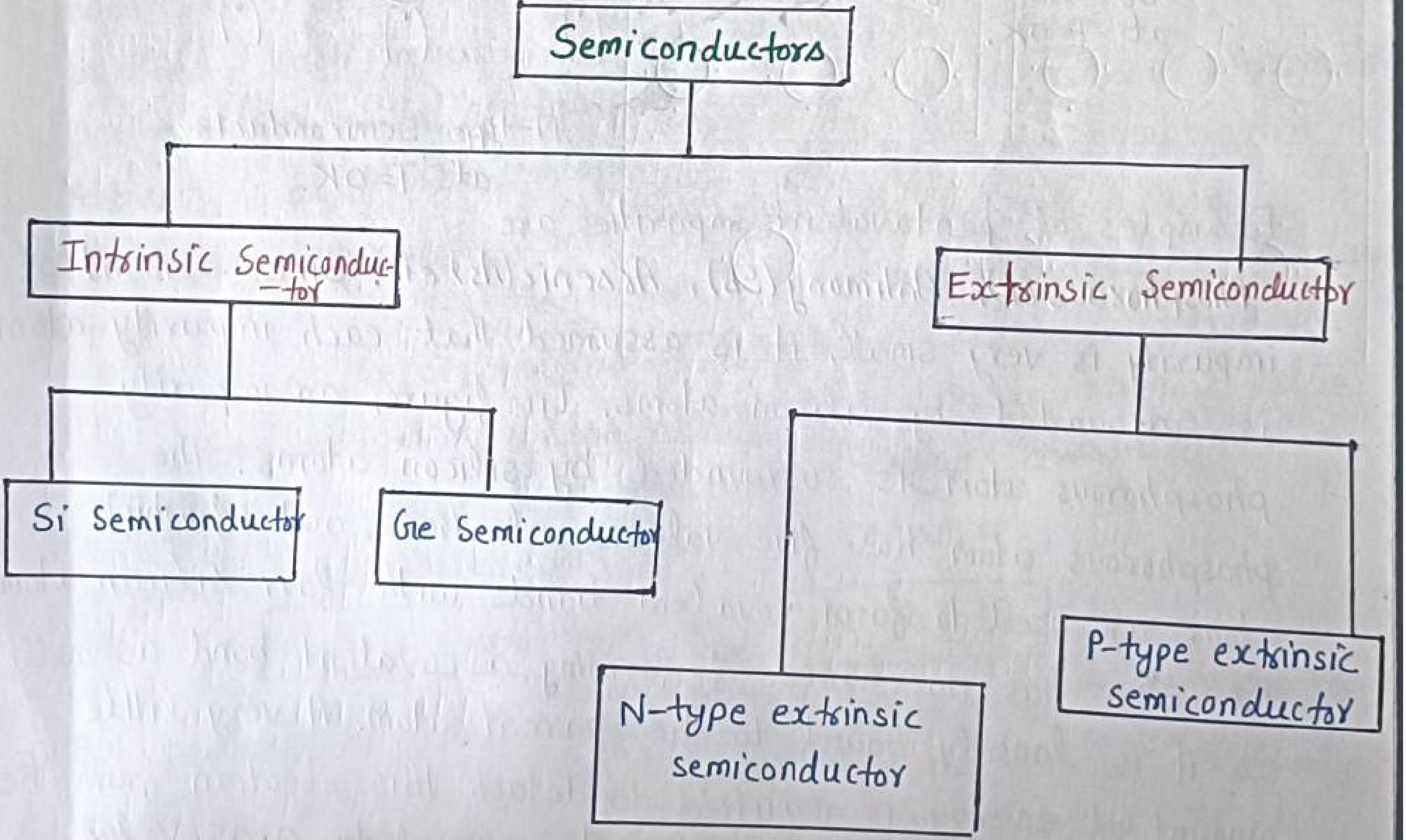
The material which is used as impurity in the process of doping is called as dopant. When the dopant is a pentavalent atom i.e., the atom containing five electrons in the outer-most shell, then it is called as donor impurity and the doping is called as donor doping. Donor doping is used to manufacture N-type extrinsic semiconductor.

Examples:- Phosphorous, Antimony, Arsenic and Bismuth.

ⓑ Acceptor Impurity or Trivalent Impurity

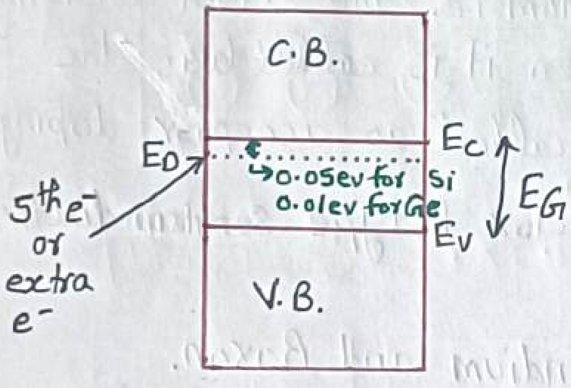
When the dopant is a trivalent atom i.e., the atom consisting of only three valence electrons, then it is called as the acceptor impurity and the doping is called as acceptor doping. Acceptor doping is used to manufactor P-type extrinsic semiconductors.

Examples:- Aluminium, Gallium, Indium and Boron.

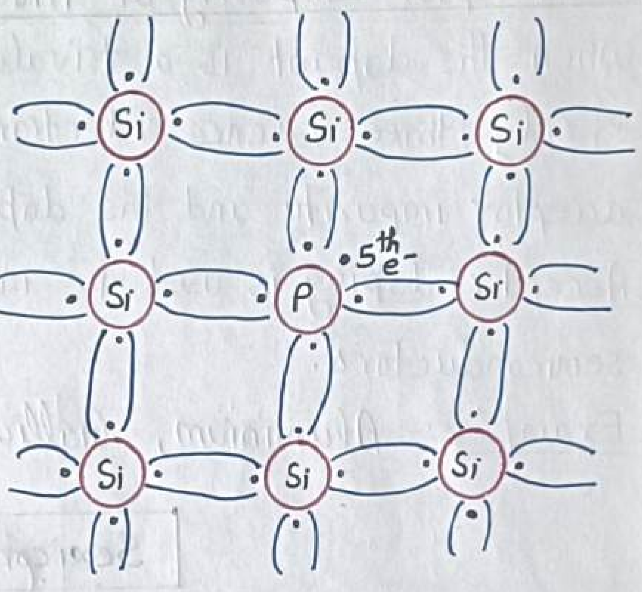


① N-type Extrinsic Semiconductor

If pentavalent impurity atoms are added to intrinsic semiconductor, N-type extrinsic semiconductor is obtained. The pentavalent impurity atoms have five electrons in the valence shell.



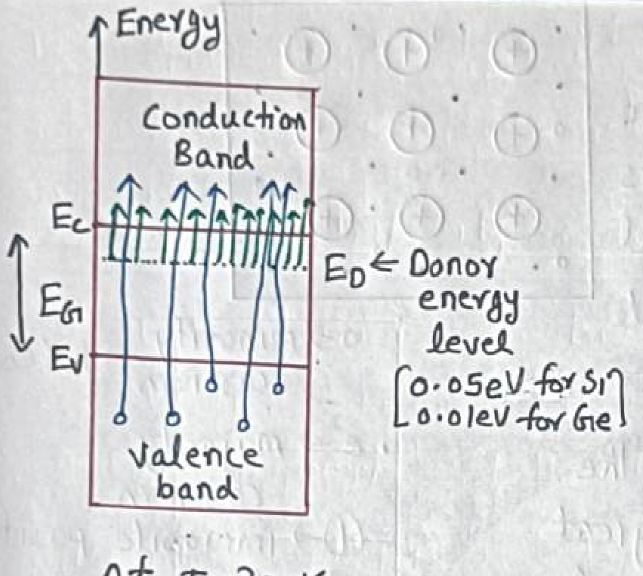
Energy band diagram at T=0K.



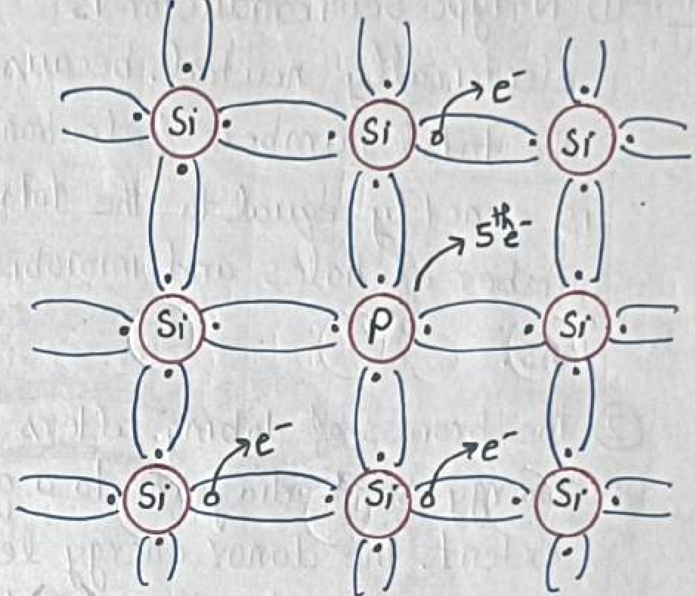
N-type semiconductor at T=0K.

Examples of pentavalent impurities are Phosphorous (P), Antimony (Sb), Arsenic (As) etc. Since amount of impurity is very small, it is assumed that each impurity atom is surrounded by silicon atoms. In figure, an impurity phosphorous atom is surrounded by silicon atoms. The phosphorous atom has five valence electrons, out of which four are used to form covalent bonds with four silicon atoms. The 5th e⁻ has no chance of forming a covalent bond as well as it is loosely bound to the parent atom. A very little amount of energy is required to detach this electron from the nucleus of its parent atom and it is equal to 0.05eV for Silicon and 0.01eV for Germanium.

At T=0K, N-type-semiconductor acts as Insulator since their is no free charge carriers available to conduct current.



At T=300K



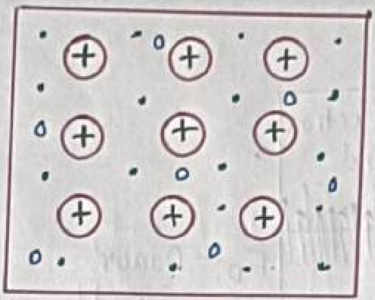
N-type Semiconductor at T=300K

When little amount of energy is provided, each impurity atom donates one electron to the conduction band. Due to this reason, pentavalent impurity is also called donor type impurity. When temperature is further increased, some electron-hole pairs are also produced. As the concentration of electrons is large, it increases the rate of recombination of electrons with holes. Hence, the net concentration of holes is much less than intrinsic value. Therefore, in N-type semiconductor, electrons are majority carriers and holes are minority carriers.

$$\boxed{\sigma_N = \text{conductivity in N-type} \approx n_e q \mu_n} \text{ S/m}$$

The pentavalent impurity atom donates one electron. After donating this electron, the impurity atom becomes a positively charged ion. This is called as donor ion. They are immobile charged ion because they are tightly held by four covalent bonds.

N-type semiconductor representatio



o → minority carriers → holes

• e^- → majority carriers

⊕ → immobile positively charged ion.

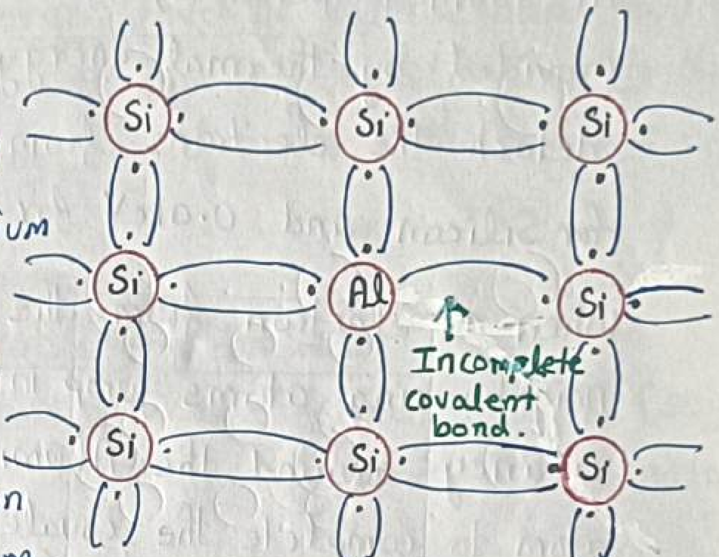
Note:- ① N-type semiconductor is electrically neutral. because the total number of electrons is exactly equal to the total number of holes and immobile ions.

② The process of doping alters the energy-band diagram to a great extent. The donor energy level (E_D) is shown by the dotted lines and it is very close to the conduction band energy level E_C. Therefore, the unbonded valence electrons of the impurity atoms can very easily jump into the conduction band and become free electrons. So, at room temperature, almost all the extra electrons (or 5th e^-) of the pentavalent impurity will jump to the conduction band. Hence, a large number of free electrons are available for conduction in N-type semiconductor.

② P-type Extrinsic Semiconductor

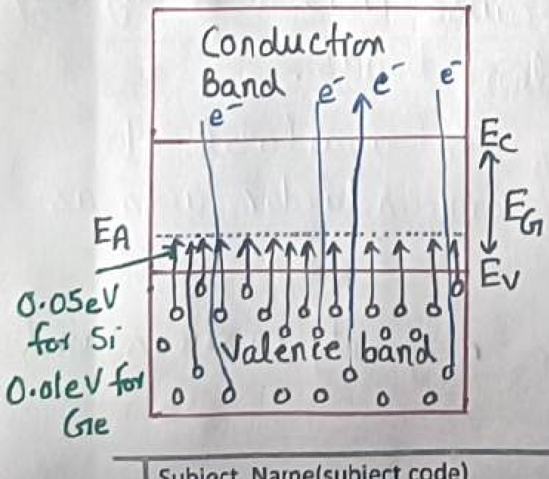
If trivalent impurity atoms are added to intrinsic semiconductor P-type semiconductor is obtained. The trivalent impurity atoms have three electrons in the valence shell. The trivalent impurities are boron, aluminium, gallium and indium. Consider a sample of intrinsic silicon to which a very small amount of trivalent impurity such as aluminium is added. Since amount of impurity is very small, it may be considered that each impurity atom is surrounded by silicon atoms.

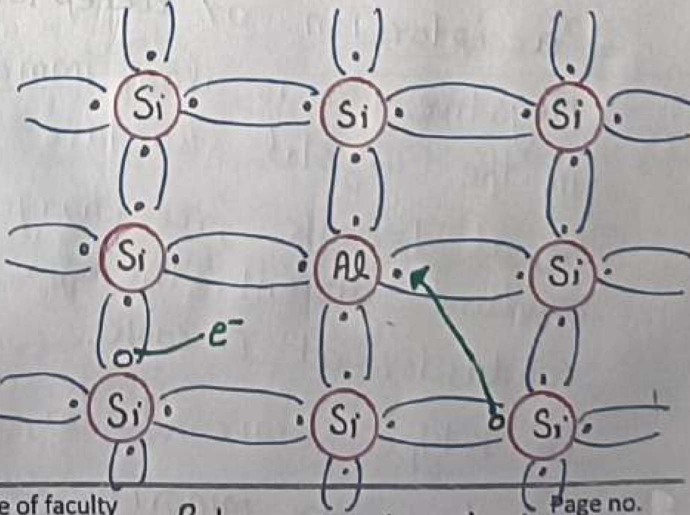
In figure, an impurity atom [Aluminium Al] is surrounded by silicon atoms. The Aluminium atom has three valence electrons and these electrons form covalent bonds with the three neighbouring silicon atoms. The fourth silicon atom cannot make a covalent bond with the Aluminium atom because the Al-atom does not have fourth valence electron. Hence, the fourth covalent bond is incomplete. This vacancy in the incomplete covalent bond have a tendency to complete the covalent bond with the neighbouring atoms.



P-type semiconductor at T=0K

At T=0K, there is no free charge carriers available for the conduction, so P-type semiconductor acts as an Insulator.



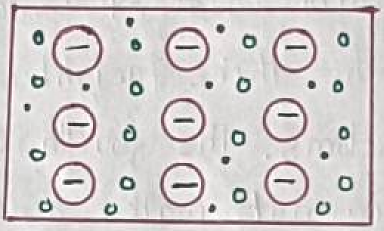


P-type Semiconductor at T= 300K

An electron from neighbouring atoms require some energy to jump into the vacancy.

At room temperature, this small amount of energy is provided by thermal energy. The energy required to detach the electrons from the covalent bond is 0·05eV for Silicon and 0·01eV for Germanium.

When an electron from the neighbouring atoms jump into the vacancy around the Aluminium atom to complete the covalent bonds, the effect is two fold. Firstly, another vacancy or hole is created in the covalent bond of surrounding atom from where the electron had jumped. Secondly, after acquiring an electron, the aluminium atom becomes a negative ion. Since, aluminium atom accepts one electron to become negative ion, it is also called acceptor ion or acceptor type impurity.



Representation of P-type semiconductor.

○→ majority carriers (holes)

•→ minority carrier (electron)

⊖→ negatively charged immobile ion

Negative ion is also immobile because it is held tightly in the crystal structure by covalent bonds.

So, at T=300K free charge carriers are available to conduct current. Therefore, P-type semiconductor acts as conductor at T=300K.

In P-type semiconductor, holes are majority carriers and electrons are minority carriers.

As a whole, P-type material is electrically neutral.

The energy level of acceptor impurity (E_A) is shown by dotted lines and it is very close to the energy level of valence band (E_V). Therefore, the valence band electrons can very easily jump to the acceptor energy level E_A leaving behind holes in the valence band.

Effect of Temperature on Extrinsic Semiconductor

When we increase the temperature of extrinsic semiconductor [say N-type semiconductor is used] then all the donor atoms will donate their 5th e^- or extra-electron into the conduction band. Now, if temperature is further increased [T>300K] then due to the thermal agitation covalent bonds will break and charge carriers will be generated. Due to this, the concentration of minority carriers will increase.

In this process, a temperature is reached when the number of covalent bonds broken is quite large such that the number of holes is nearly equal to the number of electrons. Therefore, the extrinsic semiconductor now acts like an intrinsic semiconductor with higher conductivity. This critical temperature is 200°C for Si and 85°C for Ge.

Comparison b/w Metals & SC

S:N	Metals [Conductors]	Semiconductors
1:-	Charge carriers are only electrons	→ Charge carriers are electrons & holes
2:-	Crystalline	→ Crystalline
3:-	Has low resistivity or high conductivity	→ Has moderate conductivity
4:-	Carrier density is high.	→ Carry density is moderate.
5:-	Resistivity increases with temperature	→ Resistivity decreases with temperature
6:-	Current flows only by drift process.	→ Current flows due to both drift and diffusion.

Comparison between Intrinsic and Extrinsic Semiconductor

S.N	Parameter	Intrinsic Semiconductors	Extrinsic Semiconductors
1	Purity	Extremely pure, No impurity is added	Not pure as it contains impurity atoms.
2	Doping	Not done	Is done
3	Type	—	P-type and N-type
4	Number of electrons & holes	Number of electrons is always to no. of holes	They are never equal to each other
5	Conductivity	Poor	Much higher
6	Current conduction	Due to electrons and holes	Mainly due to e^-s or holes depending on type of semiconductors
7	Position of Fermi level	At the centre of the forbidden gap.	It is either near the C.B or near the valence band.
8	Applications	None	For manufacturing of electronic components.

Electrical Properties of Si and Ge

S.N	Property	Silicon (Si)	Germanium (Ge)
1	Atomic Number	14	32
2	Atoms/cm^3	5×10^{22}	3.4×10^{22}
3	E_G(eV) at 0°K	1.12	0.785
4	E_G(eV) at 300°K	1.1	0.72
5	Intrinsic Concentration n_i at 300°K/cm^3	1.5×10^{10}	2.5×10^{13}
6	Intrinsic resistivity at 300K, Ω-cm	2,30,000	45
7	Electron mobility μ_n at 300K, cm^2/V-sec	1,300	3,800
8	Hole mobility μ_p at 300 K, cm^2/V-sec	500	1,800