Department of Electronic Engineering
N.E.D. University of Engineering & Technology,

PRACTICAL WORK BOOK

For the course

SOLID STATE DEVICES
(EL-306) For T.E(EL)

Instructors name:_____

Student Name: _____
Roll no.:_____ **Batch:** _____
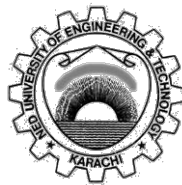**Semester :**_____ **Year:**_____
Department: _____

LABORATORY WORK BOOK
FOR THE COURSE

EL-306 SOLID STATE DEVICES

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The Board of Studies of Department of Electronic Engineering

Solid State Devices Laboratory Manual

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Department of Electronic Engineering

Lab Performance Rubrics

Rubric for Assessment of Electronic Engineering Laboratory Experiments

Session: _____   **Subject Code:** EL-306   **Subject Title:** Solid State Devices

Following rubric would be used as the basis for the assessment of each of the experiment performed in Electronic mainly for Industrial Electronic laboratory. The rubric should be shared and explained to the students in the very first practical.

Poor Less than 30%	Satisfactory 30% to 75%	Good/Excellent 75% to 100 %
• Less than 50% of lab sessions timely submitted and checked. • Most of the submissions with errors/ Incomplete	• More than 50% of the lab sessions were checked timely • Few errors in the submitted manual	• Student has timely submitted more than 90% of the lab sessions • Negligible errors

LAB SESSION 01

Familiarization with MATLAB and its application in crystalline structure

Student Name: _____ .
Roll no.: _____ **Batch:** _____ .
Semester: _____ **Year** _____ .

Total Marks	Marks Obtained

Remarks (if any) _____ .

Instructor Name _____ .

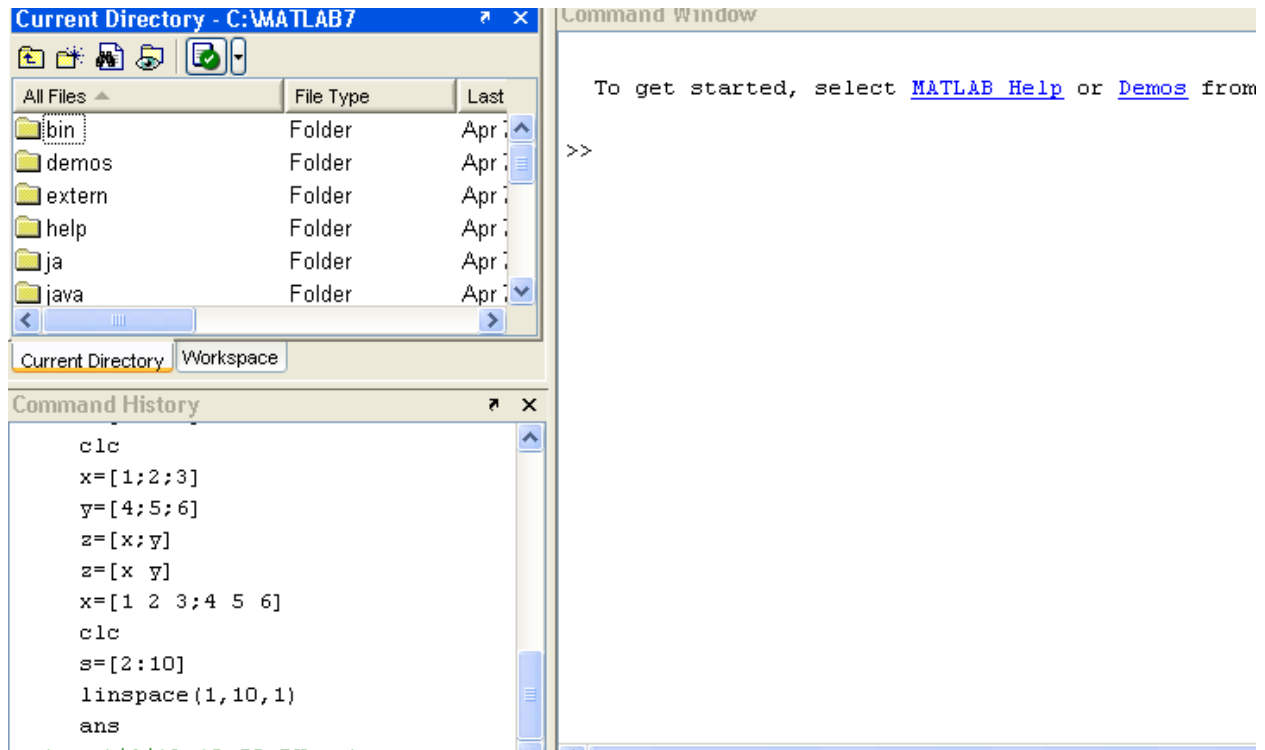**Instructor Signature:** _____ **Date:** _____ .

LAB SESSION 01

Objective:
Familiarization with Matlab and its application in crystalline structure

Software Required: MATLAB

Procedure: To start Matlab click on Matlab icon. You will see the Matlab desktop. The default desktop is shown below

There are 4 windows

   i)   Command Window
   ii)   Current Directory Window
   iii)   Workspace window
   iv)   Command History Window

Command Window: - Command window is used to communicate with the Matlab program, by typing instructions of various types called commands, functions and statements. Matlab displays the prompt (>>) to indicate that it is ready to receive instructions

Current Directory Window: - Current directory window is much like a file manger window; it can be used to access a file. Clicking on a file name with extension . m will open that file in Matlab Editor

Workspace window: -Underneath the current directory window is the workspace window. To activate it, click on its tab at the bottom of current directory window. The workspace window displays the variables created in the command window

Command History Window:- This window shows all the previous keystrokes that the user entered in the command window. It is useful for keeping track what the user has typed

Creating Row Vector in MATLAB: To create a row vector in Matlab, simply type the elements inside a pair of square brackets, separating elements with a space or a comma. For example

>> [1 2 3]

ans =

   1   2   3

>> [1,2,3]

ans =

   1   2   3

Creating Column Vector in MATLAB: To create a column vector in Matlab, simply type the elements inside a pair of square brackets, separating elements with a semicolon. For example

>> [1;2;3]

ans =

   1
   2
   3

Appending of vectors: - Vectors can be created by appending one vector to another.

 x=[1 2 3]

x =

   1   2   3

>> y=[4 5 6]

y =

   4   5   6

>> z=[x,y]

z =

   1   2   3   4   5   6

Colon Operator: - Colon operator (:) is used to generate a large vector of regularly spaced element
>>x=[m:q:n] creates a vector x of values with a spacing q. The first value is m. The ending value is n, if
m-n is an integer multiple of q. If not, the last value is less than n. If the increment q is omitted, it is
presumed to be 1. For example

>> x=[0:2:8]

x =

   0   2   4   6   8

>> x=[0:2:7]

x =

   0   2   4   6

>> x=[10:-2:4]

x =

  10   8   6   4

>> x=[2:10]

x =

   2   3   4   5   6   7   8   9   10

Creating a Matrix:- The most direct way to create a matrix is to type the matrix row by row, separating
the elements in a given row with spaces or commas and separating the rows with semicolons. For
example

>> A=[1 2 3;4 5 6;7 8 9]

A =

   1   2   3
   4   5   6
   7   8   9

Array/Matrix Addressing:- Suppose you have a matrix

>> A=[1 2 3;4 5 6;7 8 9;10 11 12;13 14 15]

A =

```
 1    2    3
 4    5    6
 7    8    9
10   11   12
13   14   15
```

To access all the elements of a matrix A write A(:)

\>\> A(:)

ans =
```
 1
 4
 7
10
13
 2
 5
 8
11
14
 3
 6
 9
12
15
```

To access the element of 2nd row and 2nd column write A(2,2)

\>\> A(2,2)

ans =

```
 5
```
To access elements in 3rd column

\>\> A(:,3)

ans =

```
 3
 6
 9
12
15
```

To access 1st and 2nd column of all rows

\>\>A(:,1:2)

ans =

```
 1    2
 4    5
 7    8
10   11
13   14
```

To access elements of 2nd through 4th row that are also present in 1st and 2nd column

>> A(2:4,1:2)

ans =

```
 4    5
 7    8
10   11
```

Some built-in Functions of Matlab:-

1) **sum(A):** sums the elements in each column of the matrix A and returns a row vector containing the sums
>> sum(A)

ans =

    35   40   45

2) **max(A):** returns a row vector containing the largest elements in each column if A is a matrix. The function returns largest element in A if A is a vector

>> max(A)

ans =

    13   14   15

3) **size(A):** returns a row vector [m n] containing the sizes of the m*n matrix A

>>size(A)

ans=

    [5,3]

4) **length(A):** returns the size of the longest dimension of A.

>> length(A)

ans =

   5

Arithmetic Operations: - Suppose you have two matrices A and B

>> A=[1 2 3;4 5 6;7 8 9]

A =

   1   2   3
   4   5   6
   7   8   9

>> B=[10 11 12;13 14 15;16 17 18]
B =

   10   11   12
   13   14   15
   16   17   18

1) **Addition**:- A+B adds A and B. A and B must have the same size

>> A+B

ans =

   11   13   15
   17   19   21
   23   25   27

2) **Subtraction: -** A-B subtracts B from A. A and B must have the same size

> A-B

ans =

   -9   -9   -9
   -9   -9   -9
   -9   -9   -9

3) **Multiplication: -** A*B multiplies matrix A with matrix B. No. of columns of matrix A should be
    equal to number of rows of matrix B

>> A*B

ans =

```
 84   90   96
201  216  231
318  342  366
```

4) Element by element Multiplication: - A.*B is the element-by-element product of the matrix A and B. A and B must have the same size

`>> A.*B`

`ans =`

```
 10   22    36
 52   70    90
112  136  162
```

Input and Output commands:-

1) Input command:-
 x=input('text') :-displays the text in quotes, waits for user input from the keyboard, and stores the value in x.

`>> x=input('enter the value of x=')`

enter the value of x=5

`x =`

   5

2) Output command:-
disp(A):- displays the contents, but not the name, of the array A.

disp('text'):- displays the text string enclosed within single quotes.

Conditional statements: - Conditional statements enable user to select at run time which block of code to execute.

1) If statement:-   if   logical_expression
                          statements
                     end
If the logical expression is true (1), MATLAB executes all the statements between if and end lines. It resumes execution at the line following the end statement. If the condition is false (0), MATLAB skips all the statements between the if and end lines, and resumes execution at the line following the end statement.

2) If else statement: -   if   expression
                            statements1

else
statements2
end

If the logical expression is true (1), MATLAB executes all the statements between the if and else lines .It then resumes execution at the line following the end statement. If the condition is false (0), MATLAB executes all the statements between else and end statement and then resumes execution at the line following the end statement.

For loop:- The for loop allows to repeat certain commands. If you want to repeat some action in a predetermined way, you can use the for loop. For loop starts with a keyword "for"

```
for   variable=initial value :increment: ending value
        statements
end
```

Task 01: Write the code to plot following polynomial function
$$y=0.025x^5-0.0625x^4-0.333x^3+x^2$$
$$\text{for } -1<=x<=4$$

Task 02: Write a program that takes a matrix as input from user and check all the elements. If the value is greater than 5 make it 1 else make it 0

Task 03: Write a program that takes a vector as an input from the user. Now arrange the elements in
   i)   Ascending order
   ii)   Descending order
 (Bubble sorting)

Task 04: Write a program that computes number of atoms/cm^3 in cubic crystals. Use Matlab **input** function to enter the number of atoms/unit-cell and the unit cell side length (a) for a specific crystal.

LAB SESSION 02

To analyze crystalline structures and miller planes of cubic, diamond and zinc blende

Student Name: **.**

Roll no.:   **Batch:**   **.**

Semester: **Year**   **.**

Total Marks	Marks Obtained

Remarks (if any)   **.**

Instructor Name   **.**

Instructor Signature: **Date:**   **.**

LAB SESSION 02

Objective: - **To analyze crystalline structures and miller planes of cubic, diamond and zinc blende** lattices.

**Tool Required**: Crystal Viewer tool (nanohub.org)

Theory:
Cubic Structure:-

1) **Simple Cubic Unit cell**: - The simple cubic system has one lattice point at each corner of the cube. Each atom at a lattice point is then shared equally between eight adjacent cubes, and the unit cell therefore contains in total one atom ($1/8 \times 8$)
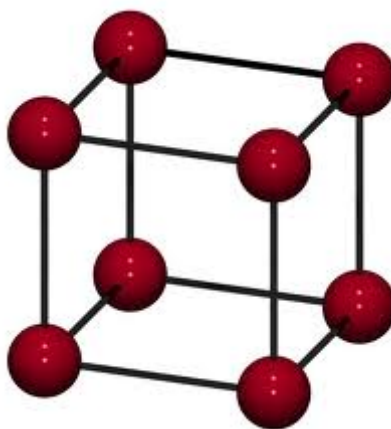

2) **Face centered Cubic Unit Cell**: - The face centered cubic system has one lattice point on each corner and one lattice point at each face of the cube. Each corner atom is equally shared between eight adjacent cubes while each face atom is shared between two adjacent cubes. Thus the unit cell contains 4 atoms in total ($^1/_8 \times 8$ from the corners + $^1/_2 \times 6$ from the faces).
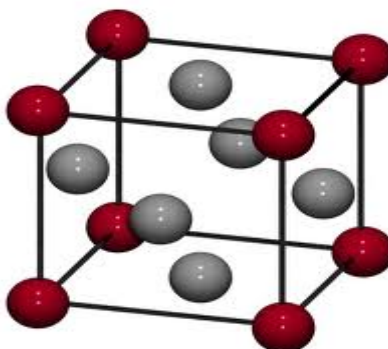

3) **Body centered Cubic Unit Cell**: - The body centered cubic system has one lattice point at each corner and one lattice point at the center of cube. Each corner atom is equally shared between eight adjacent cubes while one atom is present at the center of the cube. Thus the unit cell contains 2 atoms in total ($^1/_8 \times 8$ from the corners + 1 from the center of the body).
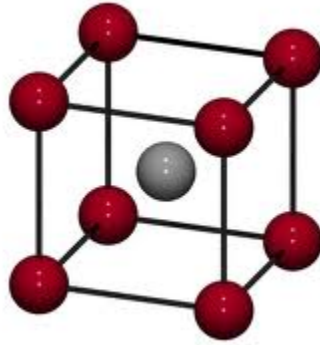
Diamond Structure:- Diamond structure can be thought of as face centered cubic lattice with an extra lattice point at $^a/_4+b/_4+^c/_4$ from each of the fcc lattice point. When vectors are drawn with components one-fourth of the cube edge in each direction, only four addition point within the same lattice point are reached. Each corner atom is equally shared between eight adjacent cubes while each face atom is shared between two adjacent cubes and there are 4 atoms inside the cube. Thus the unit cell contains 8 atoms in total ($^1/_8 \times 8$ from the corners $+ \frac{1}{2} \times 6$ from the faces$+4$ inside the unit cell).
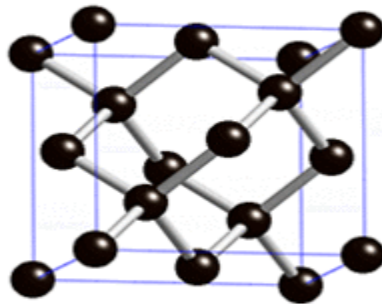

Zinc blende Structure: - Zinc blende structure is same as of diamond structure but the only difference between the two is that the atoms at $^a/_4+^b/_4+^c/_4$ in zinc blende structure are different then the atoms present at the corner and face center. Like diamond's unit cell zinc blende's unit cell also contains 8 atoms (04 of one type and 04 of other type)

16
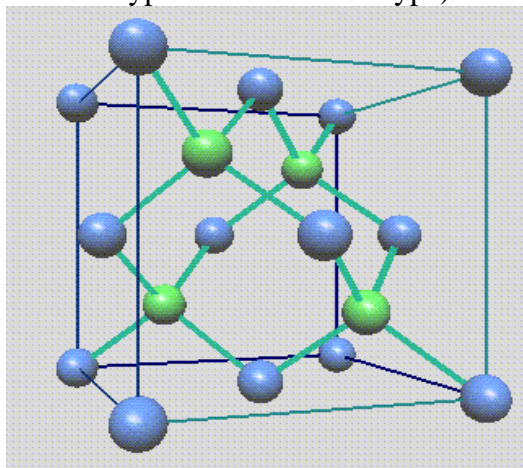
Miller Planes: - Miller indices are used for the representation of planes and direction. To transfer any plane having (x,y,z) intercepts in cartesian co-ordinate system into miller plane following steps are followed

    i)   Reciprocals of the intercepts are taken to avoid infinities in notation

    ii)   Reciprocals are reduced to the smallest set of integers h,k,l

    iii)   Then the plane is then labeled as (hkl) plane or miller plane

From a crystallographic point of view many planes in a lattice are equivalent i.e., a plane with given miller indices can be shifted about in the lattice simply by choice of the position and orientation of unit cell.
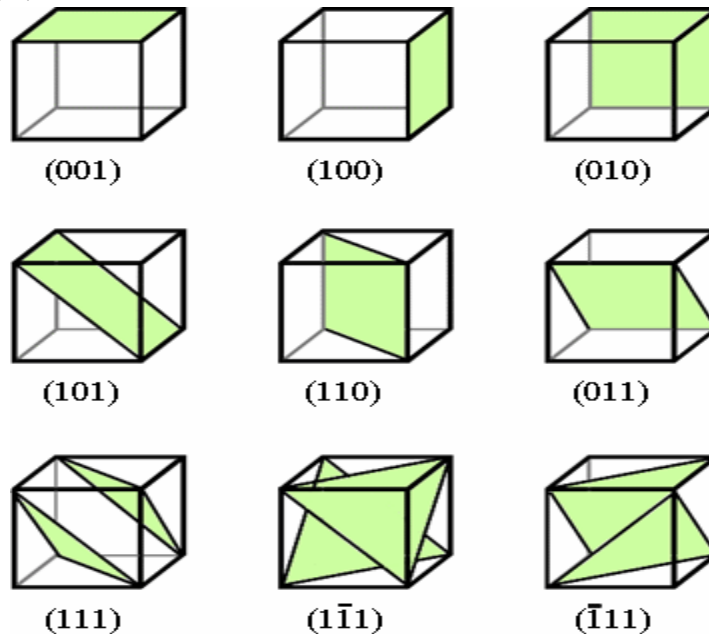
Task No. 1:- Run the simulation to view Si crystal

Task No 2:- Run the simulation to calculate number of atoms in silicon crystal

Task No. 3:- Run the simulation to view unit cell of Si

Task No. 4:- Run the simulation to calculate number of atoms in unit cell of Si

Task No. 5:- Run the simulation to view (100) plane in a unit cell of Si (Size of miller plane=1)

Task No. 6:- Run the simulation to calculate number of atoms on (100) plane in a unit cell of Si

Task No. 7:- Run the simulation to view (100) plane of Si crystal (Size of miller plane=2)

Task No. 8:- Run the simulation to view (100) plane of Si crystal (Size of miller plane=3)

Task No. 9: - Run the simulation to view (010) plane in a unit cell of Si

Task No. 10: -Run the simulation to calculate number of atoms on (010) plane in a unit cell of Si

Task No. 11:- Run the simulation to view (001) plane in a unit cell of Si.

Task No. 12:- Run the simulation to calculate number of atoms on (001) plane in a unit cell of Si

Task No. 13: - Run the simulation to view (110) plane in a unit cell of Si.

Task No. 14: - Run the simulation to calculate number of atoms on (110) plane in a unit cell of Si

Task No. 15:- Run the simulation to view GaAs crystal.

Task No. 16: - Run the simulation to calculate number of Ga and As atoms in GaAs crystal

Task No. 17: - Run the simulation to view unit cell of GaAs.

Task No. 18: - Run the simulation to calculate number of Ga and As atoms in unit cell of GaAs.

Task No. 19:- Run the simulation to view (100) plane in a unit cell of GaAs.

Task No. 20: - Run the simulation to calculate number of atoms on (001) plane in a unit cell of GaAs

Task No. 21:- Run the simulation to view simple cubic unit cell

Task No. 22: -Increase the unit cell side length and compare the results with previous simulation

Task No. 23: -Decrease the unit cell side length and compare the result with simulation number 21

Task No. 24: -Run the simulation to view the large lattice grid of simple cubic structure (grid size=3)

Task No.25: -Run the simulation to view larger lattice grid of simple cubic structure (grid size equal to 4)

Task No. 26: -Run the simulation to view (100) plane in simple cubic crystal

Task No. 27: - Run the simulation to view (010) plane in simple cubic crystal

Task No. 28: - Run the simulation to view (001) plane in simple cubic crystal

Task No. 29: -Run the simulation to show 2 layers of unit cell of simple cubic structure while viewing (100) plane (Grid size=2)

Task No. 30: -Run the simulation to show 3 layers of unit cell of simple cubic structure while viewing (100) plane (Grid size=3)

Task No. 31: -Run the simulation to view face centered cubic unit cell

Task No. 32: -Increase the unit cell side length and compare the results with previous simulation

Task No. 33: -Run the simulation to view the large lattice grid of face centered cubic structure

Task No. 34: -Run the simulation to view (100) plane in face centered cubic crystal

Task No. 35: -Run the simulation to view body centered cubic unit cell.

Task No. 36: -Decrease the unit cell side length and compare the results with previous simulation

Task No. 37: -Run the simulation to view the large lattice grid of body centered cubic structure

LAB SESSION 03

To understand Fermi function, density of states and carrier concentration. Also observe the effect of temperature on these values.

Student Name: .
Roll no.:   **Batch:**   .
Semester: **Year**   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: **Date:**   .

LAB SESSION 03

Objective: - **To understand Fermi function, density of states and carrier concentration. Also observe the effect of temperature on these values.**

Tool: _

Theory: -

Fermi-Dirac distribution function[1]:-

The Fermi-Dirac distribution function, also called Fermi function, provides the probability of occupancy of energy levels by electrons. The Fermi function is given by:
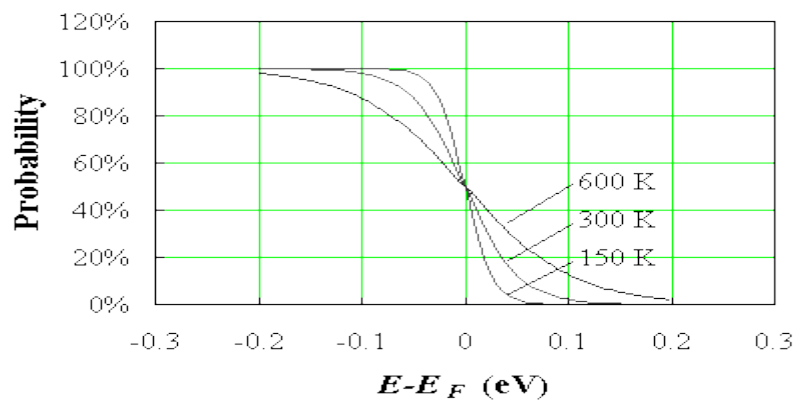
$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

The quantity E_F is called the Fermi level. For an energy equal to the Fermi level energy E_F , the occupation probability is $f(E_F)$

$$f(E_F) = {}^1\!/_2$$

Thus an energy state at the Fermi level has a probability of ½ of being occupied by an electron.

This function is plotted in figure shown below at 150, 300 and 600 K.

Density of states[2]: - The density of states in a semiconductor can be obtained by solving the Schrödinger equation for the particles in the semiconductor. For an electron which behaves as a free particle with effective mass, m*, the density of states is as follows:

$$g_c(E) = \frac{8\pi\sqrt{2}}{h^3} m_e^{*3/2} \sqrt{E - E_c}, \text{ for } E \geq E_c$$

The density of states for holes in the valence band is given by:

$$g_v(E) = \frac{8\pi\sqrt{2}}{h^3} m_h^{*3/2} \sqrt{E_v - E}, \text{ for } E \leq E_v$$

Carrier Concentration: - The density of electrons in a semiconductor is related to the density of available states and the probability that each of these states is occupied. The density of occupied states per unit volume and energy, n(E),is product of the density of states in the conduction band, g_c(E) and the Fermi-Dirac probability function, f(E).

$$n(E) = g_c(E)f(E)$$

Since holes correspond to empty states in the valence band, the probability of having a hole equals the probability that a particular state is not filled, so that the hole density per unit energy, *p(E)*, equals:

$$p(E) = g_v(E)[1 - f(E)]$$

The carrier density in a semiconductor is obtained by integrating the product of the density of states and the probability density function over all possible states. For electrons in the conduction band the integral is taken from the bottom of the conduction band, labeled, E_c, to the top of the conduction band:

$$n = \int_{E_c}^{top\ of\ the\ conduction\ band} n(E)dE = \int_{E_c}^{top\ of\ the\ conduction\ band} g_c(E)f(E)dE$$

The actual location of the top of the conduction band does not need to be known as the Fermi function goes to zero at higher energies. The upper limit can therefore be replaced by infinity. We also relabeled the carrier density as n_o to indicate that the carrier density is the carrier density in thermal equilibrium.

$$n_o = \int_{E_c}^{\infty} g_c(E)f(E)dE$$

Substituting the values of g_c(E)and f(E):

$$n_o = \int_{E_c}^{\infty} \frac{8\pi\sqrt{2}}{h^3} m_e^{*3/2} \sqrt{E - E_c} \frac{1}{1 + e^{\frac{E - E_F}{kT}}} dE$$
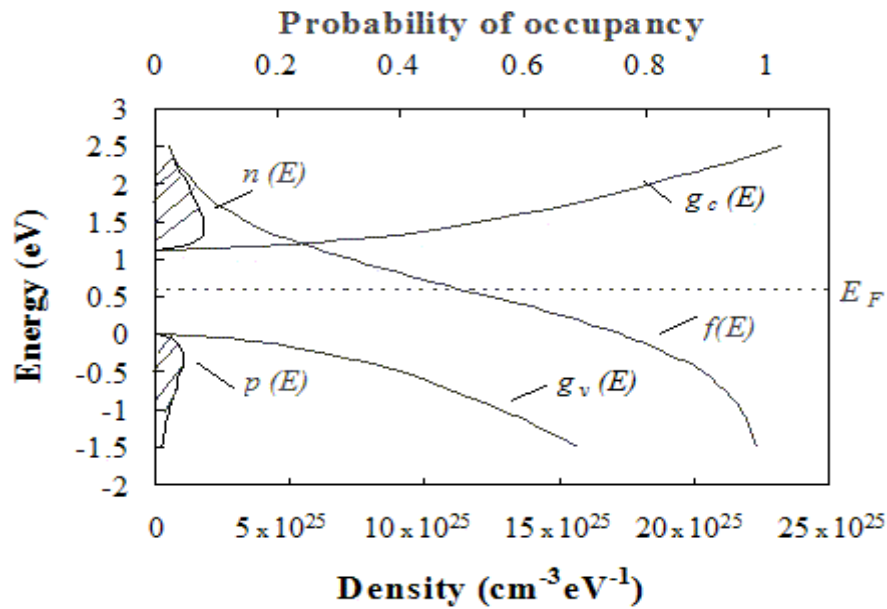
Similarly for holes one obtains:

$$p_o = \int_{-\infty}^{E_v} g_v(E)[1 - f(E)]dE$$

and

$$p_o = \int_{-\infty}^{E_v} \frac{8\pi\sqrt{2}}{h^3} m_h^{*3/2} \sqrt{E_v - E} \frac{1}{1 + e^{\frac{E_F - E}{kT}}} dE$$

The calculation of the electron and hole density in a semiconductor is further illustrated by the following figure

Non-degenerate semiconductors:- Non-degenerate semiconductors are defined as semiconductors for which the Fermi energy is at least $3kT$ away from either band edge. The reason we restrict ourselves to non-degenerate semiconductors is that this definition allows the Fermi function to be replaced with a simple exponential function, i.e. the Maxwell-Boltzmann distribution function. The carrier density integral can then be solved analytically yielding:

$$n_o \cong \int_{E_c}^{\infty} \frac{8\pi\sqrt{2}}{h^3} m_e^{*3/2} \sqrt{E-E_c}\, e^{\frac{E_F-E}{kT}}\, dE = N_c e^{\frac{E_F-E_c}{kT}}$$

where N_c is the *effective density of states* in the *conduction band*

$$N_c = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}$$

Similarly for holes, one can approximate the hole density integral as:

$$p_o \cong \int_{-\infty}^{E_v} \frac{8\pi\sqrt{2}}{h^3} m_h^{*3/2} \sqrt{E_v - E}\, e^{\frac{E-E_F}{kT}}\, dE = N_v e^{\frac{E_v - E_F}{kT}}$$

$$N_v = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}$$

Task No.1:- Set the Fermi level at 0.55eV and observe the Fermi function over a range of temperature

Task No.2:- Observe the Fermi function of an intrinsic semiconductor at very low temperature

Q.1: - Fermi level lies at _____Ev

Q.2: - Observe the density of state curve

Q.3:- Observe electron concentration w.r.t energy

Q.4:- Observe hole density w.r.t energy

Task No.03:- Now observe the same semiconductor at room temperature

Q.1:- Fermi level lies at_____ eV
Q.2:- Compare fermi functions of task 1 and task 2

Q: 3:- It is usually given in books that "If we see curves of Fermi function of an intrinsic semiconductor at different temperature we will observe that they overlap each other at Fermi level". Is it true as per your simulation results (Also attach simulation results)? Yes or no? Give reason.

Q: 4:- Observe density of states at room temperature

Q.5: - What is the density of states at the valence and conduction band edges?

Q.6: - Density of states is different for valence band and conduction band. Why?

Q.7: Compare density of states at both the temperatures. Is the bandgap independent of temperature?

Q.8: - Observe electron density w.r.t at 300K

Q.9: - As we move towards higher energy level carrier concentration decreases. Give reason

Q.10:- What is the electron concentration at the edge of conduction band.

Q.11: - Observe hole density at 300K

Q.12: - Observe both electron and hole densities w.r.t energy at 300K

Task No.04:- Now observe the occupation function of same semiconductor over a wide range of temperature

Q.1: - View electron density with energy and find out the electron density at
i) 1.13eV @ 300K
ii) 1.16eV @ 101K

Q.2:- View the hole density with respect to energy at different temperatures

Q.3:- View the electron and hole density with respect to energy at different temperatures

Q.4: - View the variation in bandgap with respect to temperature.

Q.5: - What is the bandgap of Si at 100K, 200K and 300K.

Task No.5: - View the occupation function of n type semiconductor at room temperature.

Q.1: - Fermi level lies at energy level_____eV
Q.2: - View electron density with respect to energy

Q.3:- View hole density with respect to energy

Task No.6: - Now observe the variation in ionization of dopants with the increase in temperature (of the above mentioned doped semiconductor).

References: -
[1] http://ecee.colorado.edu/~bart/book/book/chapter2/ch2_5.htm
[2] http://ecee.colorado.edu/~bart/book/book/chapter2/ch2_6.htm

LAB SESSION 04

Implement intrinsic, doped and compensated semiconductors. Analyze the position of Fermi level in these semiconductors. Understand the effect of temperature on these semiconductors.

Student Name: **.**

Roll no.:   **Batch:**   **.**

Semester: **Year**   **.**

Total Marks	Marks Obtained

Remarks (if any)   **.**

Instructor Name   **.**

Instructor Signature: **Date:**   **.**

LAB SESSION 04

Objective: - **Implement intrinsic, doped and compensated semiconductors. Analyze the position of Fermi level in these semiconductors. Understand the effect of temperature on these semiconductors.**

Tool: - _

Theory [1]: -

Expressions for n and p: -

From the previous lab we know that

$$n = N_c e^{(E_F - E_C)/kT} \qquad i)$$
$$p = N_v e^{(E_V - E_F)/kT} \qquad ii)$$

For an intrinsic semiconductor $n = p = n_i$ and $E_i = E_F$. Thus above equations become

$$n_i = N_c e^{(E_i - E_C)/kT} \qquad iii)$$
$$n_i = N_v e^{(E_V - E_i)/kT} \qquad iv)$$

Solving above equations for N_c and N_V, one obtains

$$N_c = n_i e^{(E_c - E_i)/kT} \qquad v)$$
$$N_v = n_i e^{(E_i - E_v)/kT} \qquad vi)$$

Finally eliminating N_C and N_V from equation $i)$ and equation $ii)$ we get

$$n = n_i e^{(E_F - E_i)/kT} \qquad vii)$$
$$p = n_i e^{(E_i - E_F)/kT} \qquad viii)$$

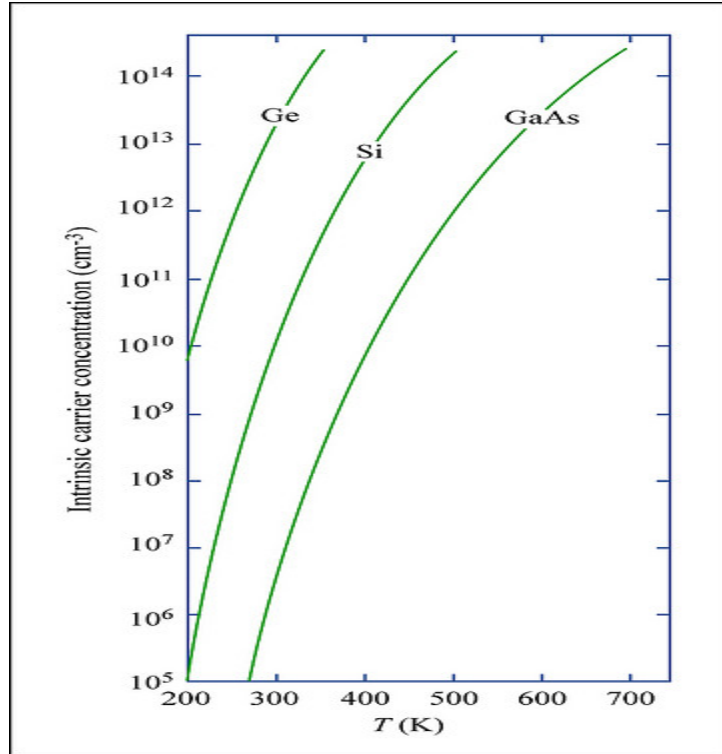## n_i and the np Product: -

By multiplying equation $iii)$ and equation $iv)$ one obtains

$$n_i^2 = N_C N_V e^{-(E_c - E_V)/kT} = N_C N_V e^{-E_G/kT}$$

Or

$$n_i = \sqrt{N_C N_V} e^{-E_G/2kT} \qquad ix)$$

Above equation shows that intrinsic carrier concentration is a function of temperature. Figure below shows intrinsic carrier concentration in Ge, Si, GaAs as a function of temperature.

A second very important n_i based relationship follows directly from equation vii) and $viii$) .Multiplying the corresponding sides of equations together yields

$$np = n_i^2 \qquad x)$$

If one of the carrier concentrations is known the remaining carrier concentration is readily determined using the above equation provided that semiconductor is in **equilibrium** and **non-degenerate**.

Charge Neutrality Relationship:-

For a uniformly doped material to be everywhere charge neutral clearly requires

$$\frac{charge}{cm^3} = qp - qn + qN_D^+ - qN_A^- = 0$$
$$p - n + N_D^+ - N_A^- = 0 \qquad xi)$$

Where

$$N_D^+ = \text{number of ionized (positively charged) donors/cm}^3$$
$$N_A^- = \text{number of ionized (negatively charged) acceptors/cm}^3$$

As we know that at room temperature there is sufficient thermal energy available to ionize all of the donor and acceptor sites

Defining

$$N_D = \text{total number of donors/cm}^3$$
$$N_A = \text{total numbr of acceptor/cm}^3$$

And setting

$$N_D^+ = N_D$$
$$N_A^- = N_A$$

One then obtains

$$p - n + N_D - N_A = 0 \qquad xii)$$

Carrier concentration calculation:-

Now we will calculate the carrier concentration in a uniformly doped semiconductor under equilibrium conditions. We will specifically make the **assumptions** of **nondegeneracy** and **total ionization of dopant atoms**. n_i which appears in np product expression, N_A and N_D, which appears in charge neutrality are known quantities while n and p are two unkowns. Thus there are two equations and two unknowns

Starting with np product equation (eq. x))

$$p = \frac{n_i^2}{n} \qquad xiii)$$

Eliminating p in eq..xii) using eq. $xiii$) gives

$$\frac{n_i^2}{n} - n + N_D - N_A = 0$$

Or

$$n^2 - n(N_D - N_A) - n_i^2 = 0 \qquad xiv)$$

Solving quadratic equation for n then yields

$$n = \frac{N_D - N_A}{2} + \left[\left(\frac{N_D - N_A}{2} \right)^2 + n_i^2 \right]^{1/2} \qquad xva)$$

and

$$p = \frac{n_i^2}{n} = \frac{N_A - N_D}{2} + \left[\left(\frac{N_A - N_D}{2} \right)^2 + n_i^2 \right]^{1/2} \qquad xvb)$$

Special Cases:-

Equations xv) are general-case solutions. In the vast majority of practical computations it is possible to simplify these equations prior to substituting in numerical values for N_D, N_A and n_i. Special cases of specific interest are:

Case I: - Intrinsic Semiconductor ($N_A = 0, N_D = 0$)
For this special case equations xv) simplify to
$n = n_i$ and $p = n_i$

Case II: - Doped Semiconductor where either $N_D - N_A \cong N_D \gg n_i$ or $N_A - N_D \cong N_A \gg n_i$
This is the special case of greatest practical interest and is mostly used
For $N_D - N_A \cong N_D \gg n_i$, equation xva) reduces to

$$n \cong N_D$$

and

$$p = \frac{n_i^2}{n} \cong n_i^2 \big/ N_D$$

Similarly for $N_A - N_D \cong N_A \gg n_i$, equation xvb) reduces to

$$p \cong N_A$$

and

$$n = \frac{n_i^2}{p} \cong n_i^2 \big/ N_A$$

Case III: - Doped Semiconductor where $n_i \gg |N_D - N_A|$
Systematically increasing the ambient temperature causes monotonic rise in intrinsic carrier concentration. At sufficiently elevated temperatures, n_i will eventually equal and then exceed the net doping concentration. If $n_i \gg |N_D - N_A|$ then equations xv) reduce to

$$n \cong p \cong n_i$$

In other words, all semiconductor become intrinsic at sufficiently high temperatures where $n_i \gg |N_D - N_A|$

Case IV: - Compensated Semiconductor ($N_D - N_A = 0$)

It is possible to produce intrinsic-like material by making $N_D - N_A = 0$. When N_A and N_D are comparable and nonzero, the material is said to be compensated. If the semiconductor is compensated, both N_A and N_D must be retained in all carrier concentration expressions and equations xv) reduce to

$$n = p = n_i$$

Determination of exact position of Fermi level E_F :-

The general positioning of the Fermi level in donor- and acceptor-doped semiconductors, assumed to be nondegenerate, in equilibrium, and maintained at temperatures where the dopants are fully ionized, can be obtained from the equation vii) and $viii$). Solving these equations for $E_F - E_i$, one obtains

$$E_F - E_i = kT \ln\left(\frac{n}{n_i}\right) = -kT \ln\left(\frac{p}{n_i}\right) \qquad\qquad xvi)$$

For a doped semiconductor where $N_D - N_A \cong N_D \gg n_i$

$$E_F - E_i = kT \ln\left(\frac{N_D}{n_i}\right) \qquad\qquad xvii)$$

For a doped semiconductor where $N_A - N_D \cong N_A \gg n_i$

$$E_i - E_F = kT \ln\left(\frac{N_A}{n_i}\right) \qquad\qquad xviii)$$

Task No. 01:-At 300K observe the intrinsic Semiconductor

Q.1: - What is the intrinsic carrier concentration?

Q.2: - Where does Fermi level lie?

Q.3: - Write down the concentration of electron and hole

Task No. 02: Increase the temperature and observe the semiconductor

Q.1: - Write down the intrinsic carrier concentration.

Q.2: - Where does Fermi level lie? Is there any effect of temperature on position of Fermi level? Yes/No. Give reason.

Q.3: - Write down the concentration of electron and hole. Is there any effect on the concentration of electron and hole? Yes/no. Give reason

Task No. 03:- Suppose the semiconductor is doped with acceptor atoms. Observe the semiconductor at 300K

Q.1: - What is the intrinsic carrier concentration?

Q.2: - Write down the concentration of electrons and holes.

Q.3: - Where does Fermi level lie? At, above or below E_i ? Give reason.

Q.4: - What is the position of E_F relative to E_i?

Task No. 04: - Observe the above doped semiconductor at 550K.

Q.1: - What is intrinsic carrier carrier concentration?

Q.2: - What is the concentration of electron and holes?

Q.3: - What is the position of E_F relative to E_i?

Q.4: - Despite of the fact that semiconductor is doped only by acceptor atoms, electron concentration is almost equal to the hole concentration. Explain why?

Task No.05: - Observe the semiconductor at 300K for which $N_A = N_D$

Q.1: - What is the intrinsic carrier concentration, concentration of electrons and holes?

Q.2: -What is the position of E_F relative to E_i?

Q.3: - Based on the results of question 1, is there any advantage of equal acceptor and donor doping (i.e. $N_A = N_D$)? If yes, specify its application. If no, give reason?

References:-
[1]   Semiconductor Device Fundamentals by Robert F. Pierret, Chapter 2

LAB SESSION 05

Understand and analyze the effect of different type of carrier action (diffusion, thermal generation n recombination and photogeneration) on carrier concentration

Student Name: .

Roll no.:   **Batch:**   .

Semester: **Year**   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: **Date:**   .

LAB SESSION 05

Objective: - **Understand and analyze the effect of different type of carrier action (diffusion, thermal generation n recombination and photogeneration) on carrier concentration**.

Tool: - _

Theory: -

Equilibrium: - A semiconductor is said to be in equilibrium when there is no external excitation and thus no net motion of charges. There is no discontinuity in equilibrium Fermi level i.e. $\frac{dE_F}{dx} = 0$. In a non-degenerated semiconductor which is at equilibrium the condition $n_o p_{o=} n_i^2$ is valid

Non-equilibrium[1]: - A semiconductor is said to be in non-equilibrium when it is either illuminated with light or a non-zero voltage is applied across it. In non-equilibrium situations the condition $np = n_i^2$ is violated. **Steady state** refers to a non-equilibrium condition in which all processes are constant and are balanced by opposing processes

Injection of Carriers: - There are two types of deviation from equilibrium (i.e. $np \neq n_i^2$). When $np > n_i^2$, we talk of injection of excess carriers

Low level Injection: - The condition in which excess carrier concentration is negligibly small in comparison to the doping concentration is known as low level injection. For example in an n-type semiconductor, $= \delta p \ll N_D$, is referred to as low level injection

Under normal operating conditions the three primary types of carrier actions occurring inside semiconductors are drift, diffusion and recombination-generation.

Drift [2]: - Drift is the charged particle motion in response to an applied electric field. When a voltage is applied across a semiconductor, carriers will experience a net force.

Drift current density (Ampere/unit area) for electrons can be written as

$$J_{n|drift} = q\mu_n n\mathcal{E} \qquad i)$$

Drift current density (Ampere/unit area) for holes can be written as

$$J_{p|drift} = q\mu_p p\mathcal{E} \qquad ii)$$

Diffusion: - When excess carriers are created non-uniformly, the electron and hole concentrations vary with position in the semiconductor. Any such spatial variation (gradient) in n and p calls for a net motion of carriers from the regions of high carrier concentration to regions of low carrier concentration. This type of motion is called diffusion and represents an important charge transport process in semiconductors. Flux density (particle flow per unit area) can be written as:

Electron flux density

$$\emptyset_n(x) = -D_n \frac{dn(x)}{dx} \qquad iii)$$

Similarly hole flux density

$$\emptyset_p(x) = -D_p \frac{dp(x)}{dx} \qquad iv)$$

The diffusion current density (current crossing a unit area) can be obtained by multiplying particle flux density by the charge of the carrier:

$$J_n(diff.) = -(-q)D_n \frac{dn(x)}{dx} = +qD_n \frac{dn(x)}{dx} \qquad v)$$

$$J_p(diff.) = -(+q)D_p \frac{dp(x)}{dx} = -qD_p \frac{dp(x)}{dx} \qquad vi)$$

Above equations show that minority carriers can contribute significantly to the current through diffusion. Since the drift terms are proportional to the carrier concentration, minority carriers seldom provide much drift current. On the other hand, diffusion current is proportional to the gradient of concentration. Thus minority carrier current through diffusion can sometimes be as large as majority carrier currents.

Einstein Relation: - If an electric field is present in addition to the carrier gradient, the current densities will have drift component and a diffusion component

$$J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{dn(x)}{dx} \qquad vii)$$

$$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{dp(x)}{dx} \qquad viii)$$

Assuming an electric field $\mathcal{E}(x)$ in the x-direction, we can draw the energy bands as shown in the figure, to include the change in potential energy of electrons in the field. Since electrons drift in a direction opposite to the field, we expect the potential energy for electrons to increase in the direction of the field, as shown in the figure. The electrostatic potential $\mathcal{V}(x)$ varies in the opposite direction, since it is defined in terms of positive charges and is therefore related to the electron potential energy $E(x)$ displayed in the figure by

$$\mathcal{V}(x) = \frac{E(x)}{-q} \qquad ix)$$
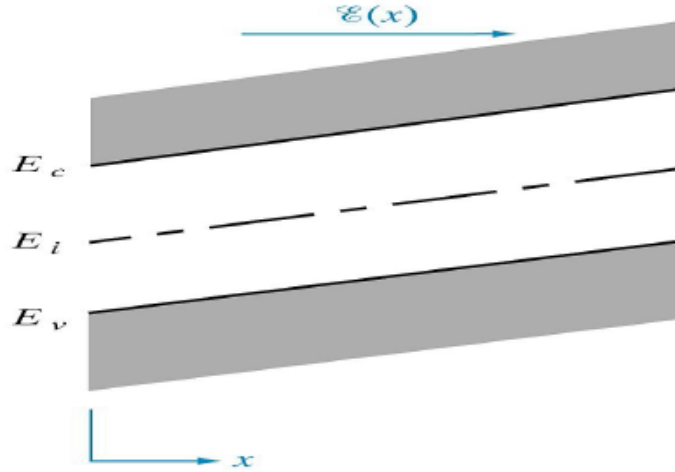
From the definition of electric field

$$\mathcal{E}(x) = -\frac{d\,V(x)}{dx} \qquad\qquad x)$$

$$\mathcal{E}(x) = -\frac{d\,V(x)}{dx} = -\frac{d}{dx}\left[\frac{E_i}{(-q)}\right] = \frac{1}{q}\frac{d\,E_i}{dx} \qquad\qquad xi)$$

At equilibrium no net current flows in a semiconductor. Thus any fluctuation that which would begin diffusion current also sets up an electric field which redistributes carriers by drift. Thus equating equation $viii)$ with 0 we can obtain

$$q\mu_p p(x)\mathcal{E}(x) = qD_p \frac{dp(x)}{dx}$$

$$\mu_p p(x)\mathcal{E}(x) = D_p \frac{dp(x)}{dx}$$

$$\mathcal{E}(x) = \frac{D_p}{\mu_p}\frac{1}{p(x)}\frac{dp(x)}{dx}$$

Using equation $viii)$ $of\ lab\#04$ we have

$$\mathcal{E}(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left(\frac{dE_i}{dx} - \frac{dE_F}{dx}\right)$$

The equilibrium Fermi level will not vary with x and the derivative of E_i is given by equation $xi)$. Thus above equation becomes

$$\mathcal{E}(x) = \frac{D_p}{\mu_p}\frac{1}{kT}\left(\frac{\mathcal{E}(x)}{q}\right)$$

$$\frac{D}{\mu} = \frac{kT}{q} \qquad x)$$

The above expression equation $x)$ is known as Einstein relation

Continuity Equation[3]: - Each and every type of carrier action gives rise to a change in the carrier concentrations with time. The combined effect of all types of carrier action can therefore be taken into account by equating the overall change in the carrier concentration per unit time to the sum of due to individual processes: i.e,

$$\frac{\partial n}{\partial t} = (\frac{\partial n}{\partial t})_{diff} + (\frac{\partial n}{\partial t})_{drift} + (\frac{\partial n}{\partial t})_{R-G} + (\frac{\partial n}{\partial t})_{photogeneration} \qquad xi)$$

$$\frac{\partial p}{\partial t} = (\frac{\partial p}{\partial t})_{diff} + (\frac{\partial p}{\partial t})_{drift} + (\frac{\partial p}{\partial t})_{R-G} + (\frac{\partial n}{\partial t})_{photogeneration} \qquad xii)$$

Above equations are known as continuity equation. The continuity equation can be written as in somewhat compact form by noting

$$(\frac{\partial n}{\partial t})_{diff} + (\frac{\partial n}{\partial t})_{drift} = \frac{1}{q}\frac{\partial J_n}{\partial x} \qquad xiii)$$

$$(\frac{\partial p}{\partial t})_{diff} + (\frac{\partial p}{\partial t})_{drift} = -\frac{1}{q}\frac{\partial J_p}{\partial x} \qquad xiv)$$

Working with continuity equation for electrons only, substituting equation $xiii)$ in equation $xi)$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + (\frac{\partial n}{\partial t})_{R-G} + (\frac{\partial n}{\partial t})_{photogeneration} \qquad xv)$$

As we know that

$$(\frac{\partial n}{\partial t})_{R-G} = -\frac{\delta n}{\tau_n} \qquad xvi)$$

From equation $vii)$

$$J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n\frac{\partial n(x)}{dx}$$

If $\mathcal{E} = 0$ then

$$J_n(x) = qD_n\frac{\partial n(x)}{dx} \qquad xvii)$$

As we know that $n = n_o + \delta n$ .Thus

$$\frac{\partial n}{\partial x} = \frac{\partial (n_o + \delta n)}{\partial x} = \frac{\partial n_o}{\partial x} + \frac{\partial \delta n}{\partial x}$$

As equilibrium carrier concentration is not a function of position. i.e. $\frac{\partial n_o}{\partial x} = 0$. Thus

$$\frac{\partial n}{\partial x} = \frac{\partial \delta n}{\partial x}$$

Thus equation $xvii$) becomes

$$J_n(x) = qD_n \frac{\partial \, \delta n}{\partial x} \qquad xviii)$$

Substituting equation xvi) and equation $xviii$) in equation xv)

$$\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial (qD_n \frac{\partial \, \delta n}{\partial x})}{\partial x} - \frac{\delta n}{\tau_n} + (\frac{\partial n}{\partial t})_{photogeneration}$$

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 \, \delta n}{\partial x^2} - \frac{\delta n}{\tau_n} + G_L \qquad xix)$$

Finally, the equilibrium carrier concentration is not a function of time. i.e. $\frac{dn_o}{dt} = 0$. Thus

$$\frac{\partial \, n}{\partial t} = \frac{\partial \, (n_o + \delta n)}{\partial t} = \frac{\partial n_o}{\partial t t} + \frac{\partial \, \delta n}{\partial t} = \frac{\partial \, \delta n}{\partial t}$$

Thus equation xix) becomes

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \, \delta n}{\partial x^2} - \frac{\delta n}{\tau_n} + G_L \qquad xx)$$

Steady State Carrier Injection: - If steady state condition is maintained then $\frac{\partial \delta n}{\partial t} = 0$. Thus, equation xx) becomes

$$0 = D_n \frac{d^2 \, \delta n}{dx} - \frac{\delta n}{\tau_n} + G_L$$

If there is no photogeneration i.e. $G_L = 0$ then above equation becomes

$$D_n \frac{d^2 \delta n}{dx} = \frac{\delta n}{\tau_n}$$

$$\frac{d^2 \delta n}{dx} = \frac{\delta n}{D_n \tau_n}$$

$$\frac{d^2 \delta n}{dx} = \frac{\delta n}{L_n^2}$$

Where $L_n = \sqrt{D_n \tau_n}$ is called the electron diffusion length. Solution of above equation is

$$\delta p(x) = C_1 e^{x/L_n} + C_2 e^{-x/L_n} \qquad xxi)$$

Quasi Fermi level: - The Fermi level E_F equation is meaningful only when no excess carriers are present. However, we can write expressions for the steady state concentrations in the same form as the equilibrium expressions by defining separate **quasi-Fermi levels** Fn and Fp for electrons and holes. The resulting carrier concentration equations

$$n = n_i e^{(F_n - E_i)/kT} \qquad xxii)$$

$$p = n_i e^{(E_i - F_p)/kT} \qquad xxiii)$$

Task No.01: - A silicon wafer ($N_D = 10^{14}/cm^3$, T=Room Temperature) is illuminated with light which generates 10^{15} electron-hole pairs per cm^3-sec throughout the volume of the silicon

Q.1:- View the energy band diagram before illumination.

Q.2: - From the simulation results determine doping, electron and hole density at equilibrium. Don't forget to attach simulation results.

Q.3: - From the simulation results determine electrostatic potential at equilibrium. Don't forget to attach simulation results.

Q.4: - View the energy band diagram under non-equilibrium

Q.5: - By using simulation results determine the value of doping, electron and hole density under non-equilibrium.

Q.6: - View the excess carrier profile. Determine the excess electron and hole density.

Task No.02: - A p-type silicon wafer is illuminated with light throughout the volume of the wafer
Q.1:- View the energy band diagram before illumination.

Q.2: - From the simulation results determine doping, electron and hole density at equilibrium. Don't forget to attach simulation results.

Q.3: - From the simulation results determine electrostatic potential at equilibrium. Don't forget to attach simulation results.

Q.4: - View the energy band diagram under non-equilibrium

Q.5: - By using simulation results determine the value of doping, electron and hole density under non-equilibrium.

Q.6: - View the excess carrier profile. Determine the excess electron and hole density.

Task No.3: - An n-type semiconductor slab is illuminated with light at its center

Q.1:- View the energy band diagram before illumination

Q.2: - View the energy band diagram under non-equilibrium

Q.3: - From the simulation results determine doping, electron and hole density at equilibrium. Don't forget to attach simulation results.

Q.4: - From the simulation results determine electrostatic potential at equilibrium. Don't forget to attach simulation results.

Q.5: - View the excess minority carrier profile. Find out excess carrier concentration at the point where semiconductor is illuminated.

References:-

[1] Physics and Technology of Semiconductor Devices by A.S.Grove, Chapter 5
[2] Solid State Electronic Devices by Streetman, Chapter 4
[3] Semiconductor Device Fundamentals by Robert F.Pierret, Chapter 3

LAB SESSION 06

To analyze the phenomenon of drift of charge carriers under the influence of electric field.

Student Name: **.**
Roll no.:   **Batch:**   **.**
Semester: **Year**   **.**

Total Marks	Marks Obtained

Remarks (if any)   **.**

Instructor Name   **.**

Instructor Signature: **Date:**   **.**

LAB SESSION 06

Objective: - **To analyze the phenomenon of drift of charge carriers under the influence of electric field.**

Tool: - _

Theory: -

Equilibrium: - A semiconductor is said to be in equilibrium when there is no external excitation and thus no net motion of charges. There is no discontinuity in equilibrium Fermi level i.e. $\frac{dE_F}{dx} = 0$. In a non-degenerated semiconductor which is at equilibrium the condition $n_o p_{o=} n_i^2$ is valid

Non-equilibrium [1]: - A semiconductor is said to be in non-equilibrium when it is either illuminated with light or a non-zero voltage is applied across it. In non-equilibrium situations the condition $np = n_i^2$ is violated. **Steady state** refers to a non-equilibrium condition in which all processes are constant and are balanced by opposing processes

Under normal operating conditions the three primary types of carrier actions occurring inside semiconductors are drift, diffusion and recombination-generation.

Diffusion: - When excess carriers are created non-uniformly, the electron and hole concentrations vary with position in the semiconductor. Any such spatial variation (gradient) in n and p calls for a net motion of carriers from the regions of high carrier concentration to regions of low carrier concentration. This type of motion is called diffusion.

Drift [2]: - Drift is the charged particle motion in response to an applied electric field. When a voltage is applied across a semiconductor, carriers will experience a net force.

Drift current density (Ampere/unit area) for electrons can be written as

$$J_{n|drift} = q\mu_n n\mathcal{E} \qquad i)$$

Drift current density (Ampere/unit area) for holes can be written as

$$J_{p|drift} = q\mu_p p\mathcal{E} \qquad ii)$$

Since the drift terms are proportional to the carrier concentration, thus the drift current flows because of majority carriers while minority carriers seldom provide much drift current.

If current is carried by both the electrons and holes then

$$J_{drift} = q\mu_n n\mathcal{E} + q\mu_p p\mathcal{E}$$

$$J_{drift} = q\mathcal{E}(\mu_n n + \mu_p p) \qquad iii)$$

If the material is intrinsic, then $n = p = n_i$. Thus above equation becomes

$$J_{drift} = q\mathcal{E}(\mu_n n_i + \mu_p n_i)$$

$$J_{drift} = q(\mu_n + \mu_p)n_i\mathcal{E} \qquad\qquad iv)$$

Task No.01: - Apply potential across an intrinsic semiconductor

Q.1: - From the simulation results determine doping, electron and hole density at equilibrium. Don't forget to attach simulation results.

Q.2: - What is the current density when 0.18V is applied across the semiconductor. Verify the simulation results by mathematical calculation.

Task No.02: - Apply potential across a n-type semiconductor

Q.1: - From the simulation results determine doping, electron and hole density at equilibrium. Don't forget to attach simulation results.

Q.2: - What is the current density when 0.18V is applied across the semiconductor. Verify the simulation results by mathematical calculation.

Task No.03: - Apply a potential across n-type semiconductor. Find out the current density. Now vary the doping and from the simulation results, observe the effect of doping on current density.

Task No.04: - Observe the effect of current saturation at high electric field in n-type semiconductor.

Task No.05: - Observe the effect of current saturation at high electric field in an intrinsic semiconductor.

References:-
[1] Physics and Technology of Semiconductor Devices by A.S.Grove, Chapter 5
[2] Solid State Electronic Devices by Streetman, Chapter 3

LAB SESSION 07

Experimentally prove the phenomenon of energy band bending under the influence of electric field.

Student Name: **.**
Roll no.:   **Batch:**   **.**
Semester: **Year**   **.**

Total Marks	Marks Obtained

Remarks (if any)   **.**

Instructor Name   **.**

Instructor Signature: **Date:**   **.**

LAB SESSION 07

Objective: - **Experimentally prove the phenomenon of energy band bending under the influence of electric field.**

Tool: - _

Theory: -

Equilibrium: - A semiconductor is said to be in equilibrium when there is no external excitation and thus no net motion of charges. There is no discontinuity in equilibrium Fermi level i.e. $\frac{dE_F}{dx} = 0$. In a non-degenerated semiconductor which is at equilibrium the condition $n_o p_{o=} n_i^2$ is valid

Non-equilibrium [1]: - A semiconductor is said to be in non-equilibrium when it is either illuminated with light or a non-zero voltage is applied across it. In non-equilibrium situations the condition $np = n_i^2$ is violated. **Steady state** refers to a non-equilibrium condition in which all processes are constant and are balanced by opposing processes

Under normal operating conditions the three primary types of carrier actions occurring inside semiconductors are drift, diffusion and recombination-generation.

Diffusion: - When excess carriers are created non-uniformly, the electron and hole concentrations vary with position in the semiconductor. Any such spatial variation (gradient) in n and p calls for a net motion of carriers from the regions of high carrier concentration to regions of low carrier concentration. This type of motion is called diffusion.

Drift [2]: - Drift is the charged particle motion in response to an applied electric field. When a voltage is applied across a semiconductor, carriers will experience a net force.

Drift current density (Ampere/unit area) for electrons can be written as

$$J_{n|drift} = q\mu_n n\mathcal{E} \qquad i)$$

Drift current density (Ampere/unit area) for holes can be written as

$$J_{p|drift} = q\mu_p p\mathcal{E} \qquad ii)$$

Since the drift terms are proportional to the carrier concentration, thus the drift current flows because of majority carriers while minority carriers seldom provide much drift current.

If current is carried by both the electrons and holes then

$$J_{drift} = q\mu_n n\mathcal{E} + q\mu_p p\mathcal{E}$$

$$J_{drift} = q\mathcal{E}(\mu_n n + \mu_p p) \qquad iii)$$

If the material is intrinsic, then $n = p = n_i$. Thus above equation becomes

$$J_{drift} = q\mathcal{E}(\mu_n n_i + \mu_p n_i)$$

$$J_{drift} = q(\mu_n + \mu_p)n_i\mathcal{E} \qquad\qquad iv)$$

Energy Band diagram in an electric field: - If an electric field $\mathcal{E}(x)$ is present across a semiconductor in the x-direction, we can draw the energy bands as shown in the figure below, to include the change in potential energy of electrons in the field. Since electrons drift in a direction opposite to the field, we expect the potential energy for electrons to increase in the direction of the field. The electrostatic potential $V(x)$ varies in the opposite direction, since it is defined in terms of positive charges and is therefore related to the electron potential energy $E(x)$ displayed in the figure by

$$V(x) = \frac{E(x)}{-q} \qquad\qquad v)$$
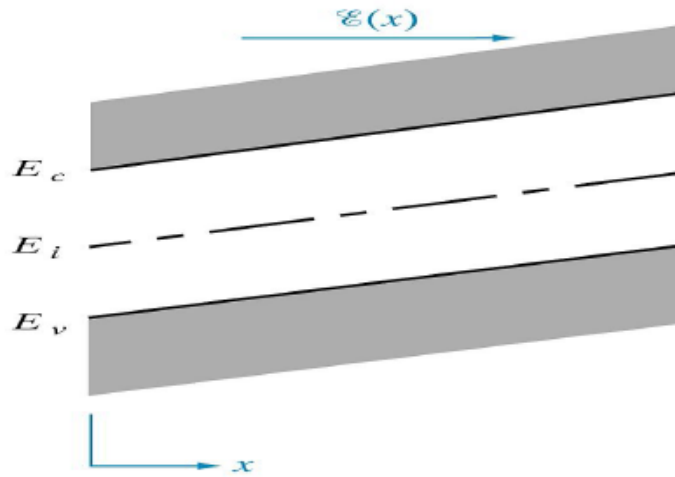
From the definition of electric field

$$\mathcal{E}(x) = -\frac{d\,V(x)}{dx} \qquad\qquad vi)$$

$$\mathcal{E}(x) = -\frac{d\,V(x)}{dx} = -\frac{d}{dx}\left[\frac{E_i}{(-q)}\right] = \frac{1}{q}\frac{d\,E_i}{dx} \qquad\qquad vii)$$

Therefore, the variation of band energies with $\mathcal{E}(x)$ as drawn in figure is correct. The direction of the slope in the bands relative to $\mathcal{E}$ is simple to remember: Since the diagram indicates electron energies, we know the slope in the bands must be such that electrons drift "downhill" in the field. Therefore, $\mathcal{E}$ points "uphill" in the band diagram.

Task No.01: - Apply potential across an intrinsic semiconductor
Q.1:- View the energy band diagram of semiconductor before applying potential across it.

Q.2: - View the energy band diagram of biased semiconductor.

Q.3: - View the elecrostatic potential under non-equilibrium

Q.4:- What is the electric field that exist across the semiconductor under biased conditions. Attach the simulation result.

Task No.02: - Apply potential across a n-type semiconductor

Q.1:- View the energy band diagram of semiconductor before applying potential across it.

Q.2: - View the energy band diagram of biased semiconductor.

Q.3: - View the elecrostatic potential under non-equilibrium

Q.4: - What is the electric field that exist across the semiconductor under biased conditions. Attach the simulation result.

References:-

[1] Physics and Technology of Semiconductor Devices by A.S.Grove, Chapter 5
[2] Solid State Electronic Devices by Streetman, Chapter 3

LAB SESSION 08

Analyze the effect of temperature and doping on mobility of charge carriers

Student Name: .
Roll no.:   Batch: .
Semester: Year   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: Date: .

LAB SESSION 08

Objective: - Analyze the effect of temperature and doping on mobility of charge carriers.

Tool: - _

Theory: -

Effect of temperature on Mobility:- The two basic types of scattering mechanism that influence electron and hole mobility at different temperatures are lattice scattering and impurity scattering.

i)   **Lattice Scattering: -** In lattice scattering a carrier moving through the crystal is scattered by a vibration of lattice, resulting from the temperature. **The frequency of such scattering events increases as the temperature increases**, since the thermal agitation of lattice becomes greater. Therefore, we should expect the mobility to decrease as the sample is heated

ii)   **Impurity Scattering: -** In impurity scattering a carrier moving through the crystal is scattered by crystal defects such as ionized impurities. **This type of scattering is dominant at low temperature** because a slowly moving carrier is likely to be scattered strongly by an interaction with a charged ion. Therefore impurity scattering events cause a decrease in mobility with decreasing temperature.

Effect of Doping on Mobility:- As the concentration of impurities increases, the effect of impurity scattering are felt . For example, the electron mobility of intrinsic Si at 300K is 1350 cm^2/V*sec. With a donor doping concentration of 10^{17}/cm^3, however, mobility of electron is 700 cm^2/V*sec. Thus the presence of the 10^{17} ionized donors/cm3 introduces a significant amount of impurity scattering. The mobility of electrons and holes in silicon at room temperature is shown in figure below
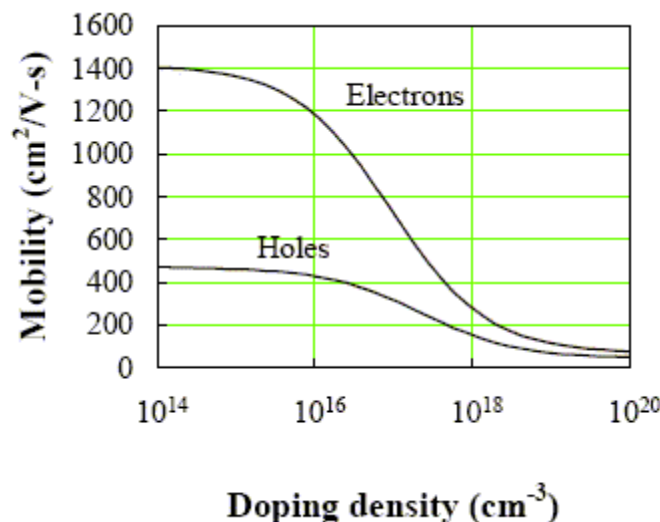
Task No.01: - Write down the mobility of electron in an intrinsic semiconductor at room temperature.

Task No.02: - Apply potential across an n-type semiconductor. From the simulation result(s) calculate the mobility of electrons. Also verify your simulation results. Compare the mobility of electrons in an intrinsic and an n-type doped semiconductor. Is there any effect of doping on mobility? Yes/No? Give reason

Task No.03: - Apply potential across a p-type semiconductor. From the simulation result(s) calculate the mobility of holes. Also verify your simulation results. Compare the mobility of holes in an intrinsic and a p-type doped semiconductor.

Task No.04: - Apply a potential across n-type semiconductor. Find out the mobility of electrons. Now vary the doping concentration and from the simulation results, observe the effect of doping concentration on mobility.

References:-
[1] Physics and Technology of Semiconductor Devices by A.S.Grove, Chapter 5
[2] Solid State Electronic Devices by Streetman, Chapter 3

LAB SESSION 09

Implement an equally doped PN junction diode. Study and analyze its charge density, electric field and electrostatic potential under equilibrium condition.

Student Name: .
Roll no.: **Batch:** .
Semester: **Year** .

Total Marks	Marks Obtained

Remarks (if any) .

Instructor Name .

Instructor Signature: **Date:** .

LAB SESSION 09

Objective: - **Implement an equally doped PN junction diode. Study and analyze its charge density, electric field and electrostatic potential under equilibrium condition.**

Tool: - _

Theory: -
Suppose we have *p*- and *n*- regions that were initially separated .Charge neutrality is assumed to prevail in the isolated, uniformly doped semiconductor. In the *p*- material the positive hole charges, the ($\oplus's$) balance the immobile acceptor- site charges($\boxminus$'s). Similarly in *n*-type material the electronic charge ($\ominus$) everywhere balances the immobile charges associated with the ionized donors ($\boxplus$)
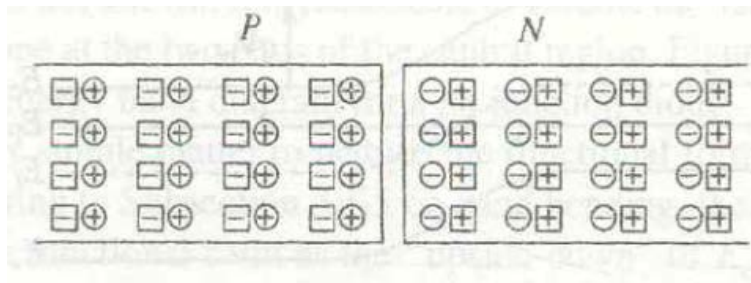
Now suppose a structurally perfect connection is made between the p and n materials.
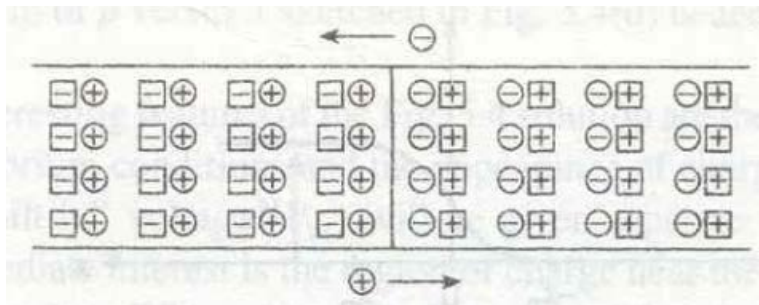
Since there are many holes on the p-side than the electrons on n-side, holes begin to diffuse from the p-side to n-side an instant after the connection is made. Similarly, electrons diffuse from the n-side to p-side of the junction. Although the electrons and holes can move to the opposite side of the junction, the donors and acceptors are fixed in space. Consequently, the diffusing away of carriers from the near –vicinity of the metallurgical junction where there is significant non-zero charge is called the space charge region or depletion region.
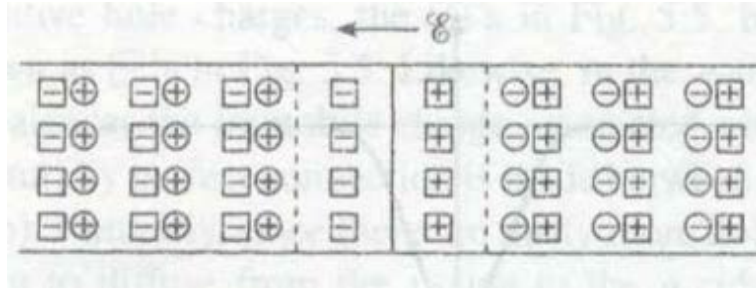
The build-up of charge and the associated electric field continues until the diffusion of carriers across the junction is precisely balance by the carrier drift.

Since the dipole about the junction must have an equal number of charges on either side, $(Q_+ = |Q_-|)$ [1]. For a sample if cross-sectional area A, the total uncompensated charge on either side of the junction is

$$qAx_pN_a = qAx_nN_d$$

Or

$$N_ax_p = N_dx_n \qquad i)$$

Where x_p is the penetration of space region into the p material and x_n is the penetration into n. The total width of the transition region (W) is the sum of x_p and x_n.

Built-in- potential (V_{bi}):- The voltage drop across the depletion region under equilibrium conditions, known as the built-in potential (V_{bi}). PN junction maintained under equilibrium conditions with $x =0$ positioned at the metallurgical boundary. The ends of the equilibrium depletion region are taken to occur at $-x_p$ and x_n.

Proceeding with the derivation, we know

$$\varepsilon = -\frac{dV}{dx}$$

Integrating across the depletion region gives

$$-\int_{-x_p}^{x_n} \varepsilon \, dx = \int_{V_{(-x_p)}}^{V_{(x_n)}} dV = V(x_n) - V(-x_p) = V_{bi} \qquad ii)$$

From equation vii) of lab 5

$$J_n = qn\mu_n\varepsilon + qD_N\frac{dn}{dx}$$

As the material is in equilibrium thus no current will flow

$$0 = qn\mu_n\varepsilon + qD_N\frac{dn}{dx}$$

Solving ε and making use of Einstein relationship, we obtain

$$\varepsilon = -\frac{D_N}{\mu_n}\frac{dn/dx}{n} = -\frac{kT}{q}\frac{dn/dx}{n}$$

Substituting this in equation ii)

$$V_{bi} = -\int_{-x_p}^{x_n}\varepsilon\,dx = \frac{kT}{q}\int_{V_{(-x_p)}}^{V_{(x_n)}}\frac{dn}{n} = \frac{kT}{q}ln\left[\frac{n(x_n)}{n(-x_p)}\right]$$

For a specific case of step junction where N_a and N_d are the p- and n- side doping concentrations, one identifies

$$n(x_n) = N_d$$

$$n(-x_p) = \frac{n_i^2}{N_a}$$

And therefore

$$V_{bi} = \frac{kT}{q}ln\left[\frac{N_aN_d}{n_i^2}\right] \qquad\qquad iii)$$

Charge Density:-

$$\rho = p - n + N_d - N_a$$

Depletion Approximation [2]**:** - The approximation has 2 components that can be stated as follow:

1) The carrier concentrations are assumed to be negligible compared to the net doping concentration in a region$-x_p \le x \le x_n$
2) The charge density outside the depletion region is taken to be identically zero.
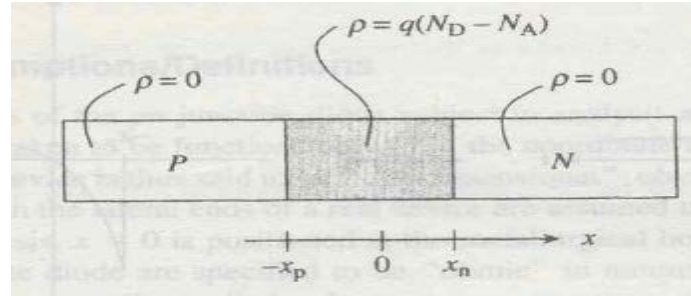
Thus overall charge density in a PN junction diode

$$\rho = \begin{cases} -qN_a, & -x_p \leq x \leq 0 \\ qN_d, & 0 \leq x \leq x_n \\ 0 & x \leq -x_p \text{ and } x \geq x_n \end{cases} \qquad iv)$$
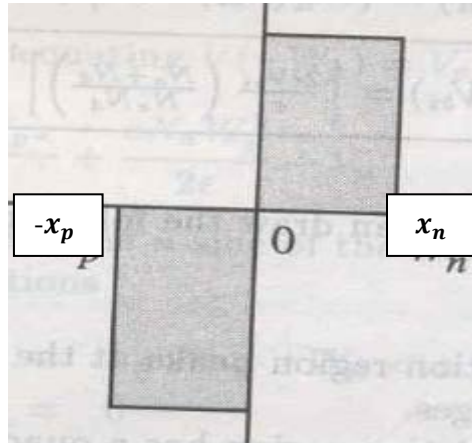
Electric field: -

As we know that Poisson's equation states that

$$\frac{d\varepsilon}{dx} = \frac{\rho}{K_s \varepsilon_o}$$

By substituting the value of ρ

$$\frac{d\varepsilon}{dx} = \begin{cases} -qN_a/K_s\varepsilon_o, & -x_p \leq x \leq 0 \\ qN_d/K_s\varepsilon_o, & 0 \leq x \leq x_n \\ 0 & x \leq -x_p \text{ and } x \geq x_n \end{cases}$$

By integrating above equation we get

$$\varepsilon(x) = -\frac{qN_a}{K_s\varepsilon_o}(x_p + x) \ldots \ldots \ldots -x_p \leq x \leq 0 \qquad va)$$

$$\varepsilon(x) = -\frac{qN_d}{K_s\varepsilon_o}(x_n - x) \ldots\ldots\ldots 0 \leq x \leq x_n \qquad\qquad vb)$$

$$\varepsilon(x) = 0 \ldots\ldots\ldots\ldots \quad x \leq -x_p \, and \, \& x \geq x_n \qquad\qquad vc)$$

From equation $va)$ and $vb)$ it's obvious that maximum electric field exists at $x = 0$

$$\varepsilon(0) = -\frac{qN_a x_p}{K_s\varepsilon_o} = -\frac{qN_d x_n}{K_s\varepsilon_o} \qquad\qquad vi)$$
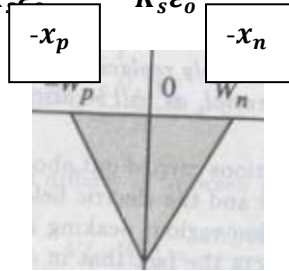
Electrostatic Potential: -

From the definition of electric field

$$\varepsilon = -\frac{dV}{dx}$$

By substituting the value of ε

$$\frac{dV}{dx} = \frac{qN_a}{K_s\varepsilon_o}(x_p + x) \ldots\ldots\ldots -x_p \leq x \leq 0$$

$$\frac{dV}{dx} = \frac{qN_d}{K_s\varepsilon_o}(x_n - x) \ldots\ldots\ldots 0 \leq x \leq x_n$$

With the arbitrary reference potential set to zero at $= -x_p$, and remembering the voltage drop is V_{bi} across the depletion region under equilibrium conditions, above equations are respectively subject to the boundary conditions

$$V = 0 \qquad at \qquad x = -x_p$$

$$V = V_{bi} \qquad at \qquad x = x_n$$

Thus we get

$$V(x) = 0 \ldots\ldots\ldots\ldots -x_p < x \qquad\qquad\qquad vii\;a)$$

$$V(x) = \frac{qN_a}{2K_s\varepsilon_o}(x_p + x)^2 \ldots\ldots\ldots -x_p \le x \le 0 \qquad vii\;b)$$

$$V(x) = V_{bi} - \frac{qN_d}{2K_s\varepsilon_o}(x_n - x)^2 \ldots\ldots\ldots 0 \le x \le x_n \qquad vii\;c)$$

$$V(x) = V_{bi} \ldots\ldots\ldots\ldots x > x_n \qquad\qquad\qquad vii\;d)$$

From equation $viib$) and $viic$) the electrostatic potential that exists at $x = 0$

$$V(0) = \frac{qN_a}{2K_s\varepsilon_o}x_p{}^2 = V_{bi} - \frac{qN_d}{2K_s\varepsilon_o}x_n{}^2 \qquad\qquad viii)$$

Solution of x_n and x_p : - Above equation can be written as

$$\frac{qN_a}{2K_s\varepsilon_o}x_p{}^2 = V_{bi} - \frac{qN_d}{2K_s\varepsilon_o}x_n{}^2 \qquad\qquad ix)$$

Specifically, x_n and x_p are the two unknown in equation i) and ix). Solving these equations we get

$$x_n = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_a}{N_d(N_a + N_d)}V_{bi}\right]^{1/2} \qquad x)$$

$$x_p = \frac{N_d x_n}{N_a} = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_d}{N_a(N_a + N_d)}V_{bi}\right]^{1/2} \qquad xi)$$

It also follows that

$$W = x_n + x_p = \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)V_{bi}\right]^{1/2} \qquad xii)$$

Task No.01: - Consider an equally doped unbiased PN junction diode
Q.1: - Observe charge density with respect to position

Q.2: - Write down the value of charge density in depletion region.

Q.3: - Observe electric field with respect to position

Q.4:- Maximum electric field is at _____ position.
Q.5: - Write down the value of maximum electric field.

Q.6:- View the electrostatic potential with respect to position

Q.7:- Write down the value of built in potential.

Task No.2: - Again consider an equally doped unbiased PN junction diode (but this time doping should be higher than task No.1)

Q.1: - Observe simulated result of charge density with respect to position

Q.2: - Write down the value of charge density

Q.3: - Compare the charge density of task number 1 and 2. Attach simulation results. Are they equal or not? Why? Support your answer with the help of equations.

Q.4: - Observe electric field with respect to position

Q.5:- Maximum electric field is at _____ position.

Q.6: - Write down the value of maximum electric field.

Q.7: - Compare the maximum electric field of task number 1 and 2. Attach simulation results. Are they equal or not? Why?

Q.8: - View the electrostatic potential with respect to position

Q.9:- Write down the value of built in potential.

Q.10: - Compare the built-in potential of task number 1 and 2. Attach simulation results. Are they equal or not? Why?

Task No.03: - Consider an equally doped unbiased NP junction diode
Q.1: - Observe simulated result of charge density with respect to position

Q.2: - Write down the value of charge density in depletion region.

Q.3: - Observe electric field with respect to position

Q.4: - Write down the value of maximum electric field.

Q.5:- View the electrostatic potential with respect to position

Q.6:- Write down the value of built in potential.

References:-

[1] Solid State Electronic Devices by Streetman, Chapter 5
[2] Semiconductor Device Fundamentals by Robert F.Pierret, Chapter 5

LAB SESSION 10

Design an unequal doped PN junction diode and analyze its charge density, electric field and electrostatic potential under equilibrium condition.

Student Name: .

Roll no.:   **Batch:**   .

Semester: **Year**   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: **Date:**   .

LAB SESSION 10

Objective: -
Design an unequal doped PN junction diode and analyze its charge density, electric field and electrostatic potential under equilibrium condition.

Tool: - _

Theory: -

Penetration of transition region into n- and p- material in an unequal doped PN junction: -
Suppose we have a PN junction where $N_a > N_d$.
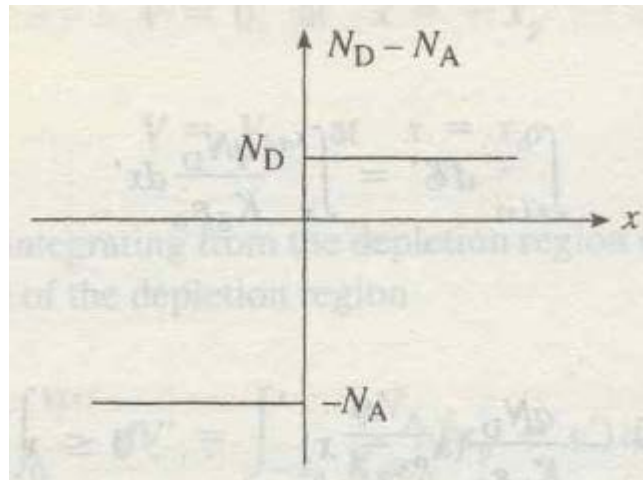
Now from last lab $eq. i)$ we know that dipole about the junction must have an equal number of charges
i.e.
$$N_a x_p = N_d x_n \quad \{eq. i) of\ last\ lab\}$$

Above equation states that if p-region is heavily doped as compared to n then x_n must be greater than x_p. (where x_p is the penetration of space region into the p material and x_n is the penetration into n. The total width of the transition region (W) is the sum of x_p and x_n).This agrees with our qualitative argument that a deep penetration is necessary in lightly doped material to uncover the same amount of space charge as for a short penetration into heavily doped.

The same can be verified from the equation $x)$ and $xi)$ of the last lab

$$x_n = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_a}{N_d(N_a+N_d)}V_{bi}\right]^{1/2} \quad \{eq.\,x)of\,last\,lab\}$$

$$x_p = \frac{N_dx_n}{N_a} = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_d}{N_a(N_a+N_d)}V_{bi}\right]^{1/2} \quad \{eq.\,xi)of\,last\,lab\}$$

As $N_a > N_d$ then x_n can be approximated

$$x_n \approx \left[\frac{2K_s\varepsilon_o}{q}\frac{N_a}{N_d(N_a)}V_{bi}\right]^{1/2} \approx \left[\frac{2K_s\varepsilon_o}{q}\frac{1}{N_d}V_{bi}\right]^{1/2}$$

As N_d is smaller thus x_n would be larger. Now

$$x_p = \frac{N_dx_n}{N_a}$$

As N_a is larger thus x_p would be smaller

Width of transition region [1]: - From $eq.\,xii)$ of last lab we know that overall width of transition region is

$$W = \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{N_a+N_d}{N_aN_d}\right)V_{bi}\right]^{1/2} \quad \{eq.\,xii)of\,last\,lab\}$$

If $N_a \gg N_d$ (p$^+$-n junction) then W can be approximated as

$$W \approx \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{N_a}{N_aN_d}\right)V_{bi}\right]^{1/2} \approx \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{1}{N_d}\right)V_{bi}\right]^{1/2} \approx x_n$$

Thus we can say that in a p$^+$-n junction the depletion region lies almost exclusively on the lightly doped side of the metallurgical boundary.

Thus Built-in- potential (V$_{bi}$):- From $eq.\,iii)$ of last lab we know that built-in potential (V_{bi}) is equals to

$$V_{bi} = \frac{kT}{q}ln\left[\frac{N_aN_d}{n_i^2}\right] \quad \{eq.\,iii)of\,last\,lab\}$$

For a PN junction diode where $N_a > N_d$ $(10^{18} > 10^{15})$ the built-in-potential V_{bi} would be larger as compared to the junction where $N_a = N_d(10^{15} = 10^{15})$

Charge Density:-

From equation **iv**) of last lab overall charge density across the depletion region a diode

$$\rho = \begin{cases} -qN_a, & -x_p \leq x \leq 0 \\ qN_d, & 0 \leq x \leq x_n \\ 0 & x \leq -x_p \, and \, x \geq x_n \end{cases} \qquad iv)$$

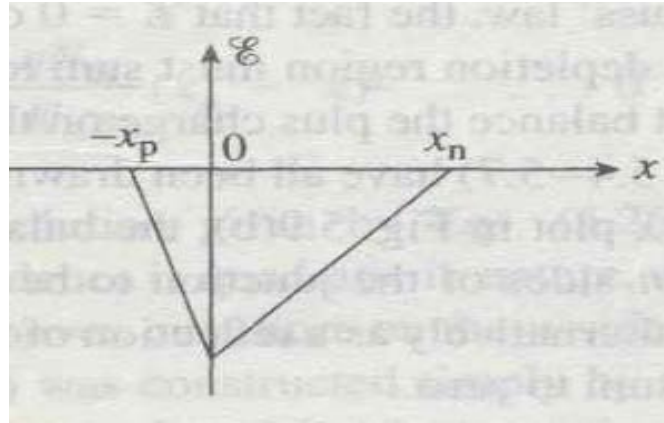For a PN junction diode where $N_a > N_d$, charge density is shown below
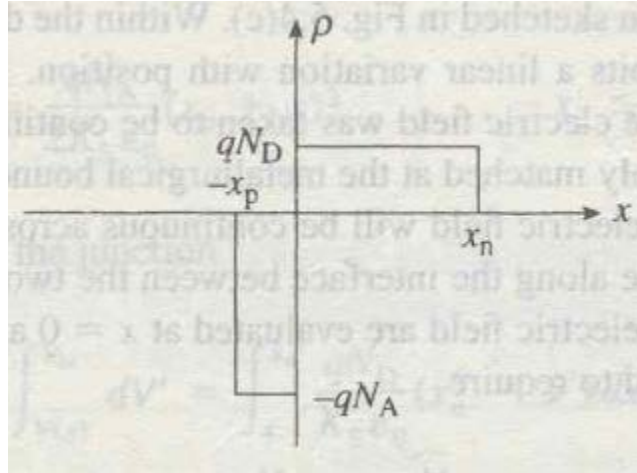
Electric field: -

As we know from **eq. v**) of last lab

$$\varepsilon(x) = -\frac{qN_a}{K_s\varepsilon_o}(x_p + x) \ldots\ldots\ldots\, -x_p \leq x \leq 0 \qquad va)$$

$$\varepsilon(x) = -\frac{qN_d}{K_s\varepsilon_o}(x_n - x) \ldots\ldots\ldots\, 0 \leq x \leq x_n \qquad vb)$$

$$\varepsilon(x) = 0 \ldots\ldots\ldots\ldots\quad x \leq -x_p \, and \, \&x \geq x_n \qquad vc)$$

For a PN junction diode where $N_a > N_d$, electric field intensity is shown below

Electrostatic Potential [2]: -

As we know from *eq. vii*) of last lab

$$V(x) = 0 \ldots\ldots\ldots\ldots -x_p < x \qquad\qquad vii\ a)$$

$$V(x) = \frac{qN_a}{2K_s\varepsilon_o}(x_p + x)^2 \ldots\ldots\ldots -x_p \le x \le 0 \qquad vii\ b)$$

$$V(x) = V_{bi} - \frac{qN_d}{2K_s\varepsilon_o}(x_n - x)^2 \ldots\ldots\ldots 0 \le x \le x_n \qquad vii\ c)$$

$$V(x) = V_{bi} \ldots\ldots\ldots\ldots x > x_n \qquad\qquad vii\ d)$$

For a PN junction diode where $N_a > N_d$, electrostatic potential is shown below
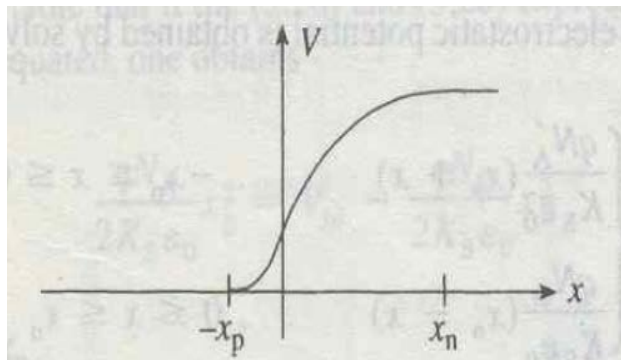
Task No.01: - Consider a n⁺-p junction under equilibrium

Q.1: - Observe charge density with respect to position

Q.2: - What is the value of charge density?

Q.3: - What is the penetration depth of depletion region in p and n regions?

Q.4: - Is the penetration depth of depletion region in p and n regions is same for an equally doped PN junction and a p⁺-n junction diode? Yes/No. Support your idea with the help of equations. Also attach simulation results.

Q.5: - Observe the electric field intensity with respect to position.

Q.6: - Write down the value of maximum electric field.

Q.7: - Observe electrostatic potential with respect to position.

Q.8: - Specify the value of built-in-potential.

Q.9: - Is the built-in-potential same for an equally doped PN junction and a p^+-n junction diode? Yes/No. Support your idea with the help of equations. Also attach simulation results.

Q.10: - During first 3 years of your undergraduate studies, have you ever used any semiconductor device that have a p^+-n junction? Yes/No. If yes then give example.

Q.11: - Let's assume that you have a semiconductor device that has 4 regions and thus 3 junctions as shown below

p^+		n^+		p		n^-

Potential drop across three junctions is
   1) 0.61V
   2) 0.89V
   3) 0.77V

From these drops how can you identify the four regions?

Task No.02: - Consider a p^+-n junction under equilibrium
Q.1: - Observe charge density with respect to position

Q.2: - What is the value of charge density?

Q.3: - What is the penetration depth of depletion region in p and n regions?

Q.4: - In PNP transistor emitter base junction is intentionally made p^+-n rather than p-n. What's the purpose behind this unequal doping?

Q.5: - Observe the electric field intensity with respect to position.

Q.6: - Write down the value of maximum electric field.

Q.7: - Observe electrostatic potential with respect to position

Q.8: - Specify the value of built-in-potential.

References:-
[1] Solid State Electronic Devices by Streetman, Chapter 5
[2] Semiconductor Device Fundamentals by Robert F.Pierret, Chapter 5

LAB SESSION 11

Experimentally analyze the energy band diagram of equal and unequal doped PN junction diode under equilibrium

Student Name: _____ .
Roll no.: _____ **Batch:** _____ .
Semester: _____ **Year** _____ .

Total Marks	Marks Obtained

Remarks (if any) _____ .

Instructor Name _____ .

Instructor Signature: _____ **Date:** _____ .

LAB SESSION 11

Objective: - **Experimentally analyze the energy band diagram of equal and unequal doped PN junction diode under equilibrium**

Tool: - _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

Theory: - Let us consider separate regions of p- and n-type semiconductor material, brought together to form a junction (it's just a thought experiment). Before they are joined, the n material has a large concentration of electrons and a few holes, whereas the converse is true for p material. Upon joining the two regions, we expect diffusion of carriers to take place because of the large concentration gradients at the junction. The resulting diffusion current cannot build up indefinitely, however, because an electric field is created at the junction. The resulting energy band diagram is shown as below:
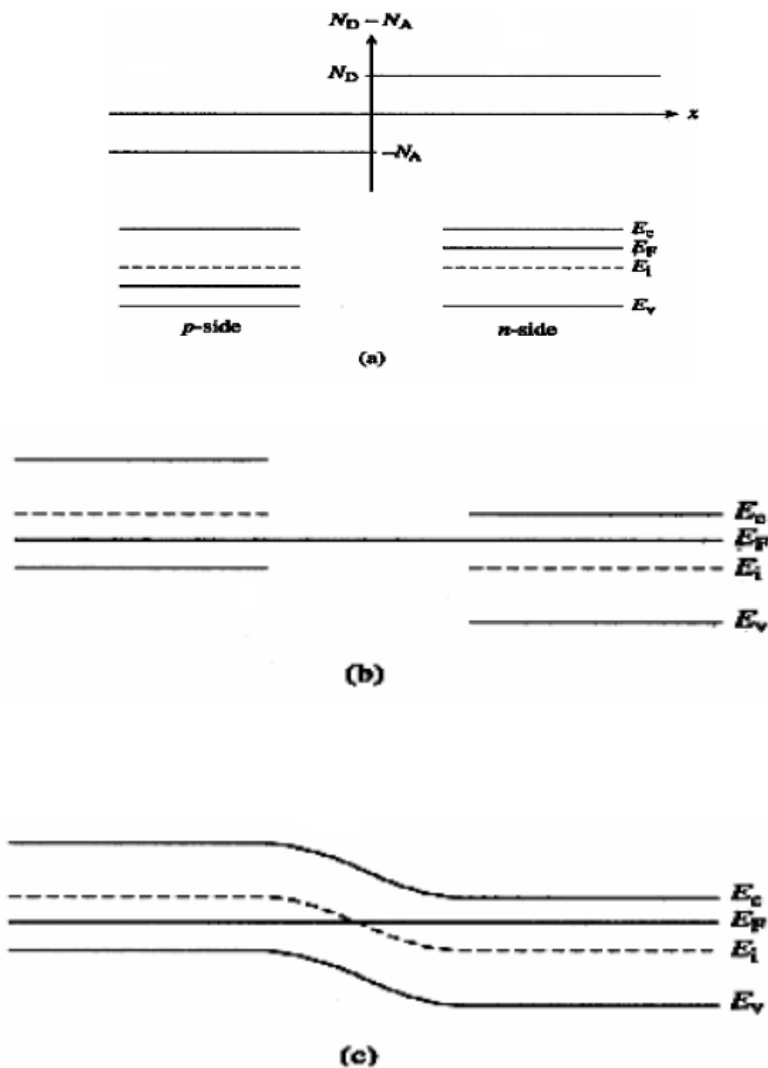
Task No.01: - Consider an equally doped PN junction diode under equilibrium.
Q.1: - Observe the energy band diagram.

Q.2: -Observe doping, electron and hole density.

Q.3: - Write down the values of p_p, p_n, n_p, n_n

Q.4: - Observe the charge density.

Q.5:- Observe the electrostatic potential.

Q.6: - Write down the value of electrostatic potential.

Q.7:- Observe the electric field

Task No.02:- Observe 3 PN junction diodes. First assume $N_d > N_a$, then assume $N_d = N_a$ and lastly $N_d < N_a$.

Q.1: - Compare the energy band diagrams of the above mentioned junctions.

Q.2: - What is the effect of doing on depletion region width?

Q.3: - Compare doping, electron density and hole density of the 3 PN junction diodes.

Q.4: - Write down the values of p_p, p_n, n_p, n_n for each diode.

Q.5: - Compare the electric field of these 3 diodes under equilibrium.

LAB SESSION 12

Understand and analyze the effect of forward biasing on Energy band diagram, Depletion region, Electric field, Electrostatic Potential. Also observe the phenomenon of Carrier Injection and Current Density under the influence of forward biasing.

Student Name: .
Roll no.:   Batch: .
Semester: Year   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: Date: .

LAB SESSION 12

Objective: - **Understand and analyze the effect of forward biasing on Energy band diagram, Depletion region, Electric field, Electrostatic Potential. Also observe the phenomenon of Carrier Injection and Current Density under the influence of forward biasing.**

Tool: - _ _ _ _ _ _ _ _ _ _ _ _ _ _

Theory: - Let us consider separate regions of p- and n-type semiconductor material, brought together to form a junction (it's just a thought experiment). Before they are joined, the n material has a large concentration of electrons and a few holes, whereas the converse is true for p material. Upon joining the two regions, we expect diffusion of carriers to take place because of the large concentration gradients at the junction. The resulting diffusion current cannot build up indefinitely, however, because an electric field is created at the junction. The resulting energy band diagram is shown as below:

Effect of biasing on PN junction diode: - We assume that an applied voltage bias appears across the transition region of the junction rather than in the neutral n and p regions because the length of each region is small compared with its area, and the doping is usually moderate to heavy;

thus the resistance is small in each neutral region, and only a small voltage drop can be maintained outside the space charge (transition) region. We shall take V_A to be positive when the external bias is positive on the p side relative to the n side and negative when the external bias is positive on the n side relative to the p side.

When $V_A > 0$, this externally imposed voltage drop lowers the potential on the n-side of the junction relative to the p-side of the junction. Conversely, when $V_A < 0$, the potential on the n-side increases relative to the p-side. In other words, the voltage drop across the depletion region, and hence the boundary condition at $x = x_n$, becomes $V_{bi} - V_A$.

Since the only modification is a change in one boundary condition, the $V_A \neq 0$ electrostatic relationship can be extrapolated from the $V_A = 0$ relationships by simply replacing all explicit appearance of V_{bi} by $V_{bi} - V_A$. Thus equation $v), vii), x), xi)$ and $xii)$ of lab no. 09 will become[1]

For $-x_p \leq x \leq 0$

$$\varepsilon(x) = -\frac{qN_a}{K_s\varepsilon_o}(x_p + x) \qquad\qquad i)$$

$$V(x) = \frac{qN_a}{2K_s\varepsilon_o}(x_p + x)^2 \qquad\qquad ii)$$

$$x_p = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_d}{N_a(N_a + N_d)}(V_{bi} - V_A)\right]^{1/2} \qquad iii)$$

For $0 \leq x \leq x_n$

$$\varepsilon(x) = -\frac{qN_d}{K_s\varepsilon_o}(x_n - x) \qquad\qquad iv)$$

$$V(x) = V_{bi} - V_A - \frac{qN_d}{2K_s\varepsilon_o}(x_n - x)^2 \qquad\qquad v)$$

$$x_n = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_a}{N_d(N_a + N_d)}(V_{bi} - V_A)\right]^{1/2} \qquad vi)$$

And

$$W = x_n + x_p = \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)(V_{bi} - V_A)\right]^{1/2} \qquad vii)$$

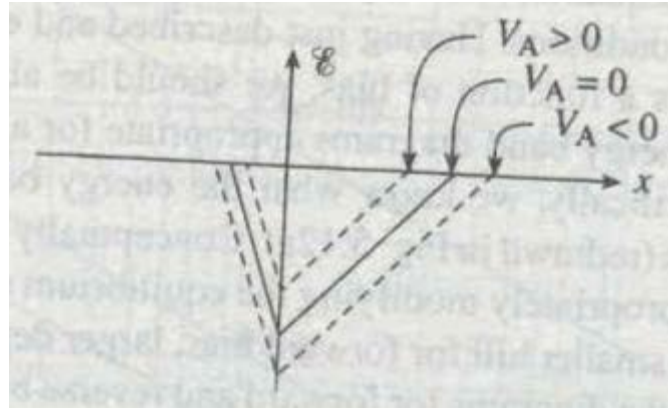For $x \geq x_n$

$$V(x) = V_{bi} - V_A \qquad\qquad viii)$$

Examining the **equations** *iii*) *and vi*) relationships for x_p and x_n, we conclude these widths decrease under forward biasing ($V_A > 0$) and increases under reverse biasing ($V_A < 0$).

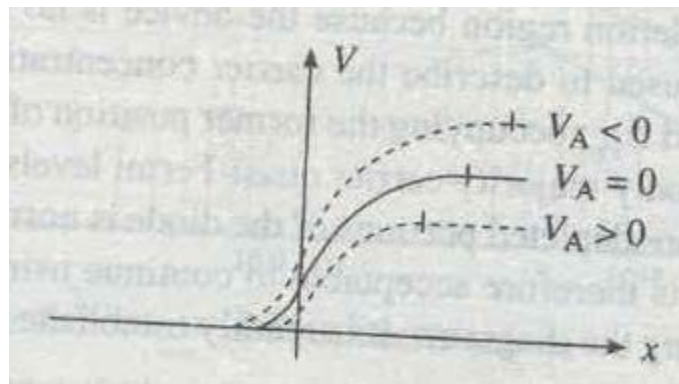A decreased depletion width when $V_A > 0$ means less charge around the junction. $V_A < 0$, on the other hand, creates a larger space charge region and a bigger electric field.
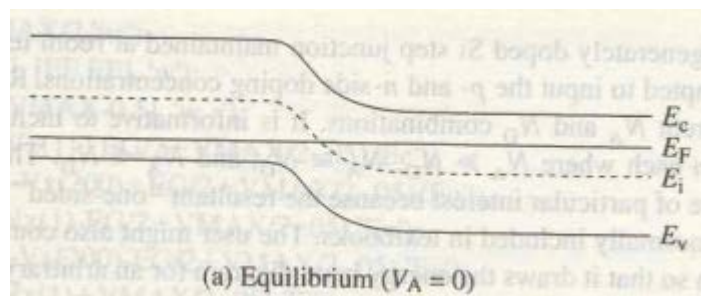

The changes in x_p and x_n likewise translates into the changes in the electric field. As deduced from **equations** *i*) *and iv*) , a smaller x_p *and* x_n under forward bias cause the ε-field to decrease everywhere inside the depletion region, while the larger x_p and x_n associated with reverse bias give rise to larger ε-field.

Similarly, the potential given by **equations** *ii*) *and v*) decreases at all points when $V_A > 0$ and increases at all points when $V_A < 0$. The potential hill shrinks in both size and x- extent under forward biasing, whereas reverse biasing gives rise wider and higher potential hill.
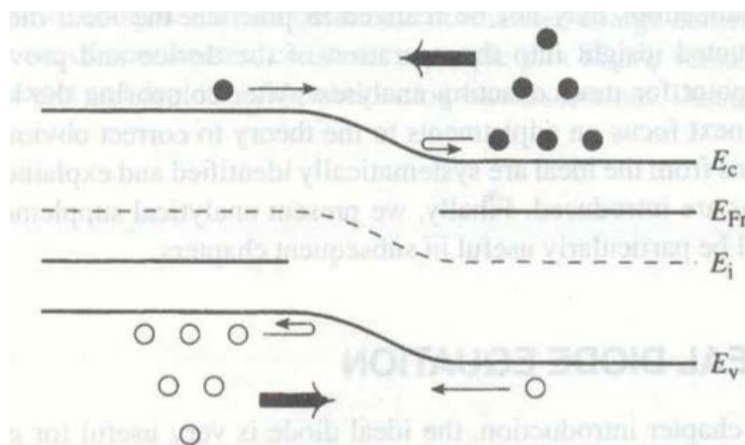

Having just described how the potential changes as a function of bias, we should be able to reverse the cited procedure to construct the energy band diagrams appropriate for a pn junction under forward bias and reverse bias. Conceptually taking the upside-down of the potential plots and appropriately modifying the equilibrium energy band diagram---- smaller depletion width and smaller hill for forward bias, larger depletion width and larger hill for reverse bias---- yield the diagrams for forward and reverse bias pictured in figures below:

(a) Equilibrium ($V_A = 0$)

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(b) Forward bias ($V_A > 0$)

(c) Reverse bias ($V_A < 0$)

Description of current flow at a junction: -

Diffusion Current: - With forward bias (when $V_A > 0$) the barrier is lowered and many electrons in n side conduction band have sufficient energy to diffuse from p to n under forward bias because of the lowered barrier.

For reverse bias (when $V_A < 0$) the barrier becomes so large that virtually no electrons in n side conduction and or holes in the p-side valence band have enough energy to surmount it.

Therefore, the diffusion current is very large for forward bias and usually negligible for reverse bias.

Drift Current: - The drift current is relatively insensitive to the height of potential barrier. The reason for this fact is that the drift current is limited not by how fast carriers are swept down the barrier, but rather how many carriers are swept down the barrier per second. Thus the drift current is independent of applied voltage.

The total current crossing the junction is composed of the sum of the diffusion and drift components.

Carrier Injection under Forward Bias: -

From equation ***iii***) of lab 09, the equilibrium ratio of hole concentrations on each side

$$V_{bi} = \frac{kT}{q} ln \left[\frac{N_a N_d}{n_i^2} \right] \qquad \{equation\ iii)of\ lab\ 10\}$$

$$V_{bi} = \frac{kT}{q} ln \left[\frac{N_a}{n_i^2 / N_d} \right]$$

Assigning p_p, p_n, n_p, n_n as equilibrium hole concentration in p region, equilibrium hole concentration in n region, equilibrium electron concentration in p region and equilibrium electron concentration in n region respectively.

$$V_{bi} = \frac{kT}{q} ln \left[\frac{p_p}{p_n} \right]$$

$$\frac{p_p}{p_n} = e^{q(V_{bi})/kT} \qquad ix)$$

From the discussion of current flow at the junction, we expect the minority carrier concentration on each side of a p-n junction to vary with the applied bias because of variation in the diffusion of carriers across the junction. Thus above equation (under biasing) becomes

$$\frac{p_p(-x_p)}{p_n(x_n)} = e^{q(V_{bi}-V_A)/kT} \qquad\qquad x)$$

For low level injection we can neglect changes in the majority carrier concentration. The relative change in majority carrier concentration can be assumed to vary only slightly with bias compared with equilibrium values. Thus we can write $p_p(-x_p) = p_p$ in equation x). Dividing equation x) by equation ix), we get

$$\frac{p(x_n)}{p_n} = e^{qV_A/kT} \qquad\qquad xi)$$

With forward bias above equation suggests a great increase in minority carrier hole concentration at the edge of transition region on the n-side $p(x_n)$ than the case at equilibrium. Conversely, the hole concentration $p(x_n)$ under reverse bias is reduced below the equilibrium value p_n. The excess hole concentration Δp_n at the edge of transition region x_n can be obtained by subtracting the equilibrium hole concentration from equation xi).
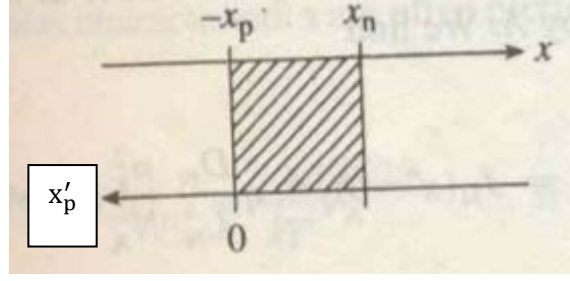
$$\Delta p_n = p(x_n) - p_n = p_n(e^{qV_A/kT} - 1) \qquad\qquad xii)$$

Similarly for excess electrons on p-side,

$$\Delta n_p = n(x_p) - n_p = n_p(e^{qV_A/kT} - 1) \qquad\qquad xiii)$$

We can write the diffusion equation as in **equation xxi**) of lab **05** for each side of the junction and solve for the distributions of excess carriers ($\delta p \ and \ \delta p$)assuming long p and n regions: (It is convenient to shift the origin of coordinates to the n-edge of the depletion region as shown in figure below)

$$\delta p(x_n') = \Delta p_n e^{-x_n'/L_p} = p_n(e^{qV_A/kT} - 1)e^{-x_n'/L_p} \qquad xiv)$$

$$\delta n(x_p') = \Delta n_p e^{-x_p'/L_n} = n_p(e^{qV_A/kT} - 1)e^{-x_p'/L_n} \qquad xv)$$

The hole diffusion current at any point x_n', in the n material can be calculated as

$$I_p(x_n') = -qAD_p \frac{d(\delta p(x_n'))}{dx_n} = qA \frac{D_p}{L_p} \Delta p_n e^{-x_n'/L_p} = qA \frac{D_p}{L_p} \delta p(x_n') \qquad xvi)$$

The total hole current injected into the n material at any junction can be obtained simply by evaluating equation $xiv)$ at $x = x_n$

$$I_p(x = x_n) = I_p(x_n' = 0) = qA \frac{D_p}{L_p} \Delta p_n = qA \frac{D_p}{L_p} p_n(e^{qV_A/kT} - 1) \qquad xvii)$$

By a similar analysis, the injection of electrons into the p material leads to an electron current at the junction of

$$I_n(x = -x_p) = I_n(x_p' = 0) = -qA \frac{D_n}{L_n} \Delta n_p = -qA \frac{D_n}{L_n} n_p(e^{qV_A/kT} - 1) \qquad xviii)$$

The minus sign means that the electron current is opposite to to the x_p'-direction; that is the true direction of I_n is in the $+x$-direction. If we neglect recombination in the transition region, we can consider that each injected electron reaching x_p must pass through x_n. If we take $+x$-direction as the reference direction for current flow, then the total current

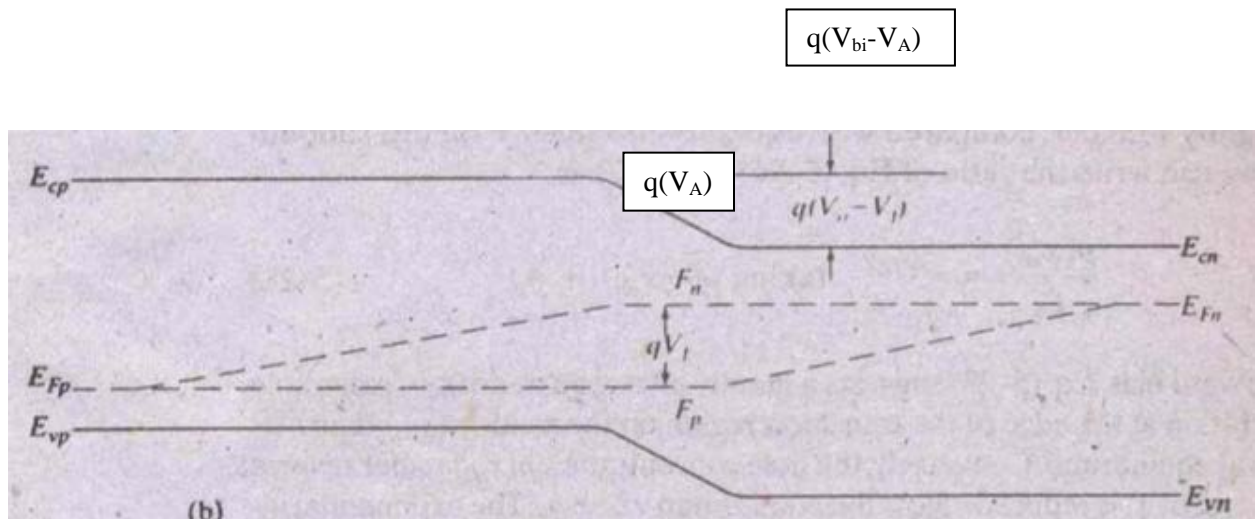$$I = I_p(x_n' = 0) - I_n(x_p' = 0) = I_p(x = x_n) - I_n(x = -x_p)$$

$$I = qA \frac{D_p}{L_p} \Delta p_n + qA \frac{D_n}{L_n} \Delta n_p = qA \left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right)\left(e^{qV_A/kT} - 1\right) = I_o\left(e^{qV_A/kT} - 1\right) \qquad xix)$$

Above equation shows that the total current at the junction is dominated by the injection of the carriers from the more heavily doped side into the side with lesser doping. For example, if the p material is very heavily doped and the n-region is lightly doped, the minority carrier concentration on the p side (n_p) is negligible compared with the minority carrier concentration on the n side (p_n).
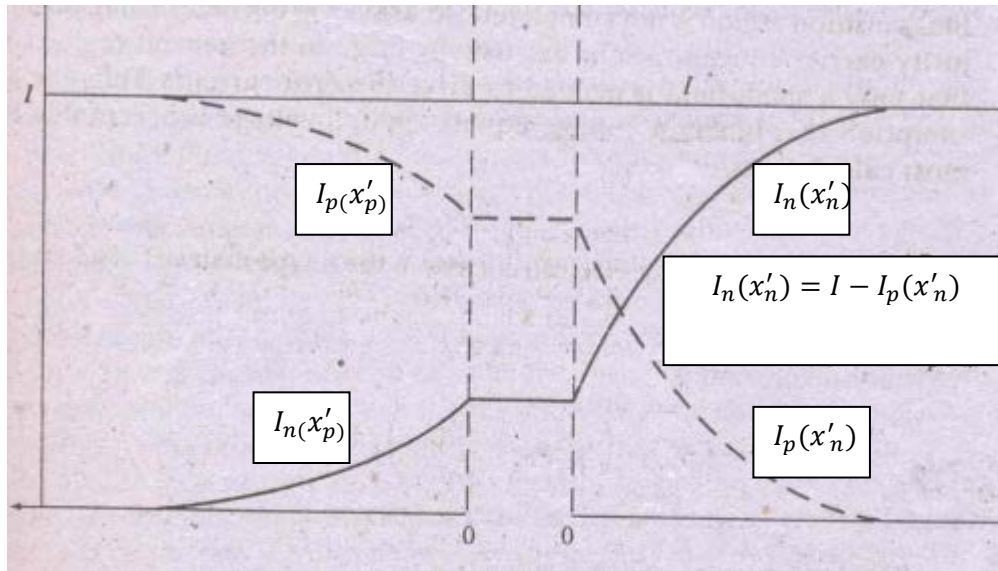
Thus the diode equation can be approximated by the injection of holes only, as shown in equation **xiv**).

To double the hole current in $p^+ - n$ junction one should not double the p^+ doping but rather reduce n-type doping by a factor of two.

Quasi Fermi Level under Forward Bias [2]: - For an ideal diode, the electron (and hole) current is constant across the depletion region, we see that within the depletion region the product of the gradient of the quasi Fermi level and the carrier concentration just be independent of position. For majority carriers, very little gradient is needed in quasi Fermi level. Outside the depletion regions, the qausi Fermi levels for the minority carriers vary linearly and eventually merge with the Fermi levels. In contrast, the minority carrier concentrations decay exponentially with distance.

$q(V_{bi}-V_A)$

(b)

Majority Carrier Current: - Since total current is constant throughout the device, thus majority carrier current can be found by subtracting minority carrier current from total current.

Near the junction (just outside of the depletion regions) the majority carrier concentration changes by the same amount as the minority carrier in order to maintain space charge neutrality. Very far from the junction, the minority carrier concentration decays to a low, constant background value. Hence, the majority carrier concentration also becomes independent of position. Here, clearly the only possible current component is majority carrier drift current. When approaching the junction there is spatially varying majority (and minority) carrier concentration and the majority carrier current changes from pure drift to drift and diffusion.

Task No.01: -Observe a PN junction diode under forward bias

Q.1: - Compare the charge density of forward biased diode with an unbiased diode

Q.2: - Is there any change in charge density and width of the depletion region by forward biasing the diode. Yes/No? Justify

Q.3:- Compare the electric field of a forward biased diode with an unbiased diode

Q.4:- Compare the electrostatic potential of a forward biased diode with an unbiased diode.

Task No.02: - Now forward bias the PN junction by applying a potential equals to $V_{bi} - 0.2V$ (Take the value of V_{bi} from task 1 of last lab)
 Q.1:- Observe the energy band diagram under applied bias

Q.2: -What information do you get about carrier concentration by looking quasi Fermi level in the energy band diagram?

Q.3:- Observe charge density at applied bias

Q.4:- Observe electrostatic potential at applied bias

Q.5: - Observe electric field at applied bias

Task No.03: - Repeat task No.**02** but this time increase the length of P and N regions.
Q.1:- Observe the energy band diagram under equilibrium.

Q.2: - What difference do you observe by increasing the length of P and N regions?

Q.3: Observe doping, electron and hole density at equilibrium

Q.4: - Observe the charge density at equilibrium

Q.5: - Observe the energy band diagram under non-equilibrium

Task No.04:- Observe 3 PN junction diodes. First assume $N_d > N_a$, then assume $N_d = N_a$ and lastly $N_d < N_a$. Forward bias these diodes by applying V_A=0.6V

Q.1: - Observe the total current that flows through the diode when $N_d < N_a$. Also mention its value.

Q.2: - Observe the total current that flows through the diode when $N_d = N_a$. Also mention its value.

Q.3: - Observe the total current that flows through the diode when $N_d > N_a$. Also mention its value.

Q.4:- Maximum current flows when $N_a=$_____ and $N_d=$_____.

Task No.05: - Suppose you have a biased PN junction diode, with $N_a = 10^{17}/cm^3$ and $N_d = 10^{16}/cm^3$. Now you want to increases the hole current at fixed applied voltage (forward bias). Can we achieve this by increasing the acceptor doping. Yes/no? Justify your point of view by simulation results and mathematical equation(s). Don't forget to specify donor and acceptor doping for increased hole current.

References: -

[1] Semiconductor Device Fundamentals by Robert F.Pierret, Chapter 6
[2] Solid State Electronic Devices by Streetman, Chapter 5

LAB SESSION 13

Understand and analyze the effect of reverse biasing on Energy band diagram, Depletion region, Electric field, Electrostatic Potential. Also observe the phenomenon of Carrier Injection and Current Density under the influence of reverse biasing.

Student Name: .
Roll no.:   Batch: .
Semester: Year   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: Date: .

LAB SESSION 13

Objective: - Understand and analyze the effect of reverse biasing on Energy band diagram, Depletion region, Electric field, Electrostatic Potential. Also observe the phenomenon of Carrier Injection and Current Density under the influence of reverse biasing.

Tool: - _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

Theory: - Let us consider separate regions of p- and n-type semiconductor material, brought together to form a junction (it's just a thought experiment). Before they are joined, the n material has a large concentration of electrons and a few holes, whereas the converse is true for p material. Upon joining the two regions, we expect diffusion of carriers to take place because of the large concentration gradients at the junction. The resulting diffusion current cannot build up indefinitely, however, because an electric field is created at the junction. The resulting energy band diagram is shown as below:

Effect of biasing on PN junction diode: - We assume that an applied voltage bias appears across the transition region of the junction rather than in the neutral n and p regions because the

length of each region is small compared with its area, and the doping is usually moderate to heavy; thus the resistance is small in each neutral region, and only a small voltage drop can be maintained outside the space charge (transition) region. We shall take V_A to be positive when the external bias is positive on the p side relative to the n side and negative when the external bias is positive on the n side relative to the p side.

When $V_A > 0$, this externally imposed voltage drop lowers the potential on the n-side of the junction relative to the p-side of the junction. Conversely, when $V_A < 0$, the potential on the n-side increases relative to the p-side. In other words, the voltage drop across the depletion region, and hence the boundary condition at $x = x_n$, becomes $V_{bi} - V_A$.

Since the only modification is a change in one boundary condition, the $V_A \neq 0$ electrostatic relationship can be extrapolated from the $V_A = 0$ relationships by simply replacing all explicit appearance of V_{bi} by $V_{bi} - V_A$. Thus equation v), vii), x), xi) **and** xii) of lab no. **09** will become[1]

For $-x_p \leq x \leq 0$

$$\varepsilon(x) = -\frac{qN_a}{K_s\varepsilon_o}(x_p + x) \qquad\qquad i)$$

$$V(x) = \frac{qN_a}{2K_s\varepsilon_o}(x_p + x)^2 \qquad\qquad ii)$$

$$x_p = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_d}{N_a(N_a + N_d)}(V_{bi} - V_A)\right]^{1/2} \qquad iii)$$

For $0 \leq x \leq x_n$

$$\varepsilon(x) = -\frac{qN_d}{K_s\varepsilon_o}(x_n - x) \qquad\qquad iv)$$

$$V(x) = V_{bi} - V_A - \frac{qN_d}{2K_s\varepsilon_o}(x_n - x)^2 \qquad\qquad v)$$

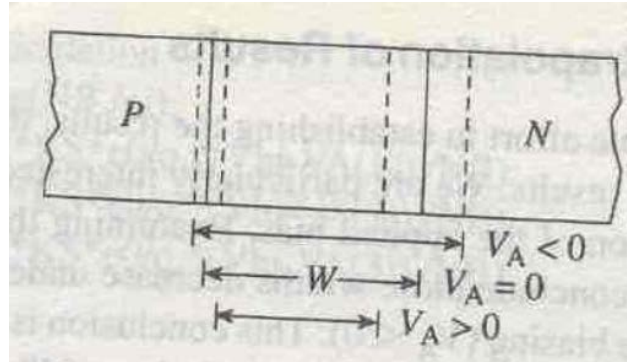$$x_n = \left[\frac{2K_s\varepsilon_o}{q}\frac{N_a}{N_d(N_a + N_d)}(V_{bi} - V_A)\right]^{1/2} \qquad vi)$$

And

$$W = x_n + x_p = \left[\frac{2K_s\varepsilon_o}{q}\left(\frac{N_a + N_d}{N_aN_d}\right)(V_{bi} - V_A)\right]^{1/2} \qquad vii)$$
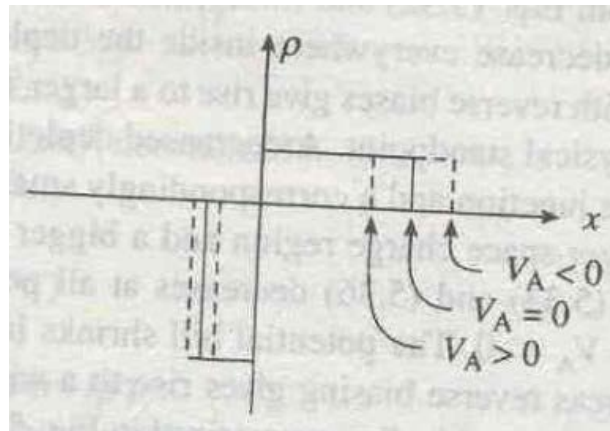
For $x \geq x_n$
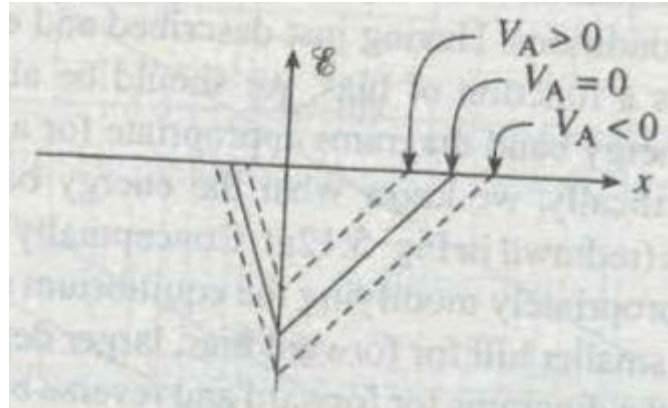
$$V(x) = V_{bi} - V_A \qquad\qquad viii)$$

Examining the **equations iii) _and_ vi)** relationships for x_p and x_n, we conclude these widths decrease under forward biasing ($V_A > 0$) and increases under reverse biasing ($V_A < 0$).
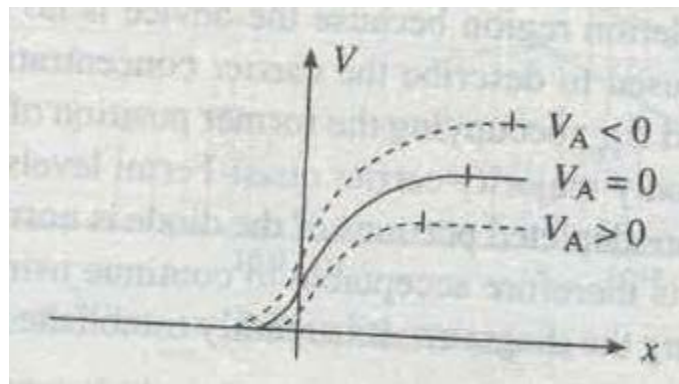

A decreased depletion width when $V_A > 0$ means less charge around the junction. $V_A < 0$, on the other hand, creates a larger space charge region and a bigger electric field.
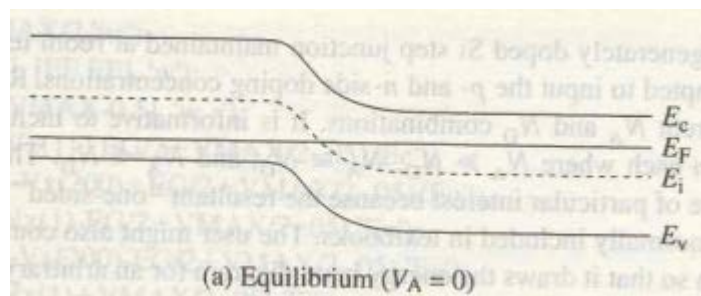

The changes in x_p and x_n likewise translates into the changes in the electric field. As deduced from **equations i) _and_ iv)** , a smaller x_p _and_ x_n under forward bias cause the ε-field to decrease everywhere inside the depletion region, while the larger x_p and x_n associated with reverse bias give rise to larger ε-field.
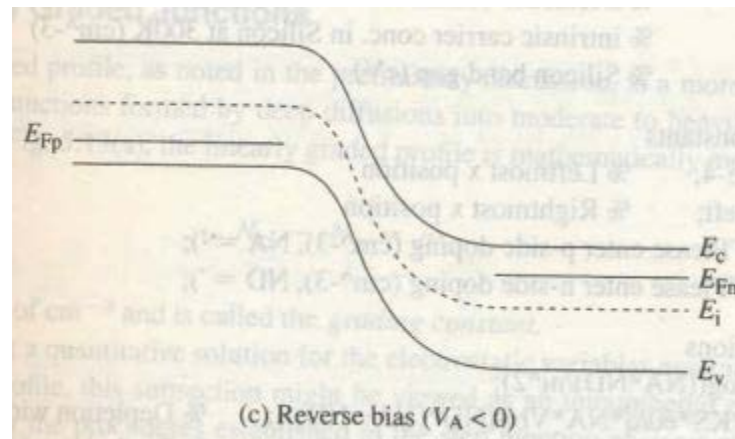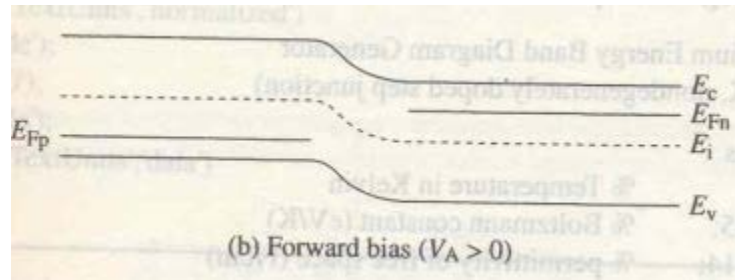
Similarly, the potential given by **equations ii**) **and v**) decreases at all points when $V_A > 0$ and increases at all points when $V_A < 0$. The potential hill shrinks in both size and x- extent under forward biasing, whereas reverse biasing gives rise wider and higher potential hill.
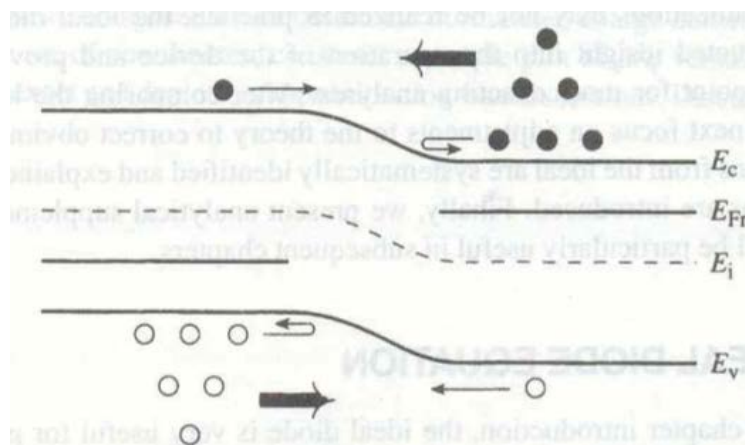

Having just described how the potential changes as a function of bias, we should be able to reverse the cited procedure to construct the energy band diagrams appropriate for a pn junction under forward bias and reverse bias. Conceptually taking the upside-down of the potential plots and appropriately modifying the equilibrium energy band diagram---- smaller depletion width and smaller hill for forward bias, larger depletion width and larger hill for reverse bias---- yield the diagrams for forward and reverse bias pictured in figures below:
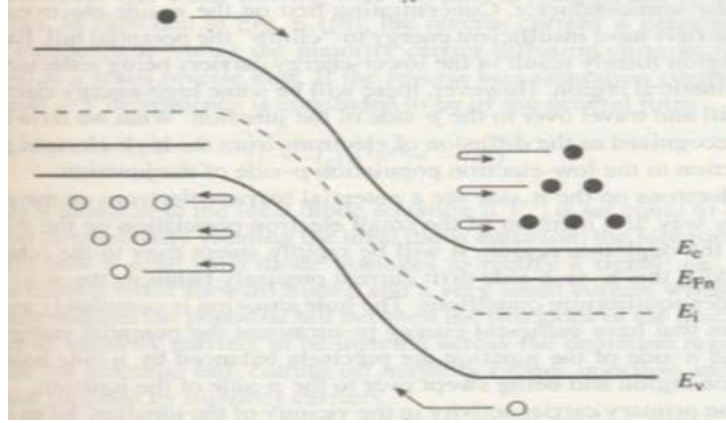

(a) Equilibrium ($V_A = 0$)

(b) Forward bias ($V_A > 0$)

(c) Reverse bias ($V_A < 0$)

Description of current flow at a junction: -

Diffusion Current: - With forward bias (when $V_A > 0$) the barrier is lowered and many electrons in n side conduction band have sufficient energy to diffuse from p to n under forward bias because of the lowered barrier.

For reverse bias (when $V_A < 0$) the barrier becomes so large that virtually no electrons in n side conduction and or holes in the p-side valence band have enough energy to surmount it.

Therefore, the diffusion current is very large for forward bias and usually negligible for reverse bias.

Drift Current: - The drift current is relatively insensitive to the height of potential barrier. The reason for this fact is that the drift current is limited not by how fast carriers are swept down the barrier, but rather how many carriers are swept down the barrier per second. Thus the drift current is independent of applied voltage.

The total current crossing the junction is composed of the sum of the diffusion and drift components.

Carrier Injection under Forward Bias: -

From equation *iii*) of lab 09, the equilibrium ratio of hole concentrations on each side

$$V_{bi} = \frac{kT}{q} \ln \left[\frac{N_a N_d}{n_i^2} \right] \qquad \{equation\ iii)of\ lab\ \mathbf{10}\}$$

$$V_{bi} = \frac{kT}{q} \ln \left[\frac{N_a}{n_i^2 / N_d} \right]$$

Assigning p_p, p_n, n_p, n_n as equilibrium hole concentration in p region, equilibrium hole concentration in n region, equilibrium electron concentration in p region and equilibrium electron concentration in n region respectively.

$$V_{bi} = \frac{kT}{q} \ln \left[\frac{p_p}{p_n} \right]$$

$$\frac{p_p}{p_n} = e^{q(V_{bi})/kT} \qquad ix)$$

From the discussion of current flow at the junction, we expect the minority carrier concentration on each side of a p-n junction to vary with the applied bias because of variation in the diffusion of carriers across the junction. Thus above equation (under biasing) becomes

$$\frac{p_p(-x_p)}{p_n(x_n)} = e^{q(V_{bi}-V_A)/kT} \qquad x)$$

For low level injection we can neglect changes in the majority carrier concentration. The relative change in majority carrier concentration can be assumed to vary only slightly with bias compared with equilibrium values. Thus we can write $p_p(-x_p) = p_p$ in equation$x$). Dividing equation x) by equationix), we get

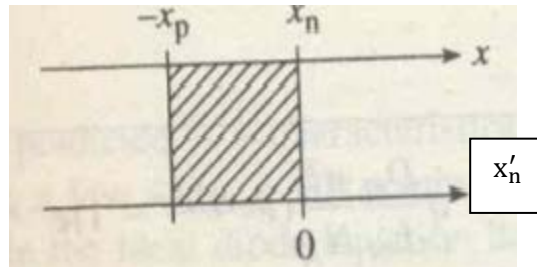$$\frac{p(x_n)}{p_n} = e^{qV_A/kT} \qquad xi)$$

With forward bias above equation suggests a great increase in minority carrier hole concentration at the edge of transition region on the n-side $p(x_n)$ than the case at equilibrium. Conversely, the hole concentration $p(x_n)$ under reverse bias is reduced below the equilibrium value p_n. The excess hole concentration Δp_n at the edge of transition region x_n can be obtained by subtracting the equilibrium hole concentration from equationxi).
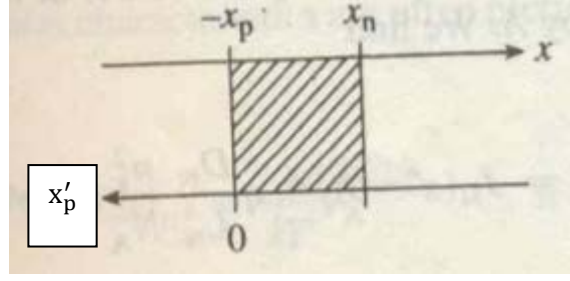
$$\Delta p_n = p(x_n) - p_n = p_n(e^{qV_A/kT} - 1) \qquad xii)$$

Similarly for excess electrons on p-side,

$$\Delta n_p = n(x_p) - n_p = n_p(e^{qV_A/kT} - 1) \qquad xiii)$$

We can write the diffusion equation as in **equation xxi**) of lab **09** for each side of the junction and solve for the distributions of excess carriers (δp *and* δp)assuming long p and n regions: (It is convenient to shift the origin of coordinates to the n-edge of the depletion region as shown in figure below)

$$\delta p(x_n') = \Delta p_n e^{-x_n'/L_p} = p_n(e^{qV_A/kT} - 1)e^{-x_n'/L_p} \qquad \qquad xiv)$$

$$\delta n(x_p') = \Delta n_p e^{-x_p'/L_n} = n_p(e^{qV_A/kT} - 1)e^{-x_p'/L_n} \qquad \qquad xv)$$

The hole diffusion current at any point x_n', in the n material can be calculated as

$$I_p(x_n') = -qAD_p \frac{d(\delta p(x_n'))}{dx_n} = qA\frac{D_p}{L_p}\Delta p_n e^{-x_n'/L_p} = qA\frac{D_p}{L_p}\delta p(x_n') \qquad \qquad xvi)$$

The total hole current injected into the n material at any junction can be obtained simply by evaluating equation $xiv)$ at $x = x_n$

$$I_p(x = x_n) = I_p(x_n' = 0) = qA\frac{D_p}{L_p}\Delta p_n = qA\frac{D_p}{L_p}p_n(e^{qV_A/kT} - 1) \qquad \qquad xvii)$$

By a similar analysis, the injection of electrons into the p material leads to an electron current at the junction of

$$I_n(x = -x_p) = I_n(x_p' = 0) = -qA\frac{D_n}{L_n}\Delta n_p = -qA\frac{D_n}{L_n}n_p(e^{qV_A/kT} - 1) \qquad \qquad xviii)$$

The minus sign means that the electron current is opposite to to the x_p'-direction; that is the true direction of I_n is in the $+x$-direction. If we neglect recombination in the transition region, we can consider that each injected electron reaching x_p must pass through x_n. If we take $+x$-direction as the reference direction for current flow, then the total current

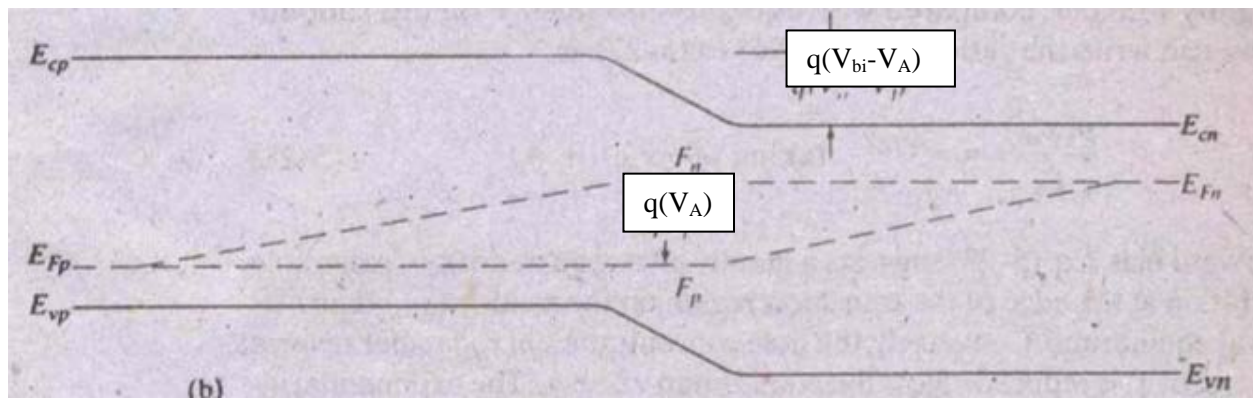$$I = I_p(x_n' = 0) - I_n(x_p' = 0) = I_p(x = x_n) - I_n(x = -x_p)$$

$$I = qA\frac{D_p}{L_p}\Delta p_n + qA\frac{D_n}{L_n}\Delta n_p = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)\left(e^{qV_A/kT} - 1\right) = I_o\left(e^{qV_A/kT} - 1\right) \qquad xix)$$

Above equation shows that the total current at the junction is dominated by the injection of the carriers from the more heavily doped side into the side with lesser doping. For example, if the p material is very heavily doped and the n-region is lightly doped, the minority carrier concentration on the p side (n_p) is negligible compared with the minority carrier concentration on the n side (p_n).
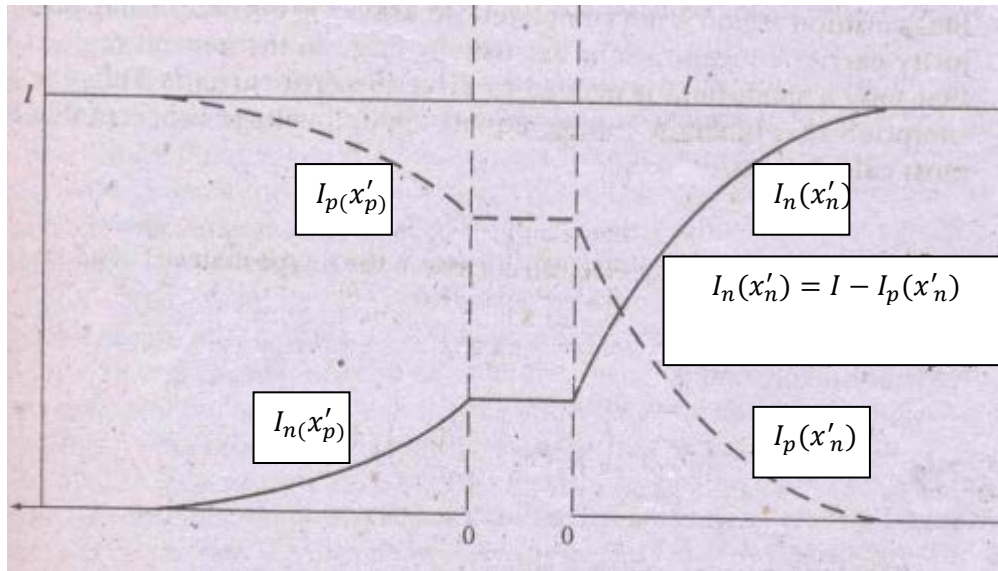
Thus the diode equation can be approximated by the injection of holes only, as shown in equation **xiv**).

To double the hole current in $p^+ - n$ junction one should not double the p^+ doping but rather reduce n-type doping by a factor of two.

Quasi Fermi Level under Forward Bias [2]**: -** For an ideal diode, the electron (and hole) current is constant across the depletion region, we see that within the depletion region the product of the gradient of the quasi Fermi level and the carrier concentration just be independent of position. For majority carriers, very little gradient is needed in quasi Fermi level. Outside the depletion regions, the qausi Fermi levels for the minority carriers vary linearly and eventually merge with the Fermi levels. In contrast, the minority carrier concentrations decay exponentially with distance.

Majority Carrier Current: - Since total current is constant throughout the device, thus majority carrier current can be found by subtracting minority carrier current from total current.

Near the junction (just outside of the depletion regions) the majority carrier concentration changes by the same amount as the minority carrier in order to maintain space charge neutrality. Very far from the junction, the minority carrier concentration decays to a low, constant background value. Hence, the majority carrier concentration also becomes independent of position. Here, clearly the only possible current component is majority carrier drift current. When approaching the junction there is spatially varying majority (and minority) carrier concentration and the majority carrier current changes from pure drift to drift and diffusion.

Distribution of carrier under Reverse Bias: - The distribution of carriers for reverse bias can be obtained from the same equation xii) , if a negative value of V_A is introduced. If applied voltage is $-V_A$ (p negatively biased with respect to n), we can approximate equation xii) as

$$\Delta p_n = p_n \left(e^{q(-V_A)/kT} - 1 \right) \approx - p_n \qquad xx)$$

Thus for a reverse bias of more than a few tenth of a volt, the minority carrier concentration at each edge of the transition region becomes essentially zero as the excess concentration approaches the negative of the equilibrium concentration.

The reverse-bias depletion of minority carriers can be thought of as **_minority carrier extraction_**. Physically, extraction occurs because minority carriers at the edges of the depletion region are swept down the barrier at the junction to the other side and are not replaced by an opposing diffusion of carriers.

Although the reverse saturation current occurs at the junction by drift of carriers down the barrier, this current is fed from each side by diffusion toward the junction of minority carriers in the neutral regions. The rate of carrier drift across the junction depends on the rate at which holes arrive at $x = x_n$ **(and** electrons at $x = x_p$) by diffusion from the neutral material. These minority carriers are supplied by thermal generation.

Quasi Fermi level under Reverse Bias: - In reverse bias, the quasi-Fermi levels split in the opposite sense than in forward bias. The F_n moves farther away from E_c (close to E_v) and F_p moves farther away from E_v, reflecting the fact that in reverse bias we have fewer carriers than in equilibrium, unlike the forward bias case where we have an excess of carriers.
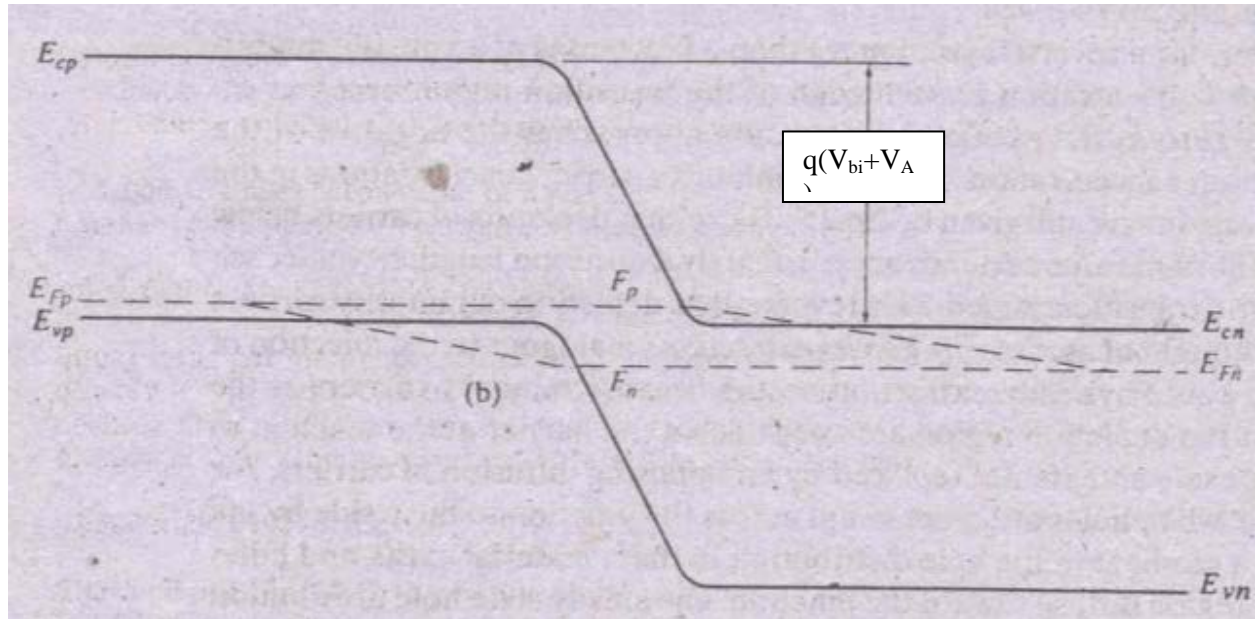
Task No.01: - Observe a PN junction diode under reverse bias

Q.1:- Compare the charge density of reverse biased diode with an unbiased diode.

Q.2: - Is there any change in charge density and width of the depletion region by reverse biasing the diode. Yes/No? Justify

Q.3:- Compare the electric field of a reverse biased diode with an unbiased diode.

Q.4: - What is the effect of reverse biasing on electric field?

Q.5:- Compare the electrostatic potential of a reverse biased diode with an unbiased diode.

Q.6: Observe the reverse current and write down its value.

Task No.02: -Reverse bias a PN junction diode
Q.1: - Observe the energy band diagram at applied bias.

Q.2: - Observe doping, electron and hole density at applied bias.

Q.3: - What is the effect of biasing on minority carrier concentration near depletion region. Will it increase or decrease? Specify the reason.

References: -
[1] Semiconductor Device Fundamentals by Robert F.Pierret, Chapter 6
[2] Solid State Electronic Devices by Streetman, Chapter 5

LAB SESSION 14

Open ended lab (MOS Capacitor)

Student Name: .

Roll no.:   **Batch:**   .

Semester: **Year**   .

Total Marks	Marks Obtained

Remarks (if any)   .

Instructor Name   .

Instructor Signature: **Date:**   .

LAB SESSION 14

Objective: - **Open ended lab (MOS Capacitor).**

Tool: - _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

Task No. 01: - Study the MOS Capacitor in detail.

Task No. 02: - Analyze the energy band diagram of MOS Capacitor under equilibrium condition.

Task No.03: - Analyze the phenomenon of accumulation in MOS capacitor.

Task No.04: - Analyze the phenomenon of depletion in MOS capacitor.

Task No.05: - Analyze the phenomenon of inversion in MOS capacitor.

Task No.06: - Analyze the phenomenon of strong inversion in MOS capacitor.