1.4 Semiconductor

1.4.1 Introduction

Based on the electrical conductivity all the materials in nature are classified as insulators, semiconductors, and conductors.

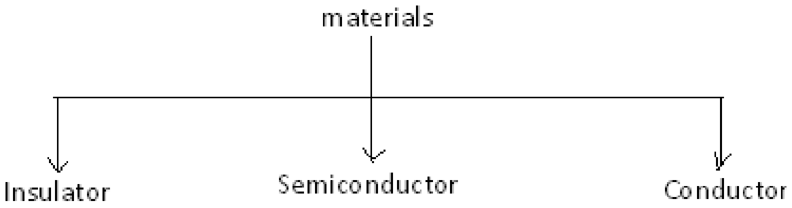


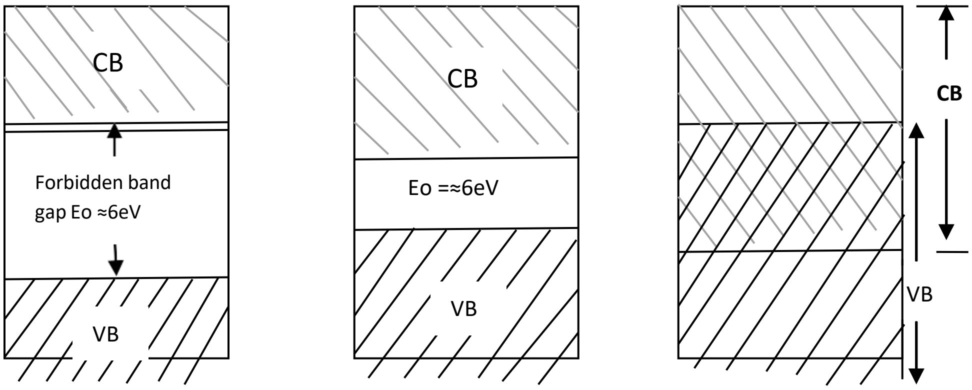
Fig.1.15 Types of Materials

1.4.1.1 Insulator: An insulator is a material that offers a very low level (or negligible) of conductivity when voltage is applied. Eg: Paper, Mica, glass, quartz. Typical resistivity level of an insulator is of the order of 10^{10} to 10^{12} Ω-cm. The energy band structure of an insulator is shown in the Fig.1.15. Band structure of a material defines the band of energy levels that an electron can occupy. Valance band is the range of electron energy where the electron remain bended too the atom and do not contribute to the electric current. Conduction bend is the range of electron energies higher than valance band where electrons are free to accelerate under the influence of external voltage source resulting in the flow of charge.

The energy band between the valance band and conduction band is called as forbidden band gap. It is the energy required by an electron to move from balance band to conduction band i.e. the energy required for a valance electron to become a free electron.

$$1 \text{ eV} = 1.6 \text{ x } 10^{-19} \text{ J}$$

For an insulator, as shown in the Fig.1.16 there is a large forbidden band gap of greater than 5Ev. Because of this large gap there a very few electrons in the CB and hence the conductivity of insulator is poor. Even an increase in temperature or applied electric field is insufficient to transfer electrons from VB to CB.



Insulator Semiconductor Conductor

Fig.1.16 Energy band diagrams insulator, semiconductor and conductor

1.4.1.2 Conductors: A conductor is a material which supports a generous flow of charge when a voltage is applied across its terminals. i.e. it has very high conductivity. Eg: Copper, Aluminum, Silver, Gold. The resistivity of a conductor is in the order of 10^{-4} and 10^{-6} Ω-cm. The Valance and conduction bands overlap Fig.1.16 and there is no energy gap for the electrons to move from valance band to conduction band. This implies that there are free electrons in CB even at absolute zero temperature (0K). Therefore at room temperature when electric field is applied large current flows through the conductor.

1.4.2 Semiconductor: A semiconductor is a material that has its conductivity somewhere between the insulator and conductor. The resistivity level is in the range of 10 and 10^{4} Ω-cm. Two of the most commonly used are Silicon (Si=14 atomic no.) and germanium (Ge=32 atomic no.). Both have 4 valance electrons. The forbidden band gap is in the order of 1eV. For eg., the band gap energy for Si, Ge and GaAs is 1.21, 0.785 and 1.42 eV, respectively at absolute zero temperature (0K). At 0K and at low temperatures, the valance band electrons do not have sufficient energy to move from V to CB. Thus semiconductors act a insulators at 0K. as the temperature increases, a large number of valance electrons acquire sufficient energy to leave the VB, cross the forbidden bandgap and reach CB. These are now free electrons as they can move freely under the influence of electric field. At room temperature there are sufficient electrons in the CB and hence the semiconductor is capable of conducting some current at room temperature.

Inversely related to the conductivity of a material is its resistance to the flow of charge or current. Typical resistivity values for various materials' are given as follows.

Insulator	Semiconductor	Conductor
10^{-6} Ω-cm (Cu)	50Ω-cm (Ge)	10^{12} Ω-cm (mica)
	$50\text{x}10^{3}$ Ω-cm (Si)	

Fig.1.17 Typical resistivity values

1.4.2.1 Semiconductor Types

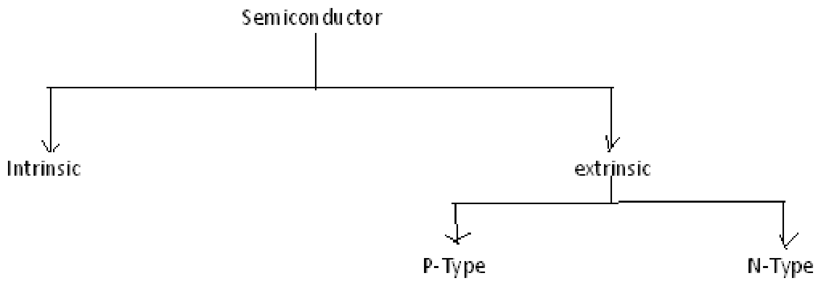


Fig.1.18 Types of Semiconductor

A pure form of semiconductors is called as intrinsic semiconductor. Conduction in intrinsic sc is either due to thermal excitation or crystal defects. Si and Ge are the two most important semiconductors used. Other examples include Gallium arsenide GaAs, Indium Antimonide (InSb) etc.

Let us consider the structure of Si. A Si atomic no. is 14 and it has 4 valance electrons. These 4 electrons are shared by four neighboring atoms in the crystal structure by means of covalent bond. Fig.1.19 shows the crystal structure of Si at absolute zero temperature (0K). Hence a pure SC acts has poor conductivity (due to lack of free electrons) at low or absolute zero temperature.

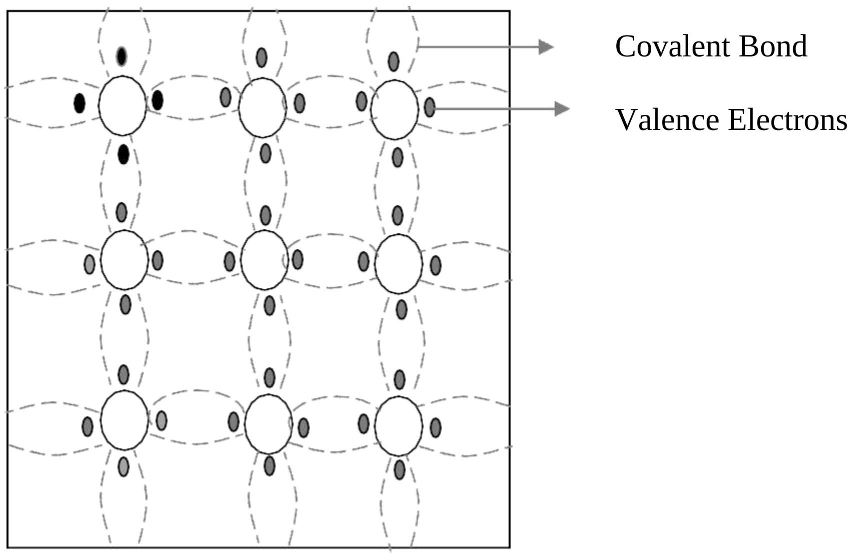


Fig.1.19 Crystal structure of Si at 0K

At room temperature some of the covalent bonds break up to thermal energy as shown in Fig.1.20. The valance electrons that jump into conduction band are called as free electrons that are available for conduction.

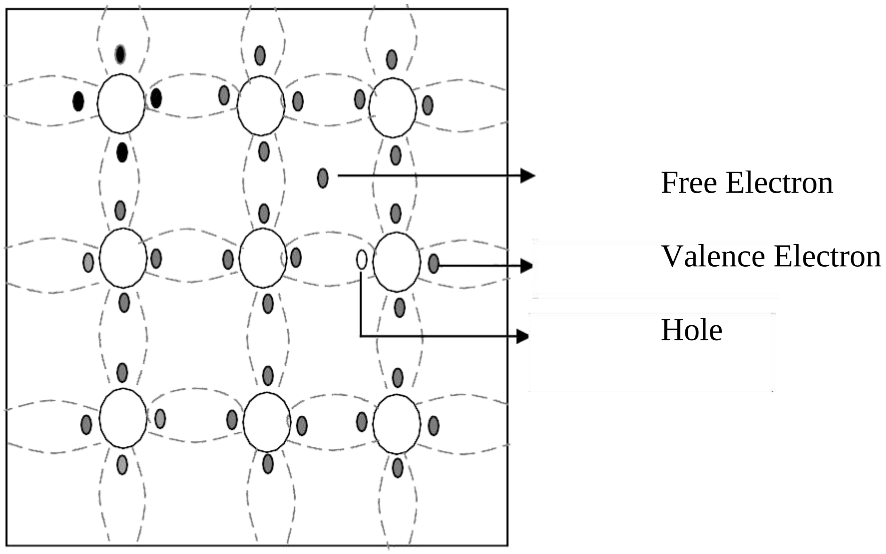


Fig.1.20 Crystal structure of Si at room temperature 0K

The absence of electrons in covalent bond is represented by a small circle usually referred to as hole which is of positive charge. Even a hole serves as carrier of electricity in a manner similar to that of free electron.

The mechanism by which a hole contributes to conductivity is explained as follows:

When a bond is in complete so that a hole exists, it is relatively easy for a valance electron in the neighboring atom to leave its covalent bond to fill this hole. An electron moving from a bond to fill a hole moves in a direction opposite to that of the electron. This hole, in its new position may now be filled by an electron from another covalent bond and the hole will correspondingly move one more step in the direction opposite to the motion of electron. Here we have a mechanism for conduction of electricity which does not involve free electrons. This phenomenon is illustrated in Fig. 1.21.

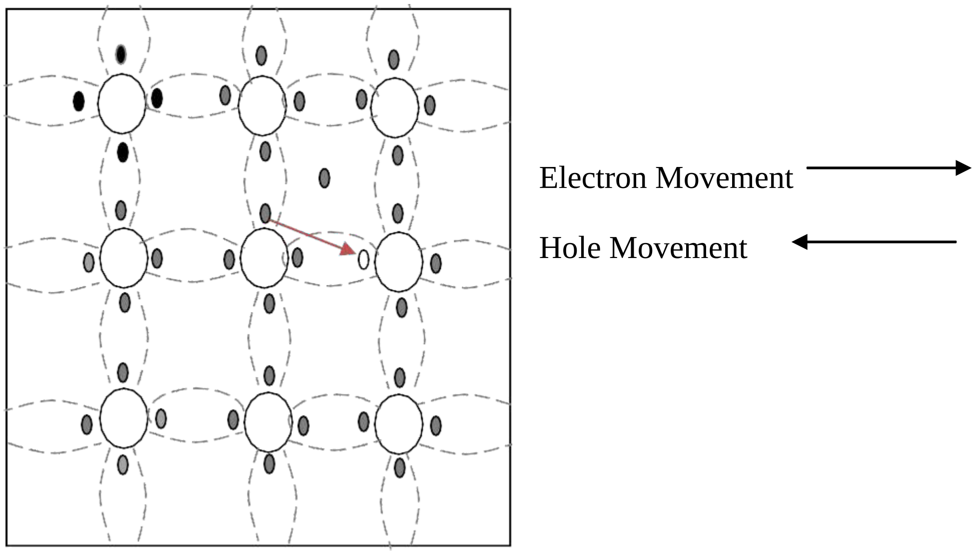


Fig. 1.21 (a)

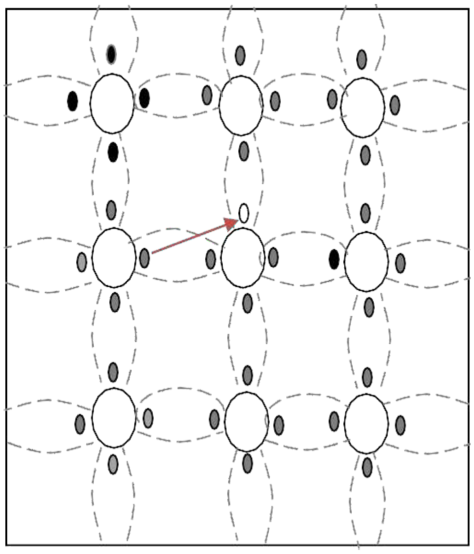


Fig. 1.21 (b)

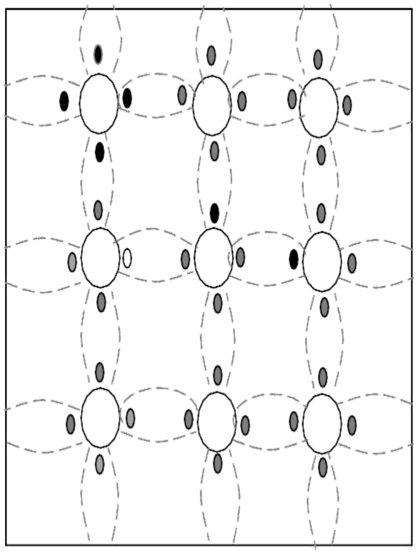


Fig. 1.21 (c)

Fig 1.21 (a) show that there is a hole at ion 6.Imagine that an electron from ion 5 moves into the hole at ion 6 so that the configuration of Fig 1.21 (b) results. If we compare both Fig. 1.21 (a) and Fig 1.21 (b), it appears as if the hole has moved towards the left from ion 6 to ion 5. Further if we compare Fig. 1.21 (b) and Fig. 1.21 (c), the hole moves from ion 5 to ion 4. This discussion indicates the motion of hole is in a direction opposite to that of motion of electron. Hence we consider holes as physical entities whose movement constitutes flow of current.

In a pure semiconductor, the number of holes is equal to the number of free electrons.

1.4.2.2 Extrinsic semiconductor

Intrinsic semiconductor has very limited applications as they conduct very small amounts of current at room temperature. The current conduction capability of intrinsic semiconductor can be increased significantly by adding a small amounts impurity to the intrinsic semiconductor. By adding impurities it becomes impure or extrinsic semiconductor. This process of adding impurities is called as doping. The amount of impurity added is 1 part in 10^6 atoms.

1.4.2.3 N type semiconductor: If the added impurity is a pentavalent atom then the resultant semiconductor is called N-type semiconductor. Examples of pentavalent impurities are Phosphorus, Arsenic, Bismuth, Antimony etc.

A pentavalent impurity has five valance electrons. Fig.1.22 (a) shows the crystal structure of N-type semiconductor material where four out of five valance electrons of the impurity atom(antimony) forms covalent bond with the four intrinsic semiconductor atoms. The fifth electron is loosely bound to the impurity atom. This loosely bound electron can be easily

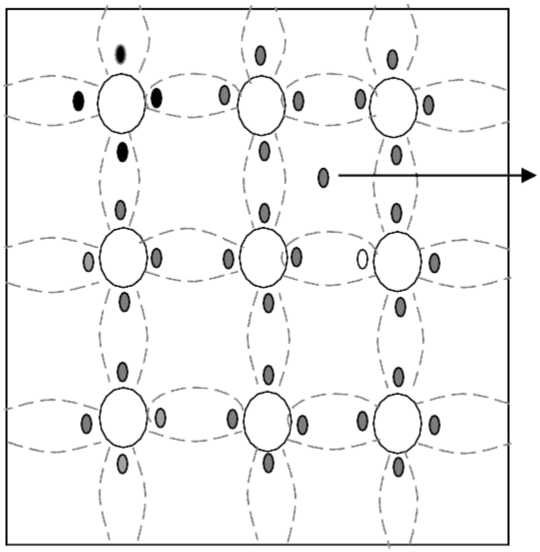


Fig.1.22 (a) Crystal structure of N type SC

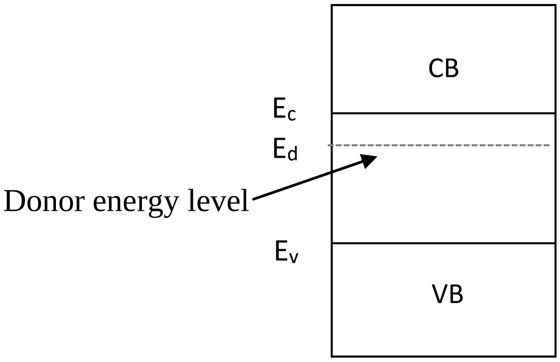


Fig. 1.22 (b) Energy band diagram of N type

Excited from the valance band to the conduction band by the application of electric field or increasing the thermal energy. The energy required to detach the fifth electron form the impurity atom is very small of the order of 0.01ev for Ge and 0.05 eV for Si.

The effect of doping creates a discrete energy level called donor energy level in the forbidden band gap with energy level Ed slightly less than the conduction band Fig. 1.22 (b) The difference between the energy levels of the conducting band and the donor energy level is the energy required to free the fifth valance electron (0.01 eV for Ge and 0.05 eV for Si). At room temperature almost all the fifth electrons from the donor impurity atom are raised to conduction band and hence the number of electrons in the conduction band increases significantly. Thus every antimony atom contributes to one conduction electron without creating a hole.

In the N-type sc the no. of electrons increases and the no. of holes decreases compared to those available in an intrinsic sc. The reason for decrease in the no. of holes is that the larger no. of electrons present increases the recombination of electrons with holes. Thus current in N type sc is dominated by electrons which are referred to as majority carriers. Holes are the minority carriers in N type sc

1.4.2.4 P type semiconductor: If the added impurity is a trivalent atom then the resultant semiconductor is called P-type semiconductor. Examples of trivalent impurities are Boron, Gallium , indium etc.

The crystal structure of p type sc is shown in the Fig. 1.23 (a). The three valance electrons of the impurity (boon) forms three covalent bonds with the neighboring atoms and a vacancy exists in the fourth bond giving rise to the holes. The hole is ready to accept an electron from the neighboring atoms. Each trivalent atom contributes to one hole generation and thus introduces a large no. of holes in the valance band. At the same time the no. electrons are decreased compared to those available in intrinsic sc because of increased recombination due to creation of additional holes.

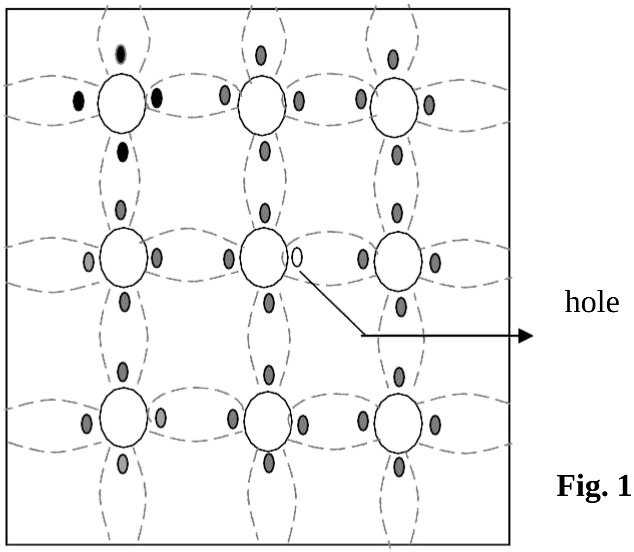


Fig. 1.23 (a) Crystal structure of P type sc

Thus in P type sc , holes are majority carriers and electrons are minority carriers. Since each trivalent impurity atoms are capable accepting an electron, these are called as acceptor atoms. The following Fig. 1.23 (b) shows the pictorial representation of P type sc

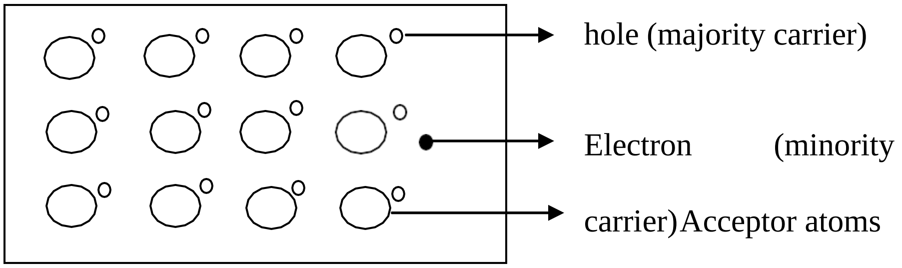


Fig. 1.23 (b) Crystal structure of P type sc

- The conductivity of N type sc is greater than that of P type sc as the mobility of electron is greater than that of hole.
- For the same level of doping in N type sc and P type sc, the conductivity of an Ntype sc is around twice that of a P type sc

1.4.3 Conductivity of semiconductor

In a pure sc, the no. of holes is equal to the no. of electrons. Thermal agitation continue to produce new electron- hole pairs and the electron hole pairs disappear because of recombination. with each electron hole pair created , two charge carrying particles are formed . One is negative which is a free electron with mobility μ_n. The other is a positive i.e., hole with mobility μ_p. The electrons and hole move in opppsitte direction in a an electric field E, but since they are of opposite sign, the current due to each is in the same direction. Hence the total current density J within the intrinsic sc is given by

$J = J_n + J_p$

$= q\, n\, \mu_n\, E + q\, p\, \mu_p\, E$

$= (n\, \mu_n + p\, \mu_p) qE$

$= \varsigma\, E$

Where n=no. of electrons / unit volume i.e., concentration of free electrons P=

no. of holes / unit volume i.e., concentration of holes

E=applied electric field strength, V/m

q= charge of electron or hole I n Coulombs

Hence, ς is the conductivity of sc which is equal to (n μ_n + p μ_p)q. he resistivity of sc is reciprocal of conductivity.

P = 1/ ς

It is evident from the above equation that current density with in a sc is directly proportional to applied electric field E.

For pure sc, n=p= n_i where n_i = intrinsic concentration. The value of n_i is given by

$n_i^2 = AT^3 \exp(-E_{GO}/KT)$

therefore, $J = n_i (\mu_n + \mu_p) q E$

Hence conductivity in intrinsic sc is $\varsigma_i = n_i (\mu_n + \mu_p) q$

Intrinsic conductivity increases at the rate of 5% per ° C for Ge and 7% per ° C for Si.

1.4.3.1 Conductivity in extrinsic sc (N Type and P Type):

The conductivity of intrinsic sc is given by $\varsigma_i = n_i (\mu_n + \mu_p) q = (n \mu_n + p$

$\mu_p)q$ For N type , n>>p

Therefore $\varsigma = q\ n$

μ_n For P type

,p>>n Therefore ς=

$q\ p\ \mu_p$

1.4.4 Charge densities in p type and n type semiconductor

1.4.4.1 Mass Action Law

Under thermal equilibrium for any semiconductor, the product of the no. of holes and the concentration of electrons is constant and is independent of amount of donor and acceptor impurity doping.

$n.p = n_i^2$

where n= eleetron concentration p

= hole concentration n_i^2=

intrinsic concentration

Hence in N type sc , as the no. of electrons increase the no. of holes decreases. Similarly in P type as the no. of holes increases the no. of electrons decreases. Thus the product is constant and is equal to n_i^2 in case of intrinsic as well as extrinsic sc.

The law of mass action has given the relationship between free electrons concentration and hole concentration. These concentrations are further related by the law of electrical neutrality as explained below.

1.4.4.2 Law of electrical neutrality:

Sc materials are electrically neutral. According to the law of electrical neutrality, in an electrically neutral material, the magnitude of positive charge concentration is equal to tat of negative charge concentration. Let us consider a sc that has N_D donor atoms per cubic centimeter and N_A acceptor atoms per cubic centimeter i.e., the concentration of donor and acceptor atoms are N_D and N_A respectively. Therefore N_D positively charged ions per cubic centimeter are contributed by donor atoms and N_A negatively charged ions per cubic centimeter are contributed by the acceptor atoms. Let n, p is concentration of free electrons and holes respectively. Then according to the law of neutrality

$N_D + p = N_A + n$.. **eq 1.1**

For N type sc, $N_A = 0$ and $n >> p$. Therefore $N_D \approx n$..**eq 1.2**

Hence for N type sc the free electron concentration is approximately equal to the concentration of donor atoms. In later applications since some confusion may arise as to which type of sc is under consideration a the given moment, the subscript n or p is added for Ntype or P type respectively. Hence eq1.2 becomes $N_D \approx n_n$

Therefore current density in N type sc is $J = N_D \mu_n q E$

And conductivity $\varsigma = N_D \mu_n q$

For P type sc, $N_D = 0$ and $p >> n$. Therefore $N_A \approx p$

Or $N_A \approx p_p$

Hence for P type sc the hole concentration is approximately equal to the concentration ofacceptor atoms.

Therefore current density in N type sc is $J = N_A \mu_p q E$

And conductivity $\varsigma = N_A \mu_p q$

Mass action law for N type, $n_n p_n = n_i^2$

$$p_n = n_i^2 / N_D \text{ since } (n_n \approx N_D)$$

Mass action law for P type, $n_p \, p_p = n_i^2$

$$n_p = n_i^2 / N_A \quad \text{since } (p_p \approx N_A)$$