DEPARTMENT OF ELECTRNICS & COMMUNICATION ENGINEERING, KITSW

COURSE: **U14EI 205 - BASIC ELECTRONICS ENGINEERING**	**ECE-I, Semester-II, 2015-16**

ASSIGNMENT-1 HINTS &SOLUTIONS

I appreciate the effort put in by ECE-I students. Majority, who are following class lectures, did really well. You got very good material in your answer, but are failing in presentation. PRESENTATION OF MATERIAL IS MORE IMPORTANT.

Certain observations I made while correcting your assignments:

- **YOU NEED TO DRAW ATTENTION OF THE EXAMINER**

  (*Examiners will be correcting hundreds of answer scripts,* ***Your answers must look unique****…..*)
  - Keep side-headings, wherever necessary, and underline them
  - Present the material point-wise
  - Underline important statements
  - Keep important expressions and calculated answers for given problem in a BOX
  - Use technical terms related to question and underline them ***when used for first time***

- **A PICTURE IS WORTH A 1000 WORDS**
  - Present your material with necessary figures
  - You are studying engineering. Make every effort to draw figures very neatly and to the scale.
  - Make sure that axes are properly marked without fail
- **AN EAQUATION IS WORTH A 100 WORDS**
  - Present your material with necessary equations related to the question asked
  - Mention all the variables with their units
- **STATEMENTS AND DEFINITIONS ARE TO BE REPRODUCED AS THEY ARE STATED**

When I interacted with few of you, I got the following answer: *" sir, in question it was asked to "describe". So we wrote complete theory".*

Dear students !, Please remember, you are going to become technocrats. Math is the basis. You all need to be well equipped with math and its effective use in engineering. Be prepared & Do not hesitate to write equations related to theory.

Example 1: Most wrote the following statement and left.

Reverse saturation current of a diode boubles for every 10 ^0C rise in temperature.

Remember, it would be worth writing the following equation:

$I_{02} = I_{01}\left(2^{\left(\frac{\Delta T}{10}\right)}\right)$; Don't leave here. Mention what are those variables …

Where, I_{01} = Reverse saturation current at temp $T_1 \; {}^0C$

I_{02} = Reverse saturation current at temp $T_2 \; {}^0C$

$\Delta T = (T_2 - T_1)\, {}^0C$

Example 2: Most wrote about V-I characteristics of PN junction diode without writing equation for diode current equation (*school going children interested in electronics can do that* !).
Without that equation you can't justify that the forward characteristics rise exponentially.

$$I = I_0\, e^{\left(\frac{v}{\eta V_T}\right)};$$

Do not stop here. Mention all the variables with units …

Where, I = forward current through the diode (Amp)

I_0 = Reverse saturation current through the diode (Amp)

v = forward voltage applied across the diode (Volts)

$$\eta = \begin{cases} 1\,;\; for\ Ge \\ 2;\;\; for\ Si \end{cases}$$

V_T = Volt equivalent of temperature (Volts) = $\frac{T}{11,600}$ Volts, T in Kelvin

At room temperature (27 ${}^0C$ = 300 K), V_T = 300/11,600= 0.025862 V ≈ 26mV

Example 3: You derived expression for Fermi level for an intrinsic semiconductor and stated correctly that it lies in the middle of the forbidden band.

You should have also shown it in energy band diagram (EBD).

Also while drawing EBDs, they must be drawn to scale. Then only you will be successful in showing that for

(i) **Conductors**: No forbidden band gap (E_g= 0 eV) as VB and CB overlap
(ii) **Insulators**: Wide forbidden band gap (E_g > 5 eV)
(iii) **Semiconductors**: Band gap (E_g ≈ 1 eV) is in between that of a conductor and insulator

Example 4: Few wrote about signals, without showing or drawing any signal

Bottom-line: PLEASE ATTEND CLASSES REGULARLY, CONCENTRATE AND FOLLOW LECTURES , TAKE RUNNING NOTES OF THE LECTURE …

1 What is a signal? Sketch and explain different types of signals.

- Signal: A signal is defined as a physical quantity that varies with time, space or any other independent variable(s).

  Ex: 1. $y(t)=mt$; 'y' is function of independent variable 't'

  2. $s(x,y)=2x+5xy+3y^2$; 's' is function of two independent variables 'x' and 'y'

- Signal carries some kind of information available for observation

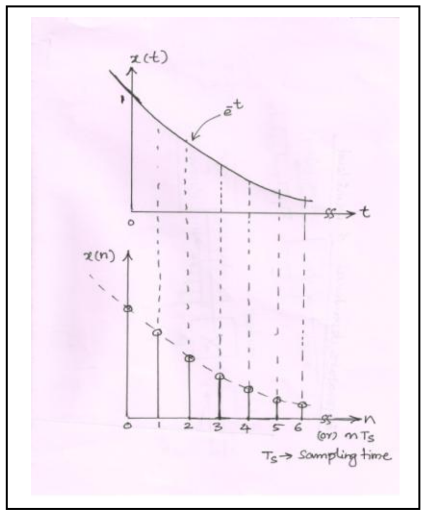
  Ex: 1) Speech signal
  2) Electrocardiogram (ECG) signal provides information about patient's heart
  3) Electroencephalogram (EEG) signal provides information about the brain activity

- Signals can be categorized as

  1) Continuous-time (CT) signals , 2) Discrete-time (DT) signals, 3) Digital signals

- Continuous-time (CT) signals: Signals that vary continuously in time and amplitude

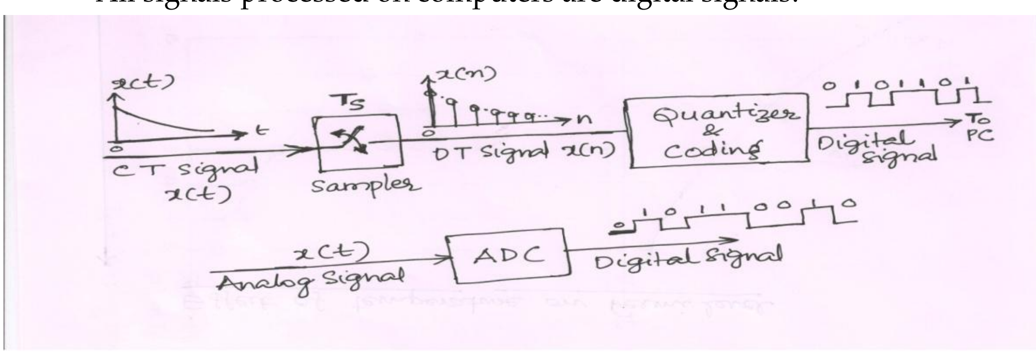
  Ex: $x(t)=e^{-t}$, $-\infty<t<\infty$, Both 'x' and 't' vary continuously
  - CT signals are also called analog signals



- Discrete-time (DT) signals: Signals that have continuous amplitude but defined only at discrete time instants.

  Ex: $x(n)=e^{-n}$, $-\infty<n<\infty$, 'x' will take conti-nuous amplitude ,while 'n' is an integer, indicating discretised time.
  - DT signals are obtained by sampling CT signals

- Digital signals: Signals that have discrete amplitude and time
  - Digital signals are obtained by quantization and coding of the DT signals.
  - Digital signals are represented by sequence of numbers 1s and 0s.
  - All signals processed on computers are digital signals.



- In practice, an analog-to-digital converter (ADC) will perform all the functions, viz., sampling, quantization & coding.

2 Explain the differences among conductors, insulators and semiconductors using the Energy Band Diagrams

- The range of énergies that an electron may possess in an atom is known as the energy band. The energy-bands are:
  1) Valence band, 2) Conduction band, and 3) Forbidden energy band gap.
- Valance band (VB) is the highest range of energy of electrons at absolute zero (0 K or -273 ^0C)
- Conduction band (CB) is the lowest energy range of vacant electronic states
- Forbidden energy gap (E_g) is the energy gap between valance band and conduction band.
  - An electron can be lifted from VB to CB by giving an energy equal to E_g.
- Conduction takes place when an electron jumps from VB to CB. Conductivity of a material is directly proportional to concentration of free electrons.
- Based on conductivity, solids are classified as conductors, insulators, and semiconductors.

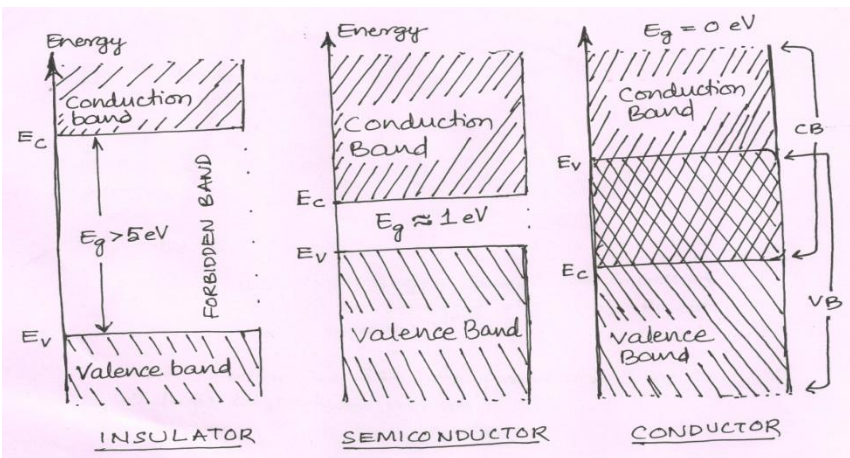
$$E_g = \begin{cases} 0\ eV & , for\ \ conductors \\ \approx 1 eV & , for\ \ semiconductors \\ > 5 eV & , for\ \ insulators \end{cases}$$

- Conductors: Metals are good conductors of electricity. They contain large number of free electrons at room temperature.
  - Ex: Copper, Silver
  - In conductors, there is no forbidden gap between VB and CB.
  - The VB and CB overlap, i.e., $E_g = 0$
  - Hence, without supplying additional energy, a metal has already large number of free electrons
- Insulators are the materials, which have extremely low conductivity.
  - The forbidden gap is very large.
  - Ex: Carbon, $E_g = 6$ eV, and Mica
  - Due to high E_g, it is practically impossible for an electron in VB to jump the forbidden gap to reach CB
  - Insulator may conduct at very high voltage applied across it. It is called breakdown of insulator.

- Semiconductors: Semiconductor is a material that has conductivity level between extremes of an insulator and a conductor.
  - Ex: Germanium (Ge), Silicon (Si), Gallium Arsenide (GaAs) are the three most widely used semiconductors
  - The forbidden gap is not wide. It is of order of 1 eV

$$E_g = \begin{cases} 0.72\ eV\ ,\ for\ \ Ge \\ 1.12\ eV\ ,\ for\ \ Si \\ 1.58\ eV\ ,\ for\ \ GaAs \end{cases}$$

  - At room temperature, the thermal energy is sufficient to lift electrons from VB to CB.
  - Hence, at room temperature some electrons do jump the gap and enter CB.
  - The purest form of semiconductor is called intrinsic semiconductor
  - The doped semiconductor is called extrinsic semiconductor
  - Semiconductor materials are the backbone of electronic devices and circuits
- The energy-band diagrams (EBD) of these materials are shown in figure below:



3 Define (i) Mass action law (ii) Mobility and (iii) Conductivity

1. **Mass action law**: Mass action law gives the fundamental relationship between electron and hole concentrations in a semiconductor.
   - It states that under thermal equilibrium, the product of electron and hole concentration is constant, and independent of donar or acceptor dopant concentrations.
   - Mathematically, mass action law is:

Under thermal equilibrium, $\boxed{n\,p = n_i^2}$

n = concentration of free electrons (cm^{-3}) in a doped semiconductor,

p = concentration of holes (cm^{-3}) in a doped semiconductor,

n_i = intrinsic carrier concentration (cm^{-3}) of the semiconductor (*when not doped*), given by

$$n_i^2 = N_C\, N_V\; e^{-\left(\frac{E_g}{kT}\right)};$$

where N_C = effective density of states in conduction band

N_V = effective density of states in valence band

E_g = Bandgap energy (eV)

k = Boltzman's constant (eV/K) & T=temperature in Kelvin (K)

***Additional material**: Expression for intrinsic carrier concentration*

The electron concentration in conduction band is given by

$$n = N_C\, e^{-\left(\frac{E_C - E_F}{kT}\right)};$$

where N_C = effective density of states in conduction band

E_C = conduction band bottom edge energy (eV)

E_F = Fermi level of intrinsic semiconductor (eV)

k = Boltzman's constant (eV/K) & T=temperature in Kelvin (K)

The hole concentration in valence band is given by

$$p = N_V\, e^{-\left(\frac{E_F - E_V}{kT}\right)};$$

where N_V = effective density of states in valence band

E_V = valence band top edge energy (eV)

E_F = Fermi level of intrinsic semiconductor (eV)

k = Boltzman's constant (eV/K) & T=temperature in Kelvin (K)

Invoking mass-action law ,

$$n_i^2 = n\,p$$

$$n_i^2 = N_C\, e^{-\left(\frac{E_C - E_F}{kT}\right)}\; N_V\, e^{-\left(\frac{E_F - E_V}{kT}\right)}$$

$$n_i^2 = N_C\, N_V\; e^{-\left(\frac{E_C - E_V}{kT}\right)}$$

$$n_i^2 = N_C\, N_V\; e^{-\left(\frac{E_g}{kT}\right)};$$

where $E_C - E_V$ = Bandgap energy (E_g)

2. Mobility: *Refer class notes for relevant diagram*

- Charged particles drift under the influence of the applied field
- When an electric field E (V/m) is applied across a conductor, the electrons move with a velocity called drift velocity v_d (m/s), given by

$$v_d = \mu E \quad \Rightarrow \quad \boxed{\mu = v_d \; / E}$$

μ is called mobility (m²/V-s) $\leftarrow$ ((m/s)/(V/m))

- In a semiconductor, the electrons and hole have different mobility

For Si, μ_n = mobility of electrons ≈ 1500 cm²/V-s

μ_p = mobility of holes ≈ 475 cm²/V-s

- Observation: (1) $\mu_n > \mu_p$

3. Conductivity:

- *Refer class notes for relevant diagram*
- When an electric field E (V/m) is applied across a conductor, the electrons move with a velocity called drift velocity v_d (m/s), given by

$$v_d = \mu E \quad \Rightarrow \quad \boxed{\mu = v_d \; / E}$$

μ is called mobility (m²/V-s) $\leftarrow$ ((m/s)/(V/m))

- The directed flow of these electrons will constitute current.
- The current density (J) is given by

$$J = \frac{current}{area\ of\ cross\ section\ of\ conductor} = \frac{I}{A}$$

$$J = n q v_d$$

Here, n = electron concentration (number of electrons/unit volume)

q = charge on electron (- 1.6x 10^{-19} C)

Substituting for drift velocity (v_d) in J, we get

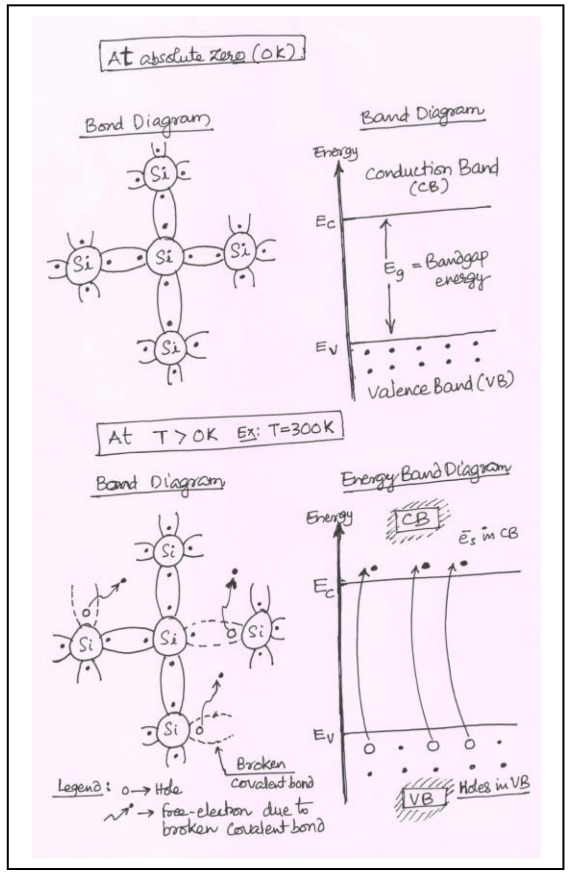
$$J = n q v_d = n q (\mu E)$$

$$J = \sigma E$$

Where σ is called conductivity $(\Omega - m)^{-1}$ of the material

$$\boxed{\sigma = n \mu q}$$

4 Explain how conduction takes place in intrinsic semiconductor



- Semiconductor (SC) in its purest form is called <u>intrinsic semiconductor</u>.
- Si, Ge and GaAs are the three most widely used semiconductors.
- Both Si and Ge are elements of IV group i.e. they have 4 valence electrons. They form covalent bond with neighbouring atom.
- **<u>At absolute zero temperature (0 K), the intrinsic SC behaves as an insulator</u>** i.e. no free carriers of electricity are available (the valence band is full while conduction band is empty)
- **<u>Thermal generation</u>**: At room temperature (300 K), due to thermal energy, some of the covalent bonds will be broken
- Broken covalent bond releases a free electron which jumps to conduction band, leaving a vacancy in the covalent bond.
- The vacancy created in the covalent bond is called a <u>hole and is positively charged</u>
- Thus free electrons and holes are generated in pairs
- *In intrinsic semiconductor, concentration of electrons (n) = concentration of holes (p) =* n_i

  Ex: A sample of Ge at 300K, the intrinsic carrier concentration, $n_i = 2.5x10^{19} / m^3$
- **<u>Semiconductors have negative temperature coefficient of resistance</u>**: With raise in temp, more electron-hole pairs are generated. The higher the temp, the higher is the concentration of charge carriers. As more charge carriers are available, the conductivity (σ) of intrinsic SC increases as the temp increases. In other words, the resistivity decreases as the temp increases. That is, the <u>Semiconductors have negative temperature coefficient of resistance.</u>
- In semiconductors, the conductivity (σ) depends on both electrons (σ_n) & holes (σ_p)

$$\sigma = \sigma_n + \sigma_p = n\mu_n q + p\mu_p q = (n\mu_n + p\mu_p) q ;$$

Where, μ_n =mobility of electrons (cm²/V-s) , n= concentration of electrons (atoms/cm³)

μ_p = mobility of holes (cm²/V-s); p = concentration of electrons (atoms/cm³)

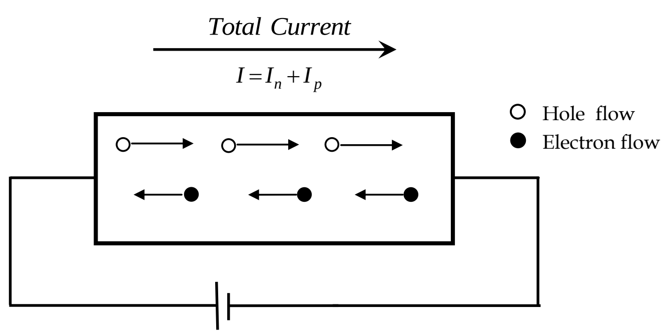
- In intrinsic semiconductors, **the electron density (*n*) equals the hole density (*p*)**

$$n = p = n_i ;$$

$$\sigma = (\mu_n + \mu_p) n_i q$$

- Holes and electrons contribute to conduction of electricity.
- Hole effectively moves in a direction opposite to that electron
- <u>Drift Current</u>: When an electric field (E) is applied across an intrinsic SC, the electrons will drift towards positive terminal of the battery and holes towards the negative terminal. The direction of electric current (conventional) is opposite to the direction of electron flow.
- Total drift current = current due to electrons + current due to holes

$$I = I_n + I_p$$



5 What is doping? Explain how N and P-type semiconductors are formed

- The carrier concentration of intrinsic semiconductors (SC), at room temperature, is very small and hence intrinsic SCs have too low conductivity for practical use.
- The conductivity of intrinsic SC can be increased by a process called <u>Doping</u>

<u>Doping:</u> The process of <u>deliberate addition of controlled quantities of impurities</u> to an intrinsic SC is called doping.

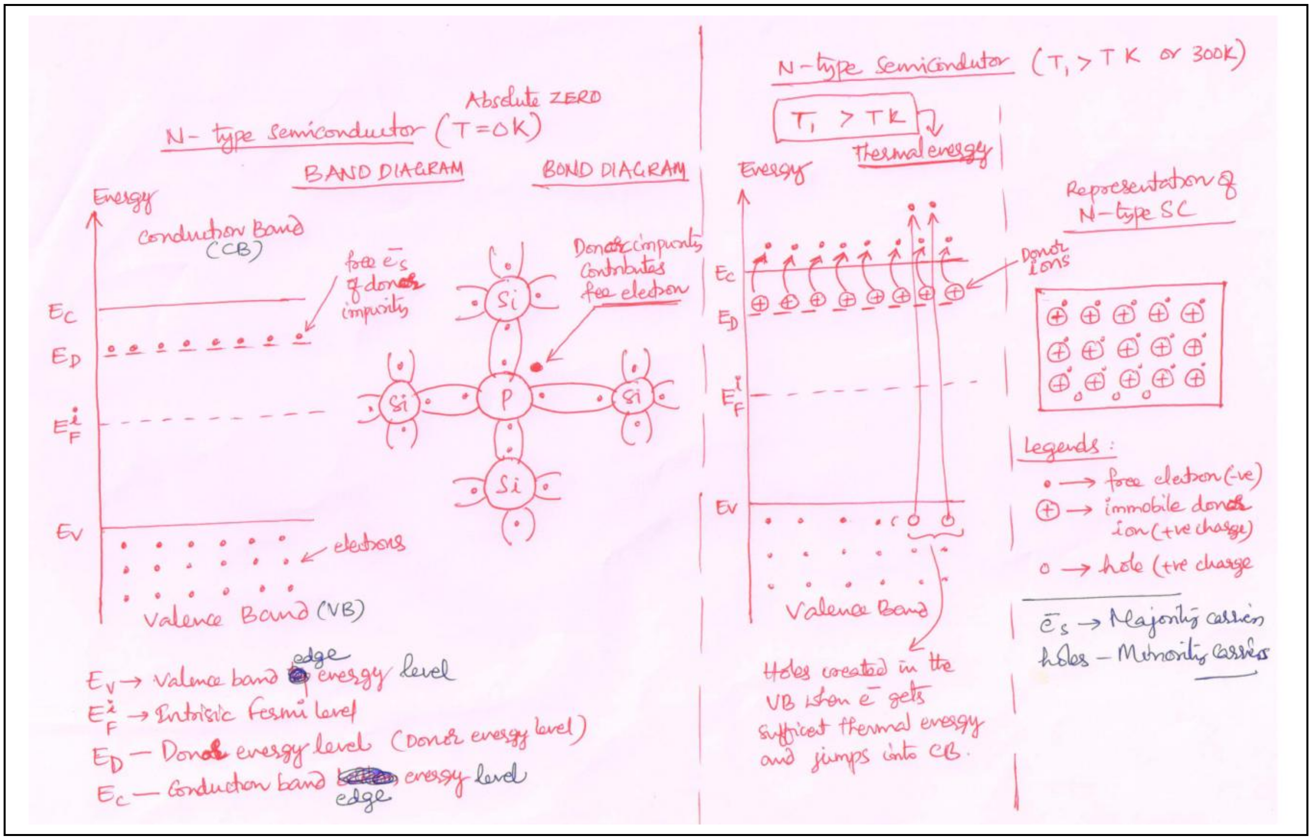
  - Doping markedly increases the conductivity of a SC
  - A doped SC is called an <u>extrinsic semiconductor.</u>
  - The impurity atoms are called <u>dopants</u>
  - The concentration of added impurity is normally **<u>one part in one million</u>**, i.e., <u>1 impurity atom for every 10^6 intrinsic atoms.</u>

- Extrinsic SC is of two types: (1) N-type semiconductor, (2) P-type semiconductor

<u>(1) N-type Semiconductor</u>:

- N-type semiconductor is formed by doping an intrinsic Si or Ge with a pentavalent impurity.

  Ex: Si+ Phosphorous (P) , Si+Antimony(Sb), Si+Arsenic (As)



- When a pentavalent dopant such as phosphorous (P) is added to Si,
  - Four of the five valence electrons of P from covalent bonds with four neighbouring Si atoms.
  - The fifth valence electron of dopant is free to move within the crystal
  - As each pentavalent impurity atom donates one electron, the pentavalent impurities are called donor impurities or donor dopants.
  - The donor atoms energy level (E_D) is close to the conduction band level (E_C).
- At room temperature (300K):
  - Due to thermal energy, the free electron of donor dopant atoms can easily jump into the CB. So good number of free electrons are available in the CB due to added impurities.
  - By donating electron, each donor impurity atom becomes a positive immobile ion (N_D^+)
  - Also, due to thermal energy, some of the Si bonds might break and the VB electrons find sufficient energy to enter CB leaving holes in the VB.
- In general, in an N-type SC: large number of free electrons are present in CB and a small number of thermally generated holes in VB.
  - *Number of electrons in the CB >> Number of holes in the VB*
  - *Majority carriers: Electrons*
  - *Minority carriers: Holes*

- However, the matter (doped SC) remains electrically neutral.
  - *As per **charge neutrality**,* Total negative charge = Total positive charge

    (Electron concentration) = (Hole concentration + positive donor ions)

    $$n = p + N_D^+$$

  - *For 100% ionization of dopant atoms;* $n = p + N_D$

    In N-type SC, $n >> p$, $n \approx N_D$

- That means, in N-type SC, the electron concentration (n) approximately equals the donor impurity concentration (N_D)
- <u>Hole concentration (p) in N-type SC</u> : Mass-action law states that $n\,p = n_i^2$

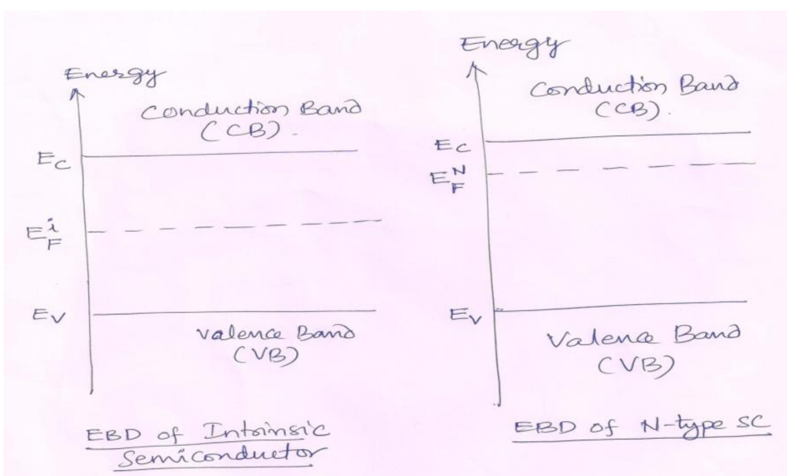
$$p = \frac{n_i^2}{n} \approx \frac{n_i^2}{N_D}$$

- In doped semiconductors, the Fermi level will be shifted by the added impurities.
- The Fermi level in N-type SC is given by the following expression:

$$E_F^N = E_C - kT \ln\left(\frac{N_C}{N_D}\right)$$

Where, k = Boltzman's constant ($1.38x10^{-24}$ J/K), N_C = Density of energy states in CB , N_D = Donor impurity concentration, T= temperature (K)
kT= 0.026 eV at room temp (300 K)

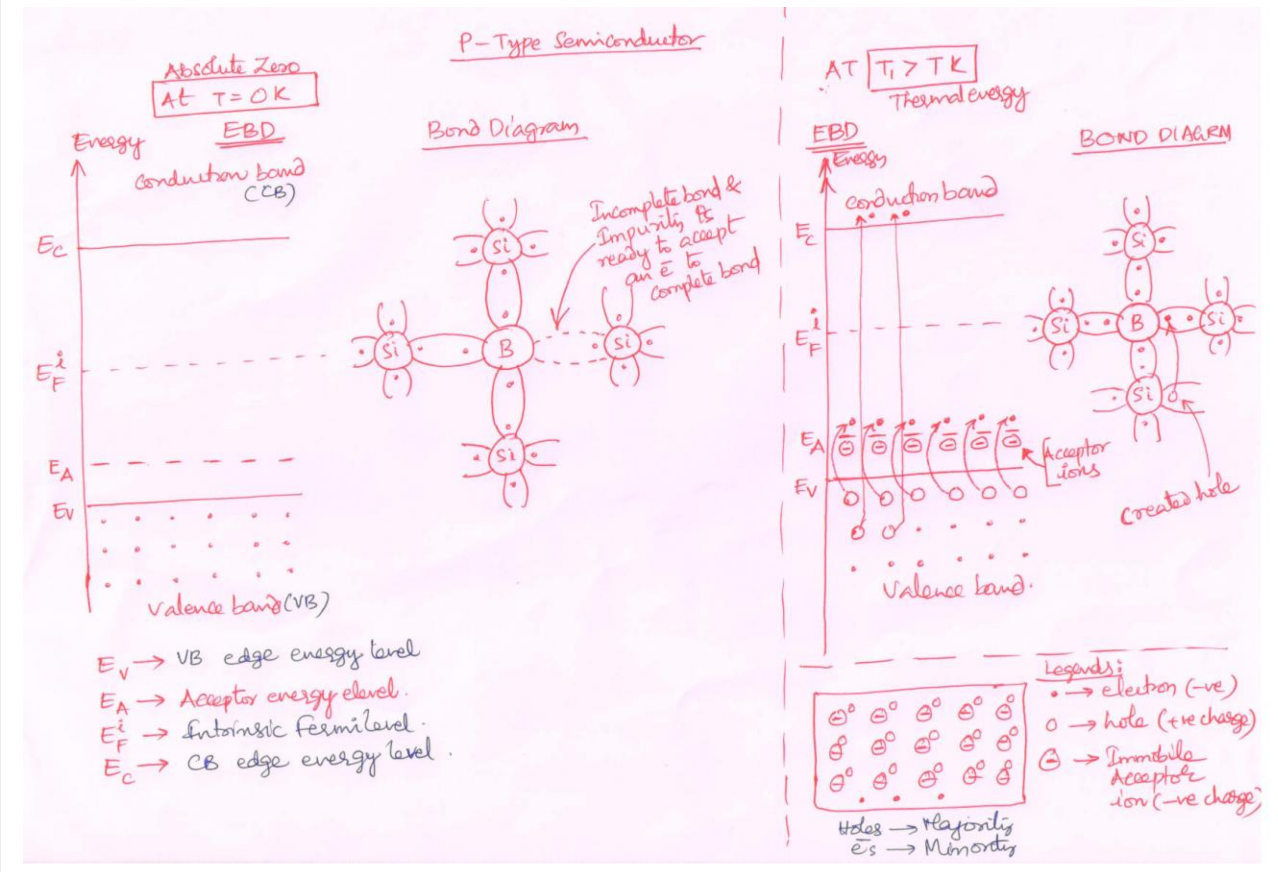
- In N-type SC, the Fermi level (E_F^N) is higher than intrinsic Fermi level (E_F^i) and close to the CB. The energy band diagram of N-type semiconductor is shown below



<u>(2) P-type Semiconductor</u>:

- P-type semiconductor is formed by doping an intrinsic Si or Ge with a trivalent impurity.

  Ex: Si+ Boron (B) , Si+ Aluminium(Al) , Si+ Gallium (Ga), Si+ Indium (In)



- When a trivalent dopant such as Boron (**B**) is added to Si,
  - All the three valence electrons of **B** form covalent bonds with three neighbouring Si atoms
  - The fourth neighbouring **Si** atom is unable to form a covalent bond with B-atom. Hence, dopant B has a tendency to accept an electron from neighbouring **Si** atom.
  - As the trivalent dopant is ready to accept one electron from the crystal (Si), the <u>trivalent impurities are called acceptor impurities or acceptor dopants</u>.
  - The acceptor atoms energy level (E_A) is close to the valence band energy level (E_V).
- <u>At room temperature (300K):</u>
  - The thermal energy breaks the covalent bonds and electrons are freed. These electrons in VB jump to fill the vacancies of the dopant atoms.

- So good number of holes are created in the VB.
- By accepting electron, each acceptor impurity atom becomes a negative immobile ion (N_A^-)
- In addition, due to thermal energy, few more Si bonds might break and those VB electrons find sufficient energy to enter CB leaving holes in the VB.

- In general, in a P-type SC: large number of holes are present in the VB and small number of thermally generated electrons in the CB
  - *Number of holes in VB >> number of electrons in CB*
  - *Majority carriers: Holes*
  - *Minority carriers: Electrons*
- However, the matter (doped SC) remains electrically neutral.
  - *As per **charge neutrality**,* Total positive charge = Total negative charge

    (Hole concentration) = (Electron concentration + Negative acceptor ions)

$$p = n + N_A^-$$

  - *For 100% ionization of dopant atoms;* $p = n + N_A$

    In P-type SC, $p >> n$, $p \approx N_A$

- That means, in P-type SC, the hole concentration (p) approximately equals the acceptor impurity concentration (N_A)
- <u>Electron concentration (*n*) in P-type SC</u> : Mass-action law states that $n\,p = n_i^2$

$$n = \frac{n_i^2}{p} \approx \frac{n_i^2}{N_A}$$

- In doped semiconductors, the Fermi level will be shifted by the added impurities.
- The Fermi level in P-type SC is given by the following expression:

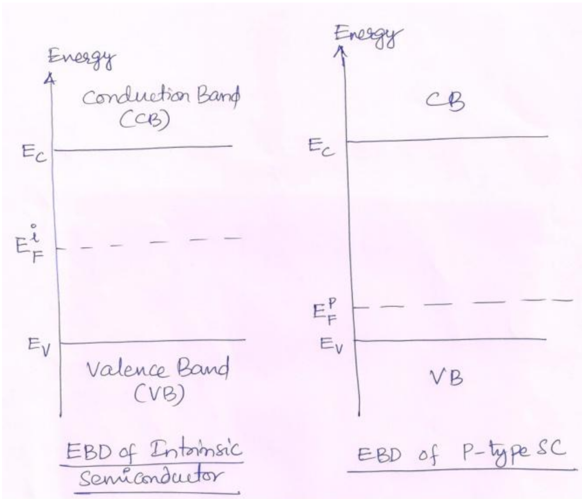
$$E_F^P = E_V + kT \ln\left(\frac{N_V}{N_A}\right)$$

Where, k = Boltzman's constant ($1.38 x 10^{-24}$ J/K), N_V = Density of energy states in VB,

N_A = Acceptor impurity concentration, T= temperature (K)

kT= 0.026 eV at room temp (300 K)

- In P-type SC, the Fermi level (E_F^p) is lower than intrinsic Fermi level (E_F^i) and close to the VB.
- Energy band diagram of P-type semiconductor is shown below



6 Explain how conductivity changes with doping

- The carrier concentration of intrinsic semiconductors (SC), at room temperature, is very small and hence intrinsic SCs have too low conductivity for practical use.
- The conductivity of intrinsic SC can be increased by a process called <u>Doping</u>

<u>Doping:</u> The process of <u>deliberate addition of controlled quantities of impurities</u> to an intrinsic SC is called doping.

- Doping markedly increases the conductivity of a semiconductor
- A doped semiconductor is called an <u>extrinsic semiconductor.</u>
- The impurity atoms are called <u>dopants</u>

- In SCs, the conductivity (σ) depends on both electrons (σ_n) & holes (σ_p)

$$\sigma = \sigma_n + \sigma_p = n\mu_n q + p\mu_p q = (n\mu_n + p\mu_p)q\,;$$

Where, μ_n =mobility of electrons (cm²/V-s) , n= concentration of electrons (atoms/cm³)

μ_p = mobility of holes (cm²/V-s); p = concentration of electrons (atoms/cm³)

- In intrinsic semiconductors, **the electron density (n) equals the hole density (p)**

$n = p = n_i$; where n_i = intrinsic carrier concentration (atoms/cm³)

$$\sigma = (\mu_n + \mu_p)n_i q$$

- Doped semiconductors are of two types: (1) N-type semiconductors, (2) P-type semiconductors

Conductivity in N-type semiconductor:

- Free electrons are the majority carriers while the holes are minority carriers ($n >> p$)
- The basic equation of conductivity in semiconductors is

$$\sigma = \sigma_n + \sigma_p = n\mu_n q + p\mu_p q = (n\mu_n + p\mu_p)q$$

  - For N-type SC, as $n >> p$, the conductivity (σ_N) equation becomes

$$\sigma_N \approx n\,\mu_n\,q$$

  - It is also known that the concentration of free electrons can be approximately assumed equal to concentration of donor dopant atoms (N_D) i.e., $n \approx N_D$
  - So, the conductivity (σ_N) equation, for N-type SC , can also be written as

$$\sigma_N \approx N_D\,\mu_n\,q$$

Conductivity in P-type semiconductor:

  - Holes are the majority carriers while the electrons are minority carriers ($p >> n$)
  - The basic equation of conductivity is $\sigma = (n\mu_n + p\mu_p)q$
  - For P-type SC , as $p >> n$, the conductivity (σ_P) equation becomes

$$\sigma_P \approx p\,\mu_p\,q$$

  - It is also known that the concentration of free electrons can be approximately assumed equal to concentration of donor dopant atoms (N_D) i.e., $n \approx N_D$
  - So, the conductivity (σ_N) equation, for P-type SC ,can also be written as

$$\sigma_N \approx N_D\,\mu_n\,q$$

7 What is Fermi level? Explain the effect of doping and temperature on Fermi level

- Fermi level is the measure of the energy of least tightly held electrons
- Fermi level also indicates the probability of occupancy of a given energy level by an electron
- The probability that the charged particle will have an energy E is given by Fermi-Dirac distribution or Fermi function $f(E) = \dfrac{1}{1 + e^{\left(\frac{E - E_F}{kT}\right)}}$

  Where E_F = Fermi energy or Fermi level (eV)

  k = Boltzman's constant ($1.38 x 10^{-24}$ J/K *or* $8.62 x 10^{-5}$ eV/K), T= temperature (K)

  kT= 0.026 eV at room temp (300 K)

  - **If $E=E_F$, then $f(E)$ = 0.5**

- **So, Fermi level is defined as the energy point where the probability of occupancy by an electron is exactly 50% , or 0.5**

Intrinsic semiconductor:

- The Fermi level of intrinsic semiconductor is given by

$$E_F^i = \left(\frac{E_C + E_V}{2}\right) + \frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right)$$

E_C = Conduction band bottom edge energy level (eV)
E_V = Valence band top edge energy level (eV)
N_C = Effective density of energy states in conduction band
N_V = Effective density of energy states in valence band
k = Boltzman's constant ($1.38 x 10^{-24}$ J/K *or* $8.62 x 10^{-5}$ eV/K), T= temperature (K)
kT= 0.026 eV at room temp (300 K)

- The second term contributes very little, hence the intrinsic Fermi level is

$$E_F^i = \left(\frac{E_C + E_V}{2}\right)$$

The Fermi level in case of intrinsic semiconductor (E_F^i) lies in the middle of bandgap,

Extrinsic semiconductor:

- **N-type semiconductor:** The Fermi level of N-type semiconductor (E_F^N) is given by

$$E_F^N = E_C - kT \ln\left(\frac{N_C}{N_D}\right)$$

Where, E_C = Conduction band bottom edge energy level (eV)
N_C = Effective density of energy states in conduction band
N_D = Donor impurity concentration (atoms/cm^3)
k = Boltzman's constant ($1.38 x 10^{-24}$ J/K *or* $8.62 x 10^{-5}$ eV/K), T= temperature (K)
kT= 0.026 eV at room temp (300 K)

  - In **N-type SC, the Fermi level (E_F^N) is higher than intrinsic Fermi level (E_F^i) and close to the conduction band.**

- **P-type semiconductor:** The Fermi level of N-type semiconductor (E_F^P) is given by

$$E_F^P = E_V + kT \ln\left(\frac{N_V}{N_A}\right)$$

Where, E_V = Valence band top edge energy level (eV)

N_V = Effective density of energy states in valence band
N_A = Acceptor impurity concentration (atoms/cm³)
k = Boltzman's constant ($1.38 x 10^{-24}$ J/K *or* $8.62 x 10^{-5}$ eV/K), T= temperature (K)
kT= 0.026 eV at room temp (300 K)

- In **P-type SC, the Fermi level (E_F^P) is lower than intrinsic Fermi level (E_F^i) and close to the valence band**.

Effect of doping and temperature on Fermi level:

- It can be seen from the expressions that Fermi level is a function of doping concentration (N_D or N_A) and temperature (in the term kT)

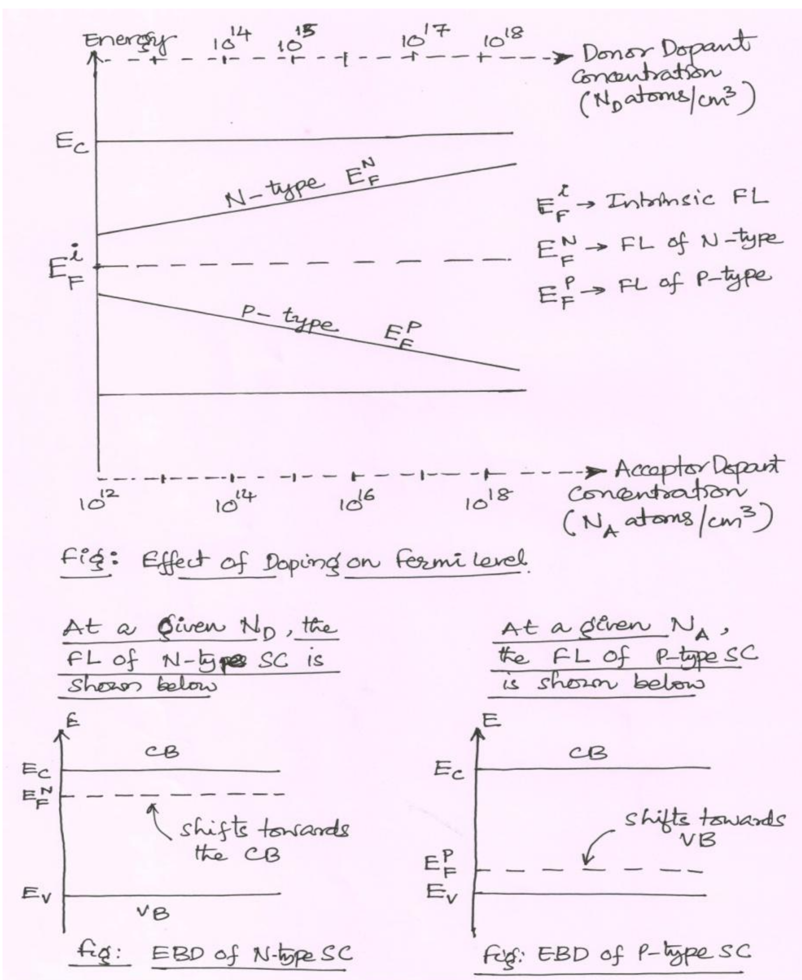
$$E_F = f(N_D, N_A, T)$$

Effect of doping levels on E_F: At constant T**,** as the doping concentrations increases, the second term of the respective Fermi levels (E_F^N and E_F^P) becomes small and hence

(i) E_F^N will continue to move towards E_C

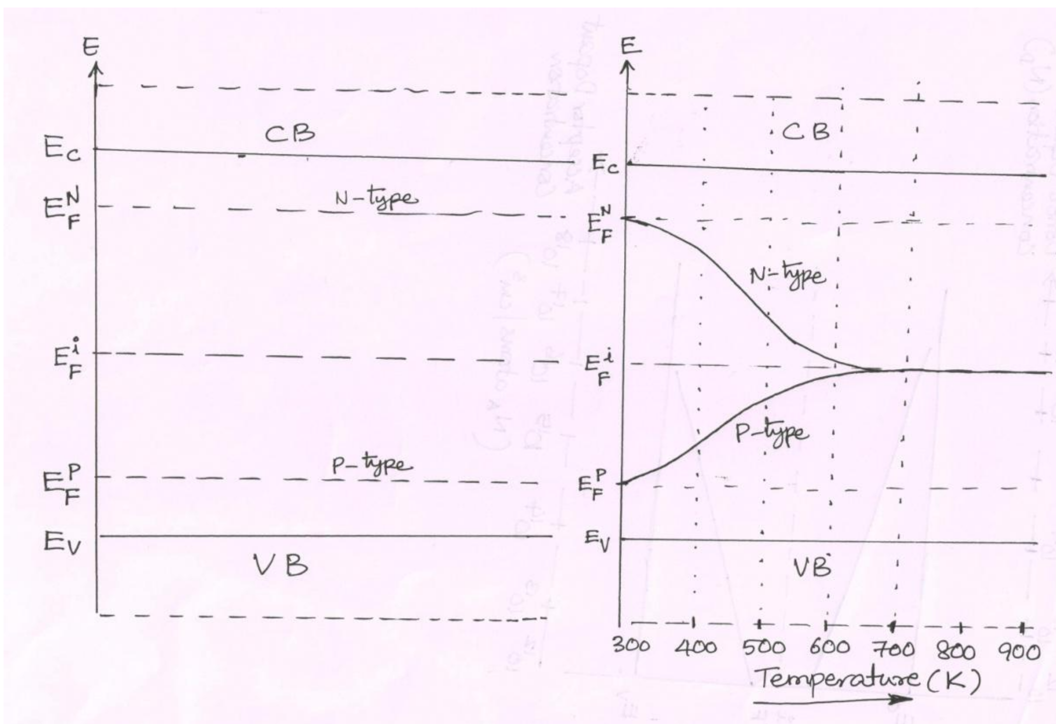
(ii) E_F^P will continue to move towards E_V

The effect of doing on Fermi level of doped semiconductor is shown in figure below:



Effect of temperature on E_F: As T increases, the doping becomes less important than the thermal generation of carriers. Due to this the Fermi level of extrinsic semiconductors (E_F^N and E_F^P) tends to intrinsic Fermi level (E_F^i). This is shown in fig below:

- ***For an N-type semiconductor***: $\frac{\partial E_F^N}{\partial T} < 0$, *i.e.* as the T increases, the E_F^N gradually decreases. At certain T, it reaches intrinsic Fermi level (E_F^i).
- ***For a P-type semiconductor*** : $\frac{\partial E_F^P}{\partial T} > 0$, *i.e.* as the T increases, the E_F^N gradually increases. At certain T, it reaches intrinsic Fermi level (E_F^i).



9.

Calculate the values of conductivity and resistivity of intrinsic Silicon semiconductor with Hole mobility $\mu_p = 0.055$ m²/V-s and $\mu_n = 0.145$ m²/V-s. Assume that the number of electrons in the intrinsic semiconductor to be 1.5625×10^{16}/m³.

Solution: Conductivity $\sigma_i = qn_i[\mu_n + \mu_p]$ Siemens/m

For an intrinsic semiconductor

$$n = p = n_i = 1.5625\times10^{16}\,/\text{m}^3$$

$$\therefore\ \sigma_i = 1.6\times10^{-19}\times1.5625\times10^{16}[0.145+0.055]$$

$$= 2.5\times10^{-3}\times0.2 = 5.0\times10^{-3}\ \text{mhos/m}$$

$$\text{Resistivity}\quad \rho_i = \frac{1}{\sigma_i} = \frac{1}{5.0\times10^{-3}} = \frac{10^3}{5.0} = 200\ \Omega\text{-m.}$$

8 An n-type Silicon bar 0.1 cm long and 100 μm² in cross-sectional area has a majority carrier concentration of 5×$10^{20}/m^3$ and the carrier mobility is 0.13 m^2/V-s at 300^0 k. If the charge of an electron is 1.6 × 10^{-19} C, then find the resistance of the bar.

Length of the n-type Si bar = 0.1cm = 0.1×10^{-2} m

Area of cross-section = 100 μm² = 100×10^{-6} m²

majority carrier conc = n = $5\times10^{20}/m^3$

μ_n = 0.13 m²/V-sec.

q = 1.6×10^{-19} C

Resistance(R) = $\frac{\rho L}{A}$ where $\rho = \frac{1}{\sigma}$

$\therefore \sigma = n\mu_n q = 5\times10^{20}(0.13)\times1.6\times10^{-19}$

$= 10.4\ (\Omega\text{-m})^{-1}$

$\rho = \frac{1}{10.4}\ (\Omega\text{-m})$

$\therefore R = \frac{\rho L}{A} = \frac{1}{10.4}\times\frac{0.1\times10^{-2}}{100\times10^{-6}}$

$= (9.6\times10^{-3})(10^{2})$

$R = (0.96\ \Omega)$

10. In a Germanium sample, a donor type impurity is added to the extent of 1 atom per 10^8 Germanium atoms. Show that the resistivity of the sample drops to 3.7 Ω-cm. The given parameters are: μ_n = 3800 cm²/Vs; μ_p=1800 cm²/V-s; n_i= 2.5×10¹³/cm³; N_{Ge} = 4.41 ×10²²/cm³; q = 1.602 × 10^{-19} C.

Given : Atomic ... = ...

Intrinsic conc. n_i = $2.5\times10^{..}$/cm.

μ_n = 3800 cm²/VS

μ_p = 1800 cm²/VS

Impurity N_D = 1 atom / 10^8 Ge atoms (Donor impurity)

$\therefore N_D = \frac{4.41\times10^{22}}{10^8} = 4.41\times10^{14}/cm^3$.

$N_D \simeq n$

we know that $np = n_i^2$ $\therefore p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D}$

$$\Rightarrow p = \frac{(2.5\times10^{13})^2}{4.41\times10^{14}} = \frac{6.25\times10^{26}}{4.41\times10^{14}} = 1.42\times10^{12}/cm^3$$

conductivity $\sigma = (n\mu_n + p\mu_p)q$

$$= (4.41\times10^{14}\times 3800 + 1.42\times10^{12}\times1800)1.6\times10^{-19} \ (\Omega\text{-cm})^{-1}$$

$$= (0.2685)(\Omega\text{-cm})^{-1}$$

Resistivity $\rho = \frac{1}{\sigma} = \frac{1}{0.2685}\ \Omega\text{-cm}$

$$= 3.72\ \Omega\text{-cm}$$