SEMICONDUCTOR PHYSICS

STUDY MATERIAL

UNIT - 4 : MEASUREMENT TECHNIQUES

BY:

DR. ARVIND SHARMA & DR. SANGEETA

ASSOCIATE PROFESSOR ASSISTANT PROFESSOR

DEPARTMENT OF APPLIED SCIENCES

CHANDIGARH ENGINEERING COLLEGE, LANDRAN

Table of content

UNIT – IV

4.1 Measurement of Wavelength using LASER

4.2 Measurement of Divergence using LASER

4.3 Hall Effect

4.4 Resistivity Measurement Techniques

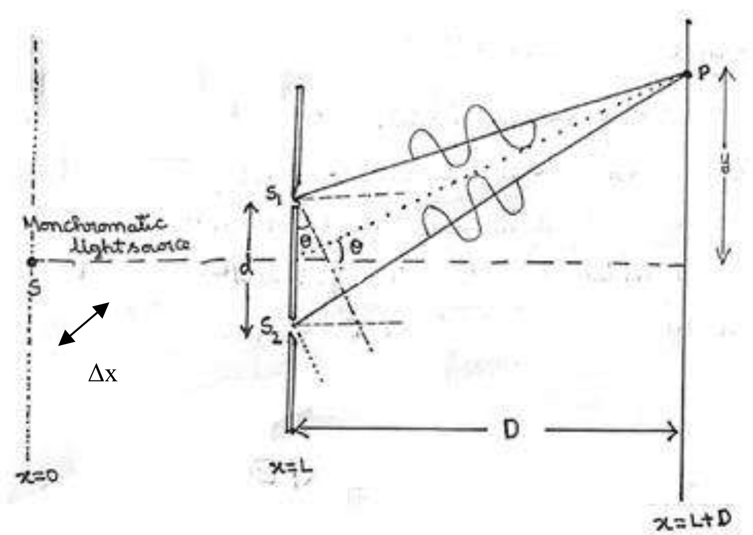
4.5 Parameter Extraction from Diode I-V Characteristics

UNIT IV – Measurement Techniques

4.1 Measurement of Wavelength using LASER:

(a) Method I: Young's Double Slit Experiment:

Consider a monochromatic light source 'S' (LASER) kept at a considerable distance from two slits s_1 and s_2. S is equidistant from s_1 and s_2. s_1 and s_2 behave as two coherent sources, as both bring derived from S. The light passes through these slits and falls on a screen which is at a distance 'D' from the position of slits s_1 and s_2. 'd' be the separation between two slits. Each slit generates a coherent spherical wave-front which superimpose on the screen placed at a separation distance 'D' from the double slit as shown the figure below.



When the slit separation (d) and the screen distance (D) are kept unchanged, to reach *P* the light waves from s_1 and s_2 must travel different distances. It implies that there is a path difference in Young's double slit experiment between the two light waves from s_1 and s_2.

Approximations in Young's double slit experiment

- Approximation 1:

  D > > d: Since D > > d, the two light rays are assumed to be parallel, then the path difference,

- Approximation 2:

$d/\lambda >> 1$: Often, d is a fraction of a millimetre and λ is a fraction of a micrometre for visible light.

Under these conditions θ is small, thus we can use the approximation; $\sin\theta \approx \tan\theta$

$$\text{Here, } \tan\theta = y / D \text{ and } \sin\theta = \Delta x / d \text{ (from the figure)}$$

$$\text{Therefore } y / D = \Delta x / d$$

$$\text{Thus, } \mathbf{y = (\Delta x * D) / d}$$

Here, Δx is the Path difference.This is the path difference between two waves meeting at a point on the screen. Due to this path difference in Young's double slit experiment, some points on the screen are bright and some points are dark. In order that constructive interference occurs at point P on the screen leading to a bright fringe, one requires

$$\Delta x = n\lambda \text{ (n = 0, ±1, ±2, ... and so on)}$$

Here, λ is the wavelength of laser. The bright fringe for n = 0 is known as the central fringe. Higher order fringes are situated symmetrically about the central fringe. The position of n^{th} bright fringe is given by,

$$y \text{ (bright)} = n\lambda D / d \text{ (n = 0, ±1, ±2, ... and so on)}$$

We now define a parameter called fringe width i.e.

Distance between two adjacent bright (or dark) fringes

$$\beta = y_n - y_{n-1}$$

$$\beta = n\lambda D / d - (n-1)\lambda D / d$$

$$\beta = \lambda D / d$$

$$\lambda = \beta d / D$$

Therefore by measuring the value of β and D for given value of small d, one can estimate the wavelength of the light source (i.e. laser light)

(b) Diffraction Grating Element:

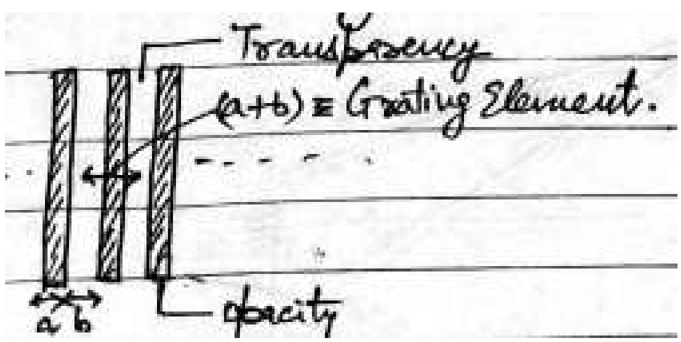
Diffraction grating is a thin film of clear glass or plastic that has a large number of lines per (mm) drawn on it. When light from a bright and small source passes through a diffraction grating, it generates a large number of sources at the grating. The very thin space between every two adjacent lines of the grating becomes an independent source. These sources are coherent sources meaning that they emit in phase waves with the same wavelength. These sources act independently such that each source sends out waves in all directions. On a screen a distance D away, points can be found whose distance differences from these sources are different multiples of λ causing bright fringes. One difference between the interference of many slits (diffraction grating) and double-slit (Young's Experiment) is that a diffraction grating makes a number of principle maxima along with lower intensity maxima in between. The principal maxima occur on both sides of the central maximum for which a formula similar to Young's formula.

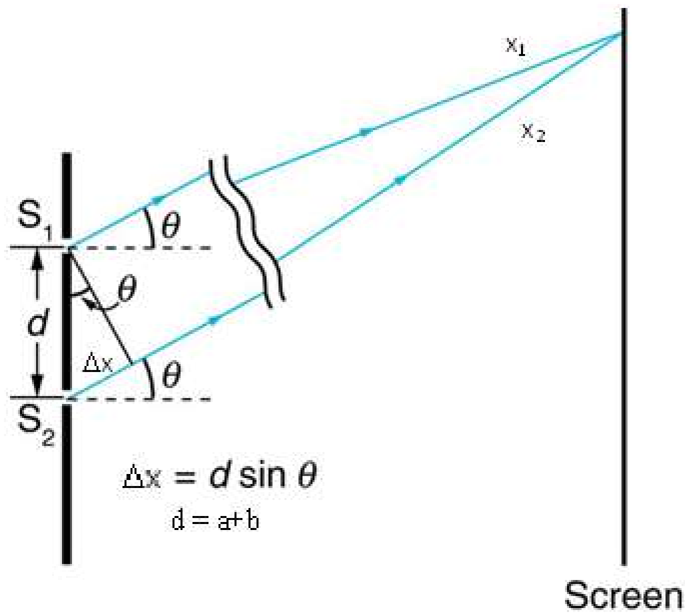
Diffraction grating:

A diffraction grating is an arrangement consisting of a large number of parallel slits of same width and separated by equal opaque spacing. It is obtained by ruling equidistant parallel lines on a glass plate with the help of a fine diamond point.

Grating element:

Let N be the number of parallel slits, each of width 'b' (transparency) and separated by opaque space 'a'. Then, the distance between the centers of the adjacent slits is d = a+b is known as grating element.





The difference between the paths is shown in the figure; simple trigonometry shows it to be dsinθ , where d is the grating element. For constructive interference, the path length difference must be an integral multiple of the wavelength,

$$\text{or } \Delta x = n\lambda$$

$$\text{or } d \sin\theta = n\lambda$$

$$\lambda = \frac{dsin\theta}{n}$$

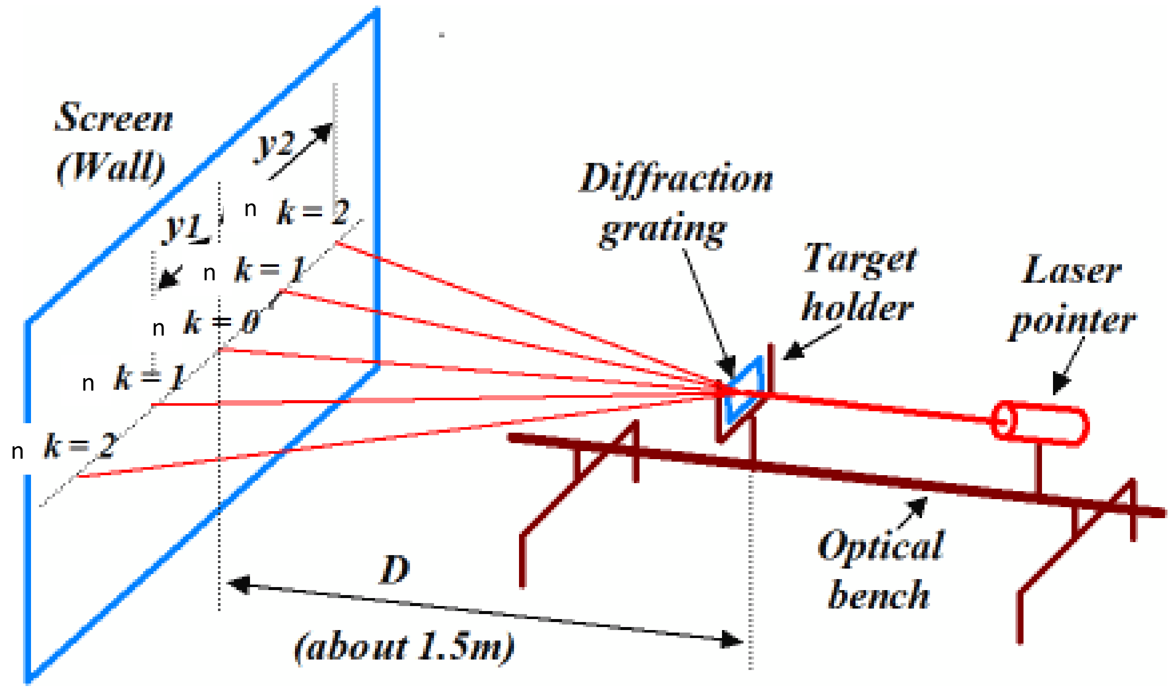
Determination of wavelength of the spectral line using diffraction grating:

The diffraction grating is often used in the Lab for the determination of wavelength of light. The diffraction pattern of the given source of laser light is obtained by using a diffraction grating element on the screen.

Symmetrical diffraction pattern consisting of different orders can be seen. The angle of diffraction θ for a particular order 'n' of the spectrum is measured.

Steps

- Fix a laser pointer and the diffraction grating (placed in a target holder) on an optical bench as shown. Try to make a distance *D* (grating to wall) of about *1.5m.*



- Make sure that the direction of the optical bench is normal (at right angle) to the wall and that you are measuring the perpendicular distance D from the grating to the wall.
- Measure y_1 , y_2 , and D with the precision of mm and record the values.
- Angles θ_1 and θ_2 may now be calculated from the measured values as follows:

$$\tan\theta_1 = \frac{y_1}{D} \quad \text{and} \quad \tan\theta_2 = \frac{y_2}{D}$$

- Use the *tan*$^{-1}$ function to calculate θ_1 *and* θ_2 .
- Use angles θ_1 *and* θ_2 along with the given value of grating element because

  The number of lines per inch of grating is written over it by the manufacturer. Hence the grating element is

$$d = \frac{1}{N} = \frac{1}{No.\ of\ lines/cm} = \frac{2.54}{No.\ of\ lines\ /inches}$$

  Thus, using equation $d \sin\theta = n\lambda$, *wavelength* of the laser is to be calculated.

4.2 Measurement of Divergence using LASER:

Divergence is defined as the angular measure of how the beam diameter increases with the distance from the laser aperture. It is measured in milli-radians (mrad) or degrees (°). Simply put, it tells you how the beam grows from the source to the target or describes the widening of the beam over the distance.

First understand the concept of directionality i.e. one of the characteristics of laser beam.

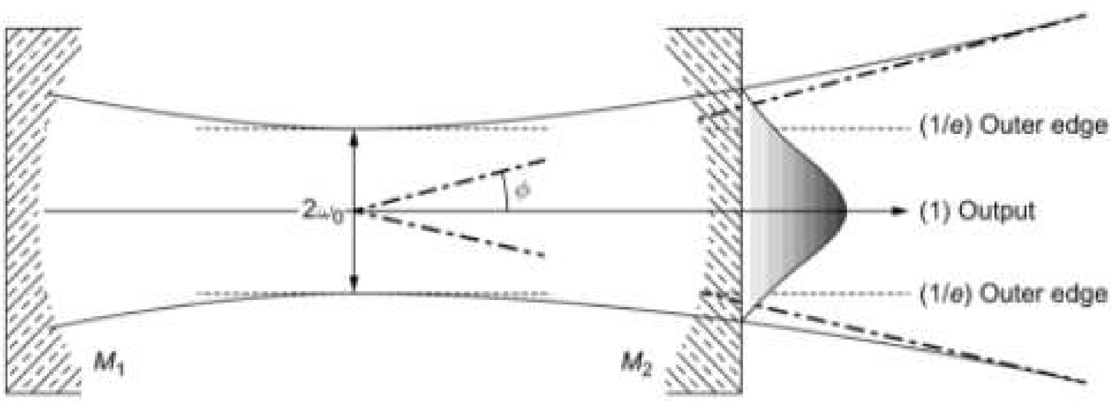
Directionality:

Laser light are highly directional unlike ordinary light that spreads in all directions. The output beam is circularly symmetric; in that case it is more intense at the centre and falls off as

$$\exp\left[-\left(\frac{r}{\omega}\right)^2\right]$$

Where r the radial distance from the centre.

At r = 0 ,the intensity is maximum and decreases as the radius increases. The is called gaussian beam . The outer edge of the beam is the radial distance from the axis at which the intensity of the beam has dropped to 1 / e of its value at the axis as shown in the figure below:

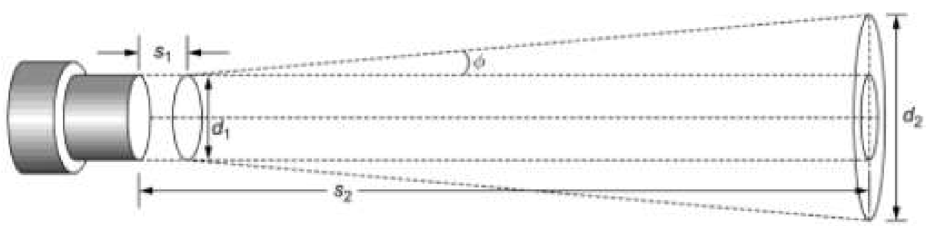


Laser radiation can travel as light parallel beam up to a distance of d^2 / λ (d is the diameter of the aperture through which the laser radiation of wavelength λ comes out) and spread angularly after travelling that distance. The full- angle beam divergence (i.e. , twice the angle of the outer edge makes with the axis of the beam) expresses the directionality of the laser radiation as

$$\phi = \frac{1.27\lambda}{2\omega o}$$

The angular spread of the laser beam ($\phi = \lambda/d$) is < 0.01 mrad, which means that beam spread is only 1mm/m. An ordinary light, on the contrary spreads at 1m/m. Because of the exceptional directionality, it is even possible to focus a laser beam on the surface of the Moon (with a beam spread of only few kms). Angle of divergence of the laser beam is expressed as

$$\phi = \frac{arc\ length}{radius}$$



i.e. $\phi = \frac{d2-d1}{2(s2-s1)}$

Where d1 and d2 are the diameters of the spots measured at distances s1 and s2 from the laser aperture. The laser beam often has a small divergence (highly collimated), but a perfectly collimated beam cannot be created due to the effect of diffraction. Nonetheless, a laser beam will spread much less than a beam of incoherent light. Thus a beam generated by a small laboratory laser like a helium-neon laser (He-Ne) laser spreads approximately 1 mile (1.6 km) in diameter if shown from the Earth's surface to the Moon. By comparison, the output of the typical semiconductor laser, due to its small diameter, diverges almost immediately on exiting aperture, at an angle that may be as high as 50^0. However, such a divergent beam can be transformed into a collimated beam by means of a lens.

4.3 Hall Effect:

Principle: Hall Effect is the production of potential difference across an electrical conductor, transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current. Edwin Hall in 1879 had first observed the phenomena, and hence this is called as Hall Effect.

Basically it is related to the behaviour of moving charge in magnetic field.

Theory

For the moment, I shall concentrate only on the theoretical explanation of Hall Effect; mathematical derivation will be discussed later on.

Let me take a metallic conductor, just like a plate and connect it to a battery, one side of the conductor to the positive terminal of the battery and other side to the negative terminal of the battery as shown in the figure below (Fig 1). Obviously, there will be flow of current from positive to negative side of the battery and electrons will flow in opposite direction. Now, If the potential difference is measured by connecting the voltmeter across the conductor, the voltmeter shows zero potential difference.

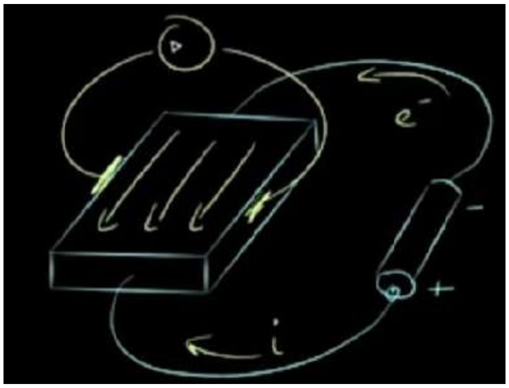


Fig. 1

Next, let me put this conductor inside a magnetic field (between north pole and south pole), the magnetic lines of force, as you know, will originate from north pole to the end at south pole. So, the direction of Magnetic field will be as shown below in Fig 2.

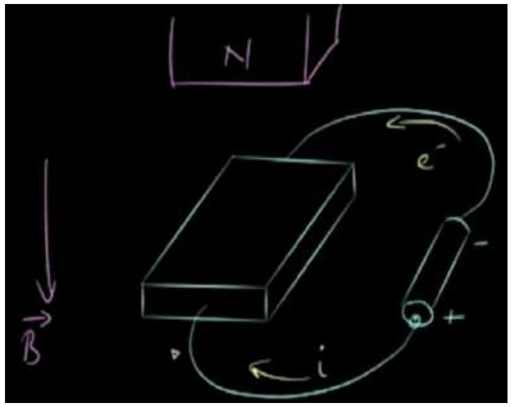


Fig 2

Now, if I measure the potential difference, then some value of the potential difference (or voltage) is obtained. This potential difference or voltage is called Hall Voltage.

Let us see why this happened?

This happened because when any charged particle moves in any magnetic field, then this charged particle experiences a force called Lorentz force and the direction of Lorentz force is determined by Fleming Left Hand Rule which states that:

If the thumb of left hand, fore finger and middle finger are perpendicular to each other and fore finger represents the magnetic field, middle finger represents the velocity of charged particle i.e. current flow (in this case positive charge) and thumb represents the force that will act on that particle (Fig 3).

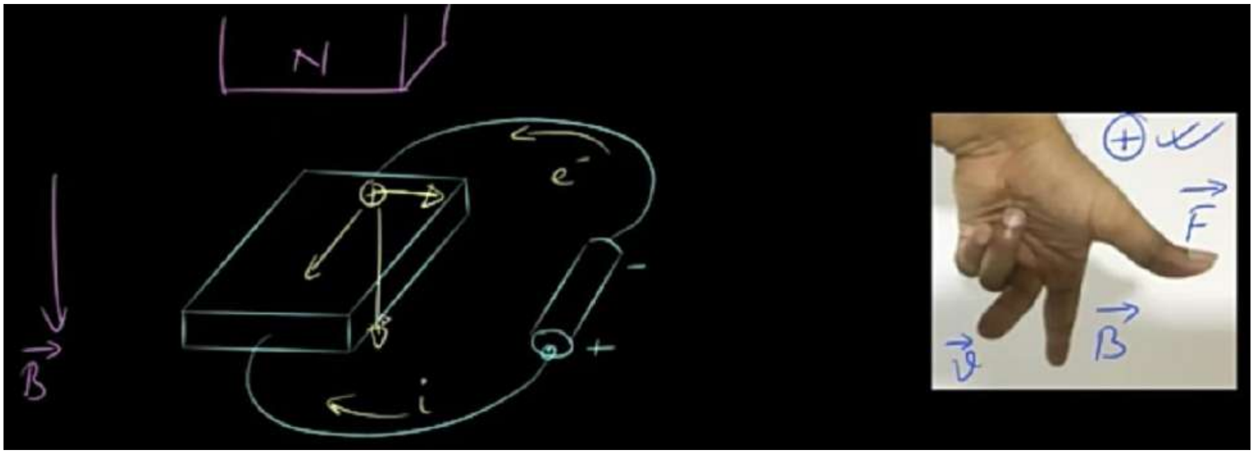


Fig. 3

In case of negative charge i.e. electrons the force applied will be in opposite direction (fig 4).

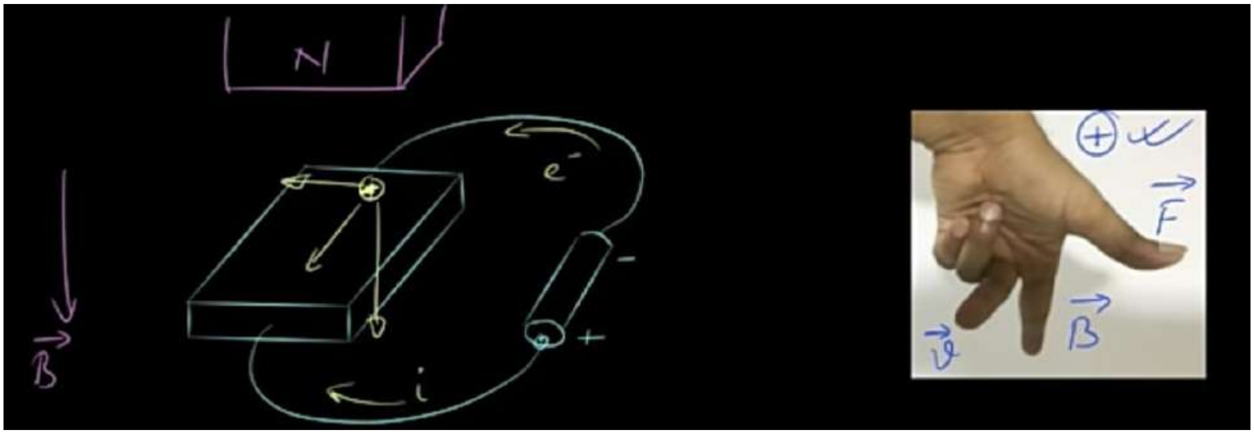


Fig. 4

Due to this force, the electrons get diverted towards one side of the conductor i.e. in that region there will be accumulation of electrons (left side of conductor) and on the other side (right side of conductor) there will be deficiency of electrons. Hence, Left side of conductor will have negative potential and right side will have positive potential (Fig 5).

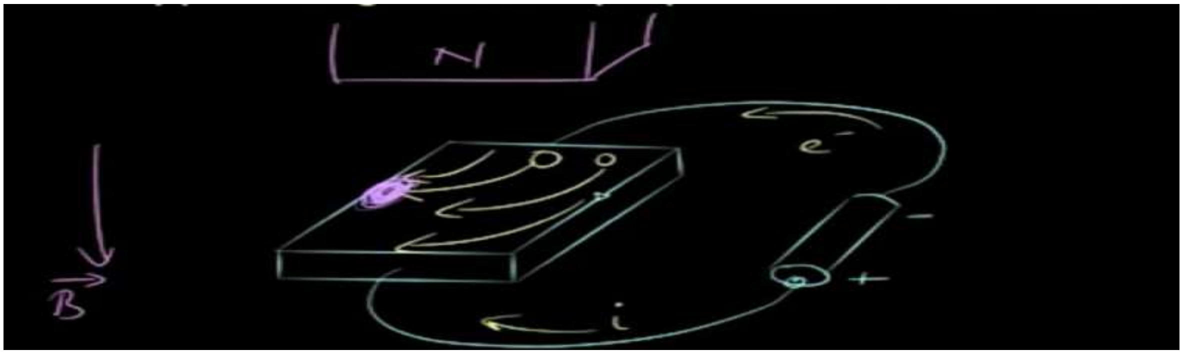


Fig. 5

Now, if I measure the potential difference by connecting the voltmeter across the conductor, there will be a potential difference appeared across the cross-section of the conductor (Fig 6). This potential difference or voltage is called Hall Voltage.

Fig. 6

Mathematical Derivation:

To understand the Hall Effect mathematically and the derive various parameters of Hall Effect, let me proceed as follows.

As explained above, after applying a voltage across the conductor (of thickness ***d*** and width ***w)***, current ***I*** start flowing from left to right that is along the x-direction. Let the direction of the magnetic field along the z-axis. Now by Fleming's Left-Hand Rule, the charge carriers will experience a force depending on both – direction of current and direction of magnetic field. So, when a magnetic field is applied in a direction transverse to the current direction, a potential difference appears across the direction perpendicular to both current and the magnetic field.

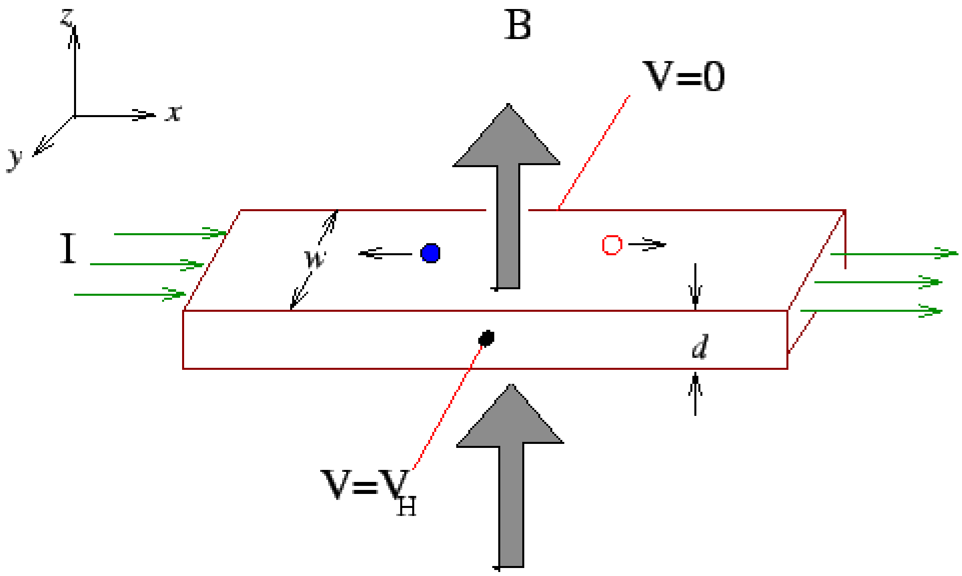


Fig 6

The electric field created due to this shifting of electrons opposes the shifting of electrons towards the surface of the metal block. Hence there may be two forces acting on the charge carriers.

1. The force due to Hall effect $\vec{F} = -\vec{v} \times \vec{B}$ or in magnitute $F = vB$
2. The force due to created electric field $\vec{F} = e\vec{E}$ or in magnitudeb $F' = eE$

Where, ***e*** the charge of the charge carrier, ***E*** is the electric field and ***B*** is the magnetic flux density.

These forces are opposite to each other. After the establishment of the certain electric field due to **Hall Effect** the system becomes in equilibrium. At that condition the force acting on the charge carriers (conduction electrons) due to the established electric field and due to Hall Effect become same, and opposite. Hence there would not be any further shifting of electrons towards the surface of the block and the system become in an equilibrium condition.

Now we can write the field created due to **Hall Effect** as, E_H. Hence, we can write the force acting on the charge carrier due to the field as

$$F^{'} = eE_H$$

Now at equilibrium

$$F = F^{'} \Rightarrow Bev = eE_H \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

If N is charge carrier concentration, then

Current Density, $J = Nev$ ………………… (ii)

From equation *(i)* and *(ii)*, we can write

$$E_H = \frac{BJ}{Ne}$$

$$\frac{E_H}{JB} = \frac{1}{Ne} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iii)}$$

We call the term $\frac{E_H}{JB} = R_H$ as the Coefficient of Hall Effect or simply Hall Coefficient. We define Hall Coefficient as the Hall field per unit magnetic field density per unit current density.

i.e. $$R_H = \frac{1}{Ne} = \frac{E_H}{JB}. \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iv)}$$

Expression for Carrier Concentration, Hall Coefficient and Mobility in terms of Hall Voltage

Since, $J = \frac{I}{A} = \frac{I}{wd}$ **and** $E = \frac{V_H}{w}$**, we get**

$$N = \frac{IB}{edV_H}$$

and hence,

$$R_H = \frac{1}{Ne} = \frac{V_H d}{IB}.$$

If ρ is the resistivity of the material of the strip, the mobility of the carrier is given by

$$\mu = \frac{1}{|\rho n q|} = \frac{|R_H|}{\rho}$$

Hall effect is a very useful phenomenon and helps to

i) Determine the Type of Semiconductor:

By knowing the direction of the Hall Voltage, one can determine that the given sample is whether n-type semiconductor or p-type semiconductor. This is because Hall coefficient is negative for n-type semiconductor while the same is positive in the case of p-type semiconductor.

ii) Calculate the Carrier Concentration:

The expressions for the carrier concentrations of electrons (n) and holes (p) in terms of Hall coefficient are given by

$$n = \frac{1}{q R_H} \quad \textbf{and} \quad p = \frac{1}{q R_H}$$

iii) Determine the Mobility (Hall Mobility):

Mobility expression for the electrons (μ_n) and the holes (μ_p), expressed in terms of Hall coefficient is given by,

$$\mu_n = \sigma R_{H_n} \quad \text{and} \quad \mu_p = \sigma_p R_H$$

Where, σ_n and σ_p represent the conductivity due to the electrons and the holes, respectively.

iv) Measure Magnetic Flux Density:

This equation can be readily deduced from the equation of Hall voltage and is given by

$$B = \frac{V_H d}{R_H I}.$$

Applications of Hall Effect:

Hall Effect Principle is used

1. To measure magnetic field using magnetometers.
2. To inspect materials such as pipes or tubing.
3. Sensing the presence of the magnetic field in industrial applications.
4. For contactless measurement of DC current in current transformers, Hall Effect sensor is used.
5. As a sensor to detect the fuel levels in automobiles.
6. As sensors used in ultra-high-reliability applications such as keyboards.
7. As Magnetic field sensing equipment.
8. Linear or Angular displacement transducers. For example – to identify the position of the car seats and seat belts and act as an interlock for air-bag control.
9. As Proximity detectors.
10. For detecting wheel speed and accordingly assist anti-lock braking system (ABS).

4.4 Resistivity Measurement Techniques:

Electrical resistivity is a basic material property that quantifies a material's opposition to current flow; it is the reciprocal of conductivity. The resistivity of a material depends upon several factors, including the material doping, processing, and environmental factors such as temperature and humidity. The resistivity of the material can affect the characteristics of a device of which it's made, such as the series resistance, threshold voltage, capacitance, and other parameters.

Determining the resistivity of a material is common in both research and fabrication environments. There are many methods for determining the resistivity of a material, but the technique may vary depending upon the type of material, magnitude of the resistance, shape, and thickness of the material.

(a) Two-Probe Method:

Two Probe technique is suitable for measuring resistivity of high resistivity samples, e.g., polymer films/sheets. The resistivity ρ can be measured by measuring the voltage drop across the sample due to the passage of known constant current through the sample as shown the figure below.

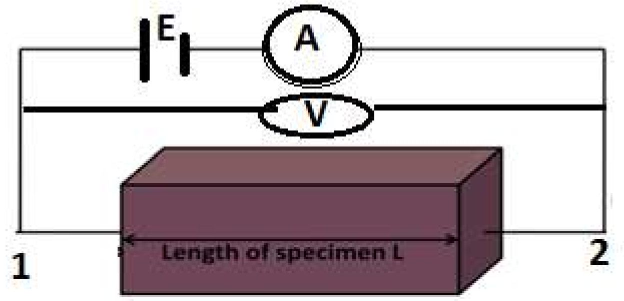


Figure 1: Measuring electrical resistivity by two probe method

The battery ***E*** supplies current (in through probe 1and out through probe 2). Let the current be ***I*** amperes. It is measured by the ammeter . The potential difference between the two probes (or contacts) at the ends of specimen is measured by the voltmeter V. Let L be the length of the specimen between the two probes and A its area of cross-section, then resistivity of the specimen is calculated as

$$\rho = \frac{VA}{IL}$$

Drawbacks of Two Probe Method

1. Major problem in this method is error due to contact resistance of measuring leads or wires.
2. This method cannot be used for materials having random shape.
3. In case of semiconductors, the heating of samples due to soldering results in injection of impurities in the material thereby affecting its intrinsic electrical resistivity. For certain

samples, soldering of contacts is difficult.

To overcome the first two problems, a collinear equidistant four probe method is used. This provides the measurement of resistivity of specimen having wide variety of shapes but with uniform cross-section. The soldering contacts are replaced by pressure contacts to eliminate the third problem listed above.

The resistivity of the materials can also be determined using two methods, four probe and Van der Pauw method. With both of these methods main objective is to find the sheet resistance (RS) of the film. The working principle and calculations involved for determining "*RS*" in these methods are entirely different and as follows.

(b) Four-Probe Method:

The easiest method for determining the resistance of the film is the two probe method. However, in this method contact resistance (RC) and wire resistance (RW) also adds up in the measurement and consequently the true resistance of the film is not measured.

This problem is solved with the four probe arrangement set up (*Figure 2*), where two additional probes are used to measure the resistance. The four point probe set up consists of four equally spaced Tungsten metal tips. Each tip is supported by springs at the back to minimize sample damage during probing. A current source is used to supply current through the two outer probes, such that the current enters the sample through probe1 and leaves through probe 4. A voltmeter measures the potential difference across the inner two probes 2 and 3. As a result, the contact resistance or wire resistance are not accounted in this case. Further, to minimize the probe contact resistance, very fine probes are used so that the surface area of contact between the probes and the sample is negligible.

Let,

S_1= distance between probes 1 and 2

S_2= distance between probes 2 and 3

S_3= distance between probes 3 and 4

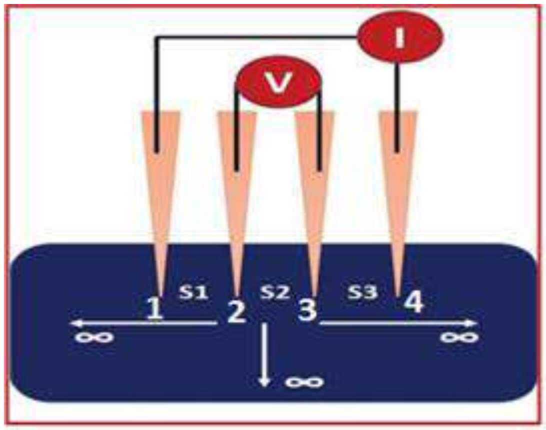


Figure 2: Typical set up for measuring resistivity of thin films using four probe method

To derive the four point probe resistivity expression, we start with the geometry as shown below (Fig 3).

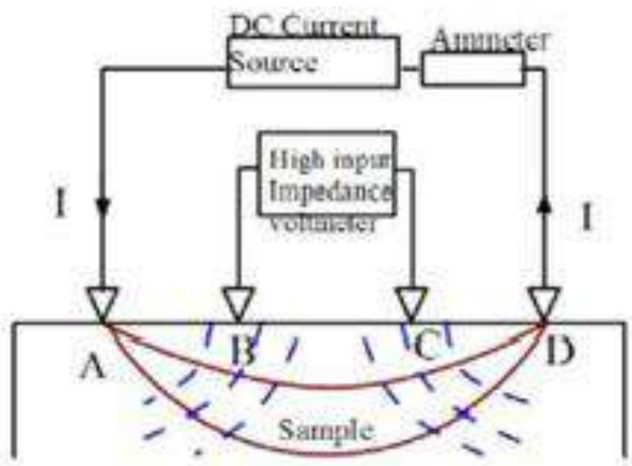


Fig 3

When a charge carrier is injected by the probe 1 at point ***A*** on the surface of the sample, it behaves as a point charge and the current spreads radially such that

$$J = \frac{I}{2\pi r^2}$$

where $2\pi r^2$ is area of half sphere. Now, we know that

$$J = \sigma E = \frac{E}{\rho}$$

i.e. $E = J\rho = -\frac{dV}{dr}$

So, we can write, $dV = -Edr = -J\rho dr = -\frac{-I\rho dr}{2\pi r^2}$

i.e. $\int_0^V dV = -\frac{-I\rho}{2\pi}\int_0^r \frac{dr}{r^2}$

i.e. $V = \frac{I\rho}{2\pi r}$

Therefore, the voltage at probe 2 will be

$$V_2 = \frac{I\rho}{2\pi}\left[\frac{1}{s_1} - \frac{1}{s_2 + s_3}\right]$$

Because probe 4 is at negative potential w.r.t probe 2 and distance between them is $S_2 + S_3$. Similarly, the voltage at probe 3 will be

$$V_3 = \frac{I\rho}{2\pi}\left[\frac{1}{s_1 + s_2} - \frac{1}{s_3}\right]$$

Hence, voltage drop across the probes 2 and 3 i.e. the potential difference between them as measured by the voltmeter will be

$$V_{23} = V_2 - V_3 = \frac{I\rho}{2\pi}\left[\frac{1}{s_1} + \frac{1}{s_3} - \frac{1}{s_2 + s_3} - \frac{1}{s_1 + s_2}\right] = V$$

When the probes are equidistant, we have $S_1=S_2=S_3=S$, so that

$$V = \frac{I\rho}{2\pi s} \text{ or}$$

$$\rho = 2\pi S\left(\frac{V}{I}\right)$$

In the four probe method, S is known and V and I are measured by the voltmeter and ammeter respectively. Hence, the resistivity of the sample can be measured.

<u>Advantage of Four Probe over Two Probe Method</u>

The four point probe is preferable over a two-point probe because the contact and spreading resistances associated with the two point probe are large and the true resistivity can't be actually separated from the measured resistivity. In a four point probe, very little contact and spreading resistance is associated with the voltage probes and hence one can obtain a fairly accurate calculation of the resistivity. Using four probes eliminate measurement errors due to the probe resistance, the spreading resistance under each probe, and the contact resistance between each metal probe and semiconductor material.

(c) Vander Pauw Method:

The Vander Pauw technique is employed to accurately measure the resistivity of a thin sample of arbitrary shape. In order to use this material, the thickness of the sample must be much less than its width and length. It uses four-point probes positioned around the perimeter of the sample rather than in straight line. The average resistivity ρ of a sample can be calculated as a product of its sheet resistance R_S and thickness t as

$$\rho = R_S t \tag{1}$$

Where't' is usually given in the experiment. Therefore, in order to measure the resistivity of the sample, one has to determine its sheet resistance R_S. This technique was invented by Vander Pauw, and is extensively employed in semiconductor industry for determination of resistivity of uniform samples. This technique requires an arbitrarily shaped thin-plate sample having four very small Ohmic contacts placed on the periphery, usually at the corners, of the plate. Figure 1 shows the schematic arrangement of a typical Vander Pauw experiment.

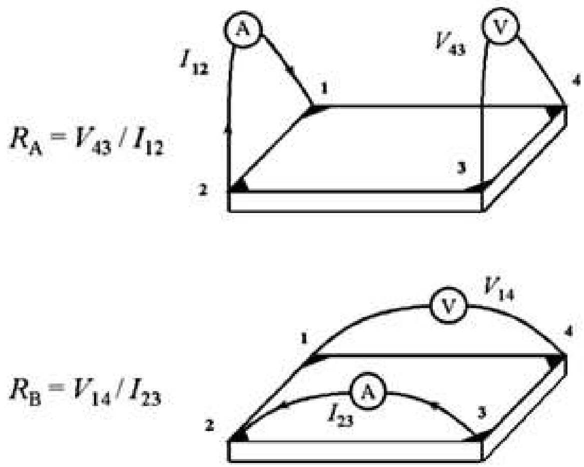


Figure 1 Schematics of a Vander Pauw experiment for determining the characteristic resistances R_A and R_B.

In order to determine the resistivity of a uniform sample, the sheet resistance R_S needs to be determined. As demonstrated by Vander Pauw, two characteristic resistances (R_A and R_B) are associated with the corresponding terminals as depicted in Figure 1. These characteristic resistances R_A and R_B are related to the sheet resistance R_S through the Van der Pauw equation, as:

$$\exp(-\pi R_A / R_S) + \exp(-\pi R_B / R_S) = 1 \qquad (2)$$

For determining R_A and R_B, a dc current (I) is applied across contact 1 and contact 2 and the voltage V_{43} is measured across contact 4 and contact 3, as depicted in Figure 1. Similarly, voltage V_{14} is measured across contacts 1 & 4 by applying a current I across the contacts 2 & 3. R_A and R_B can be obtained as follows:

$$R_A = V_{43}/I_{12} \text{ and } R_B = V_{14}/I_{23} \qquad (3)$$

Eqation (2) is solved to obtain R_S. Mostly, $R_A= R_B= R$ so that equation (2) gives,

$$2\exp(-\pi R\ /R_S)=1$$

i.e. $$\ln(2)=\frac{\pi R}{R_S}$$

i.e. $$R_S=\frac{\pi R}{\ln(2)}=4.53R=4.53\times\left(\frac{V}{I}\right)$$

and therefore

$$\rho=R_S t=4.53\times t\times\left(\frac{V}{I}\right)$$

In this way, the Resistivity of the sample can be calculated using Vander Pauw Method.

Properties of a material that can be measured by this method:

- doping type (p- or n-type)
- sheet density of majority carriers (majority carriers per unit area)
- charge density and doping level.
- mobility of majority carriers.

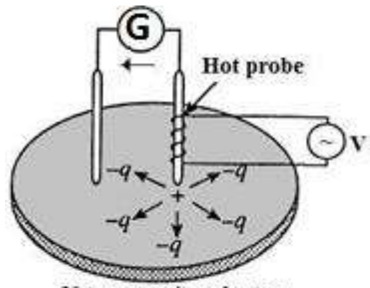
Conditions:

The following conditions must be met in order to apply this method:

1. sample must be flat shaped and uniformly thick
2. sample should not possess isolated holes
3. sample should be isotropic and homogeneous
4. contacts should be placed at sample edges
5. Contact area of individual contacts must be smaller than sample area at least by an order of magnitude.

(d) Hot-Probe Method:

A hot point probe is a method of determining conductivity type of the semiconducting sample i.e. Whether a semiconductor sample is n (negative) type or p (positive) type. A typical experimental set up for hot-point probe method is given below.



Two fine metal probes are placed on the semiconductor sample and a galvanometer is attached between them. One of the probe is kept at room temperature 9cold end) and the other is heated to about 80^0C (hot end). The hot probe heats the semiconductor beneath it so that the kinetic energy of the free carriers in this region is increased. As a result, the charge carriers diffuse from hot region to the cold region, generating a thermo voltage between these regions that produces a deflection in the galvanometer due to the corresponding thermo current. The sign of the thermo-voltage (or the nature of the deflection in the galvanometer towards right of left from the center position) corresponds to the sign of the diffusing charge carriers and hence provides a simple way to provide conductivity type. This method provides a simple way to distinguish between n-type and p-type semiconductors.

If the semiconductor is of n-type, the electrons will move away from the hot probe towards cold probe so that the hot probe acquire positive charge (i.e. potential) w.r.t. cold probe and current flows in counter clockwise direction i.e. galvanometer deflects towards left from the center position.

In a p-type semiconductor, the holes will move away from the hot probe towards cold probe so that the hot probe acquire negative charge (i.e. potential) w.r.t. cold probe and current flows in clockwise direction i.e. the direction of current flow is reversed in case of p-type semiconductor.

4.5 Parameter extraction from diode I-V characteristics:

(a) C-V measurements for diode (depletion layer capacitance of the pn-junction:

We know that the width of the (unbiased) depletion region in pn-junction diode is given by

$$W = \left[\frac{2\epsilon_s V_B (N_a + N_d)}{e\, N_a N_d}\right]^{1/2}$$

Here V_B is the barrier potential across the junction. However, if the diode is forward biased the effective potential difference across it is (V_B-V), where V is applied voltage. Therefore, the width of the depletion region becomes

$$W = \left[\frac{2\epsilon_s (V_B - V)(N_a + N_d)}{e\, N_a N_d}\right]^{1/2} \qquad (1)$$

Now, the depletion layer capacitance is defined by,

$$C = \left|\frac{dQ}{dV}\right|$$

Where, the amount of charge (on any side of the depletion layer) is,

$$|Q| = e\, N_d x_n A = e\, N_d x_p A$$

$$W = x_n + x_p = \frac{Q}{e\, A}\left[\frac{1}{N_d} + \frac{1}{N_a}\right] \qquad (2)$$

Equating (1) and (2), we get,

$$\frac{Q}{e\, A}\left[\frac{1}{N_d} + \frac{1}{N_a}\right] = \left[\frac{2\epsilon_s (V_B - V)(N_a + N_d)}{e\, N_a N_d}\right]^{1/2}$$

Squaring both sides, we get,

$$\left(\frac{Q}{e\,A}\right)^2 \left[\frac{1}{N_d}+\frac{1}{N_a}\right]^2 = \left[\frac{2\epsilon_s(V_B - V)(N_a + N_d)}{e\,N_a N_d}\right]$$

$$Q^2 = \frac{2\epsilon_s(V_B - V)eA^2N_aN_d}{(N_a + N_d)}$$

$$Q = \left[\frac{2\epsilon_s(V_B - V)eA^2N_aN_d}{(N_a + N_d)}\right]^{1/2} = (V_B - V)^{1/2}\sqrt{\frac{2\epsilon_s eA^2N_aN_d}{(N_a + N_d)}}$$

Therefore, the junction capacitance can be written as,

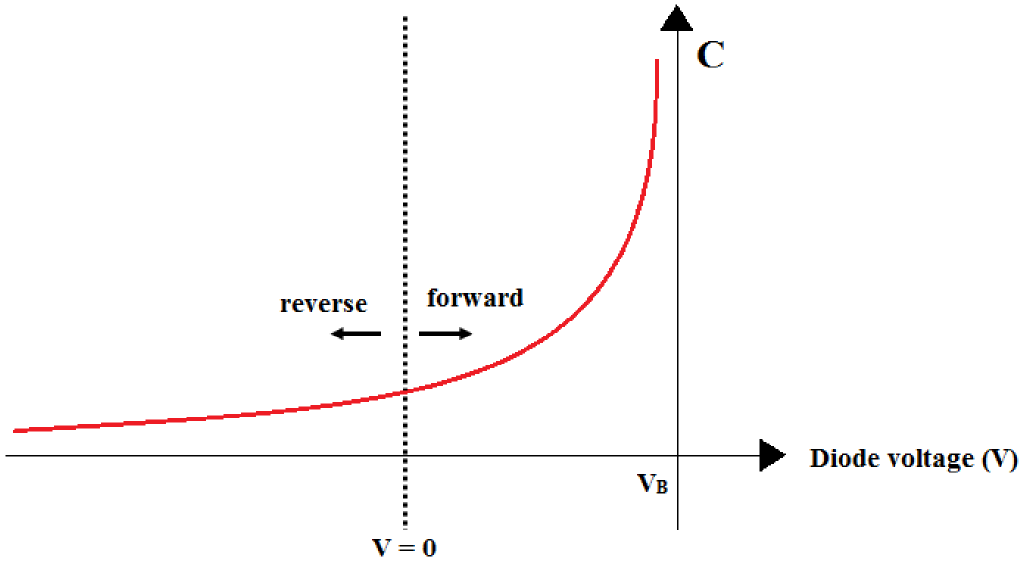
$$C = \left|\frac{dQ}{dV}\right| = \frac{1}{2}\,(V_B - V)^{-1/2}\sqrt{\frac{2\epsilon_s eA^2N_aN_d}{(N_a + N_d)}}$$

$$C = \sqrt{\frac{\epsilon_s eA^2N_aN_d}{2(V_B - V)^{1/2}(N_a + N_d)} \times \frac{\epsilon_s}{\epsilon_s}}$$

$$C = \epsilon_s\,A\sqrt{\frac{eN_aN_d}{2\epsilon_s(V_B - V)^{1/2}(N_a + N_d)}}$$

$$C = \frac{\epsilon_s\,A}{W}$$

We should note that the $C = {}^{\epsilon_s\,A}/_{W}$, is given by the same expression as that for a parallel plate capacitor, but here, 'W' is voltage dependent by virtue of equation (1). The C-V behavior in the figure below explains that the capacitance 'C' decreases with increase in the reverse bias because the width 'W' increases in reverse bias via $W \propto (V_B - V)^{1/2}$



Note that 'C' increases with forward bias. This voltage dependence of the depletion capacitance is utilized in varactor diodes which are used which are used as voltage dependent capacitor in tuning circuits. A varactor diode is reverse biased to prevent conduction and its 'C' is varied by the magnitude of the reverse bias applied to it.

(b) Diffusion capacitance and Bulk resistance of diode:

The diffusion or storage capacitance arises in the forward bias only, when a pn-junction is forward biased, we have stored a positive charge on the n-side by the continuous injection and diffusion of minority carriers (holes). Likewise, for the p-region where a negative charge is stored due to continuous injection of electrons from the n-side. These injected charges (Q) disappear due to recombination at a rate (Q/τ_h). Here, τ_h is the minority carrier lifetime. The diode current (in the forward bias for V> V_B) is then,

$$I = I_o\left[exp\left[\frac{eV}{k\,T}\right] - 1\right] \approx I_o\left[exp\left[\frac{eV}{k\,T}\right]\right]$$

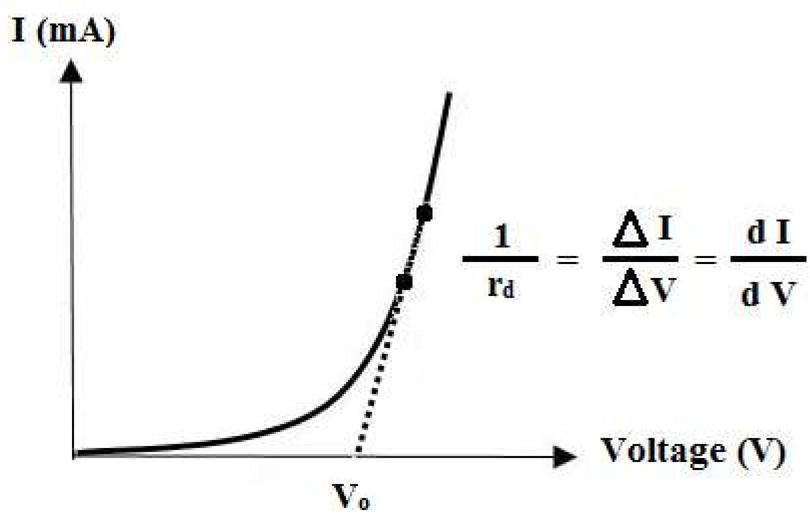
So that,

$$Q = \tau_h I = \tau_h I_o \left[exp\left[\frac{eV}{k\,T}\right]\right] \quad (3)$$

Where, we have used e/kT ≈ 1/0.025 at room temperature. Generally, the value of diffusion capacitance, typically is in Nano-farad range, far exceeds that of 'C'. We define the dynamics resistance of the diode as,

$$r_d = \frac{dV}{dI} = \frac{k\,T}{e\,I} = \frac{25}{I}\ (mA) \quad (4)$$

i.e. the dynamic resistance is the inverse of the slope of the I-V characteristics at a point and hence depends on the current I. This is known in the I-V characteristics curve below,



From equation (3) and (4), we get,

$$C = \frac{d\,Q}{d\,V} = \frac{d\,(\tau_h I)}{d\,V} = \tau_h \frac{d\,I}{d\,V} = \tau_h \frac{1}{r_d}$$

$$\therefore C = \frac{\tau_h}{r_d}$$