UNIT 5: Measurements Techniques

- Four-point probe
- Van der Pauw measurements
- Resistivity and hall mobility
- Hot-point probe measurement
- Capacitance-voltage measurements
- DLTS (Deep Level Transient Spectroscopy)
- Band gap by UV-Vis spectroscopy, absorption/transmission
- Parameter extraction from diode I-V characteristics

1. Introduction

The electrical behaviors of engineering materials are diverse, and so are their uses in electrical and optoelectronic applications. Currently this development is hastening mainly due to the research is going in the direction of finding new materials having different electronic and optical properties. Knowledge of such properties of different materials can be used to design or improve any electrical or electronic device. All these aspects have great dependence on measurements techniques through which one can deduce their suitable properties for engineering applications.

For all these purpose the resistivity of the wire can be measured by measuring voltage drop across the wire due to passage of known current supplied by the battery through two parallel probes and the potential difference (V) between the two contacts at the ends of the wire can be measured by the same probes. This is known as two probe method for resistivity measurement.

According to this method, the resistivity of the wire is obtained by;

$$\rho = \left(\frac{V}{I}\right)\frac{A}{L} \tag{1}$$

The two-probe method is a simple and advantageous but it suffers from certain issues.

- Error due to contact resistance of the measuring leads,
- Materials having random shapes,
- Soldering of the test leads on some materials would be difficult,
- Heating of the leads during soldering may inject additional impurities in materials such as semiconductors and thereby affecting the intrinsic electrical resistivity largely.

In order to overcome the above problems, four-probe method is widely proposed.

2. Four Probe method

The purpose of the four point probe is to measure the resistivity of any semiconductor material. It can measure either bulk or thin film specimen, each of which consists of a different expression.

In order to use the four-probe method, it is assumed that:

- The resistivity of the material is uniform in the area of measurement.
- If there is minority carrier injection into the semiconductor by the current – carrying electrodes, most of the carriers recombine near the electrodes so that their effect on the conductivity is negligible.
- The surface on which the probes rest is flat with no surface leakage.
- The four probes used for resistivity measurements are equally spaced and collinear.
- The diameter of the contact between the metallic probes and the semiconductor should be small compared to the distance between probes.

2.1 Resistivity for Bulk Sample:

Four probe method minimizes the other contributions (lead resistance, contact resistance, etc.) to the resistance measurement which results in an accurate measurement of sample resistance. This includes four equally spaced probes in contact with a material of unknown resistance. The outer two probes are used for sourcing the current and the two inner probes are used for measuring the resulting voltage drop across the surface of the sample as shown in figure 1.

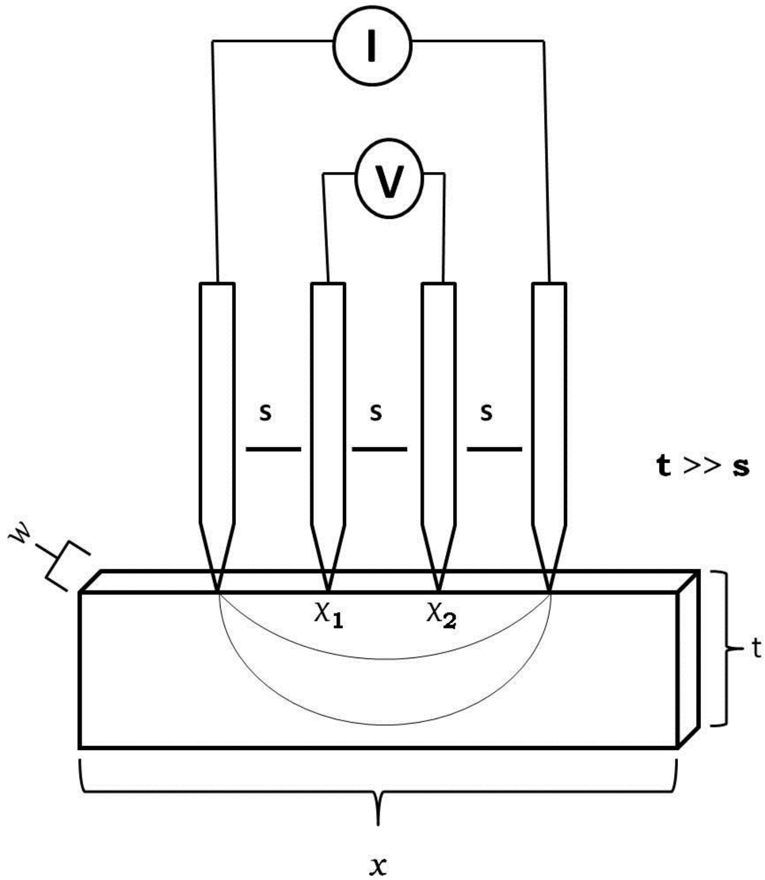


Figure 1: Four point probe arrangement for bulk sample

For derivations we assume that the metal tip is infinitesimal and samples are semi-infinite in lateral dimension. For bulk samples where the sample thickness t >>s, the probe spacing, we assume a spherical projection of current originating from the outer probe tips. The differential resistance is:

$$\Delta R = \rho \frac{dx}{A} \tag{2}$$

$$R = \frac{1}{2s}\left(\frac{\rho}{2\pi}\right) \quad (3)$$

where, probe spacing‘s’ is uniform. Due to the superposition of current at the outer two tips, R = V/2I. Thus, by solving above equation further for bulk resistivity:

$$\rho = 2\pi s \frac{(V)}{(I)} \quad (4)$$

3. Van der Pauw method:

Frequently the sample does not have uniform geometry that is favorable for the four probe method, leading to an unknown current distribution. Also, it is often difficult to determine accurately the geometry of the sample, limiting the accuracy of the calculated resistivity. In such a case, one often uses the technique of van der Pauw to determine the resistivity of the sample.

This method involves applying a current and measuring voltage using four small contacts on the circumference of a flat, arbitrarily shaped sample of uniform thickness as shown in figure 3.

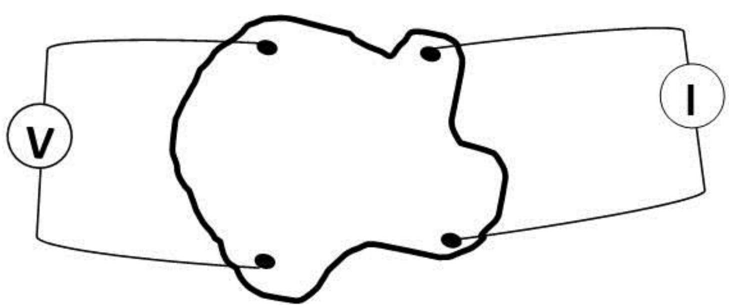


Figure 3: Four point probe arrangement for thin sheet

The resistivity can be obtained from a total of eight measurements that are made around the periphery of the sample with various possible configurations in figure 3. Once all the voltages are taken, two values of resistivity ρ_A and ρ_B can be derived as follows:

$$\rho_A = \left(\frac{\pi}{\ln 2}\right) f_A t_s \left[\frac{(V_1 - V_2 + V_3 - V_4)}{4I}\right] \tag{10}$$

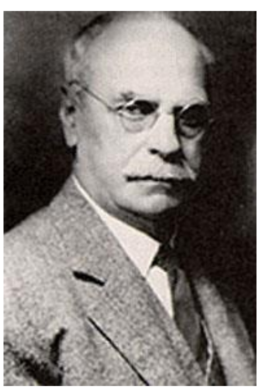
$$\rho_A = \left(\frac{\pi}{\ln 2}\right) f_A t_s \left[\frac{(V_5 - V_6 + V_7 - V_8)}{4I}\right] \tag{11}$$

where, ρ_A and ρ_B are volume resistivity in Ohm-cm, t_s is the sample thickness in cm, V_1 to V_8 represent the voltages measured by the voltmeter under eight geometrics (not mentioned here) respectively, I is the current through the sample in amperes and f_A and f_B are geometrical correction factors. For perfect symmetry system $f_A = f_B = 1$ so average resistivity is given by;

$$\rho_{avg} = \left(\frac{\rho_A + \rho_B}{2}\right) \tag{12}$$

4. Hall Effect

Hall Effect was first discovered by scientist Edwin Hall in 1879. He was an American physicist who discovered the eponymous Hall effect. Hall conducted thermoelectric research at Harvard University.



If a specimen (metal or semiconductor) carrying a current I is placed in a transverse magnetic field B an electric field E is induced in a direction perpendicular to both I and B.

This Phenomenon is called Hall Effect and generated voltage is known as Hall Voltage V_H. The Hall Effect is used today as a research tool to probe the movement of charges, their drift velocities, charge carrier concentration, mobility, resistivity, conductivity and so on, in materials.

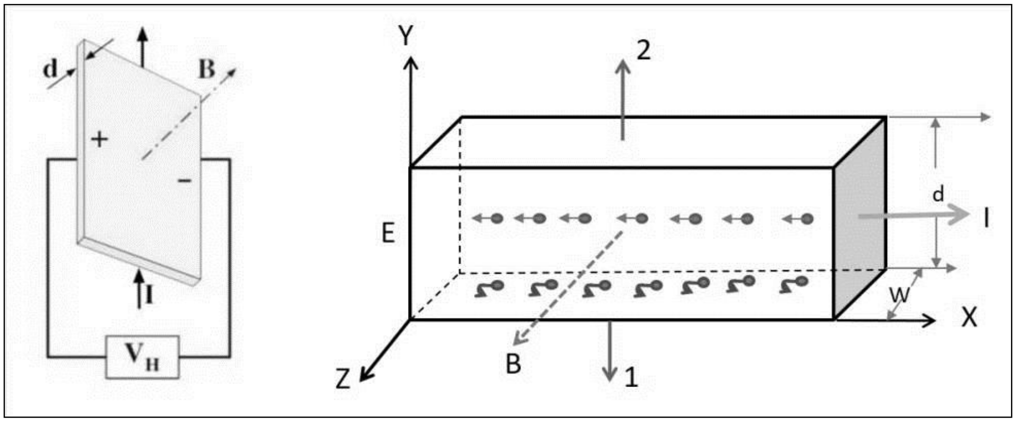


Figure 4: Schematic diagram of Hall Effect

Consider a rectangular bar with thickness d, Length L, and width W, as shown in Figure 4. Here current I flows along positive x-axis through the sample in the presence of magnetic field applied perpendicular to the current direction (positive z-direction), i.e., along the width of the sample. Due to this Lorentz force F acts on the charge carriers along negative y-direction as per Fleming's rules. Hence, electric field E is generated along the positive y-direction.

Consider the balance of forces on a moving charge in a situation where B, v and I are mutually perpendicular, such as shown in figure 4. Although the magnetic force, $F = evB$, and the electric force F = eE, eventually grows to equal it. That is,

$$evB = eE \tag{13}$$

So,
$$vB = E \tag{14}$$

But, we know that E is the Potential difference per unit length.

So,
$$E = \frac{V_H}{d} \tag{15}$$

Here, V_H is the Hall Voltage and d is the distance between two surfaces 1 and 2.

Now substitute the equation (14) in equation (13) we get,

$$Bv = \frac{V_H}{d} \tag{16}$$

$$V_H = Bvd \tag{17}$$

Now the current flowing through the semiconductor is given by;

$$I = nevA \tag{18}$$

$$v = \frac{I}{neA} \tag{19}$$

Now substitute the value of equation (18) in equation (16), we get,

$$V_H = \frac{BId}{neA} \tag{20}$$

Now consider that;

$$v = \frac{I}{neA} \tag{21}$$

Here J *is* the current density which is the current flowing per unit area. Hence, the Hall Voltage is given by,

$$V_H = \frac{1}{neA}BJd \tag{22}$$

Charge density ρ is the charge per unit volume;

$$\rho = ne \tag{23}$$

And area A is given as, $A = d \cdot w$
Now substituting all these values in equation (19),

$$V_H = \frac{BId}{\rho dw} \tag{24}$$

If the polarity of V_H is positive at the surface 2, then, majority carriers must electrons and semiconductor is of n - type. But if surface 1 has a positive polarity with respect to surface 2, then carriers is positively charged holes and semiconductor is of p - type.

The measurements of Hall Voltage V_H help us to determine whether the semiconductor is of n - type or p -type.

From equation (23) it is clear that Hall Voltage V_H is proportional to both Magnetic field B and J. Here the proportionality constant $\frac{1}{ne}$ is known as Hall Coefficient R_H.

Now from equation (22) carrier concentration and charge density can be determined.

Now the Hall Coefficient R_H is defined as;

$$R_H = \frac{1}{ne} = \frac{1}{\rho} \qquad (25)$$

Substitute the values equation (24) in equation (23). We get;

$$V_H = \frac{R_H BI}{W} \qquad (26)$$

Conductivity of the semiconducting material is given by;

$$\sigma = ne\mu \qquad (27)$$

where, μ is the mobility of the charge carriers.

So we can write

$$\sigma = \frac{\mu}{R_H} \qquad (28)$$

And from equation (24) and (27) we can write Hall resistivity ρ as,

$$\rho = \frac{1}{ne\mu} \qquad (29)$$

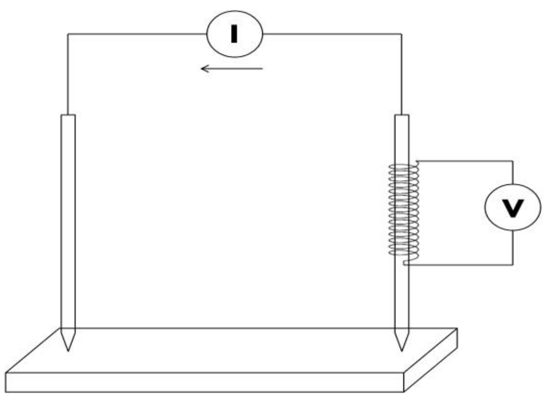
Applications of Hall Effect:

- Determination whether sample is n-type or p-type
- Determining the charge carrier concentration and mobility in sample
- Determining the magnetic field

- Designing the magnetometer and electronic meter based on Hall voltage

5. **Hot-point probe measurement**

A conventional Hot-Probe experiment enables a simple and efficient way to distinguish between n-type and p-type semiconductors using a hot probe and a standard multi-meter. A principle schematic of the experiment is shown in figure 5.



A voltmeter or ammeter is attached to the sample, and a heat source, such as a soldering iron, is placed on one of the leads. The heat source will cause charge carriers (electrons in an n-type, electron holes in a p-type) to move away from the lead.

Figure 5: Arrangement of hot point probe method

The heat from the probe creates an increased number of higher energy carriers which then diffuse away from the contact point. This will cause a current/voltage difference. For example, if the heat source is placed on the positive lead of a voltmeter attached to an n-type semiconductor, a positive voltage reading will result as the area around the heat source/positive lead becomes positively charged.

An explanation of this experiment is that the thermally excited majority free charged carriers are translated within the semiconductor from the hot probe to the cold probe. The mechanism for this motion within the semiconductor is of a diffusion type since the material is uniformly doped due to the constant heating in the hot probe contact. These translated majority carriers define the electrical potential sign of the measured current in the multi-meter.

6. Capacitance-voltage measurements

The technique uses a metal–semiconductor junction (Schottky barrier) or a p–n junction. The usual procedure for characterizing those capacitors and the material properties of the layers forming them is the Capacitance-Voltage (C-V) curve and Capacitance-Frequency (C-F) curve method which provides the variation of the capacitance with voltage, applied between the metal and semiconductor layers, for the three main regions of operation of the capacitor (accumulation, depletion and inversion regions).

Using the plot of Capacitance versus Voltage (C-V) and Capacitance versus Frequency (C-F), we can identify material properties and calculate many of its parameter.

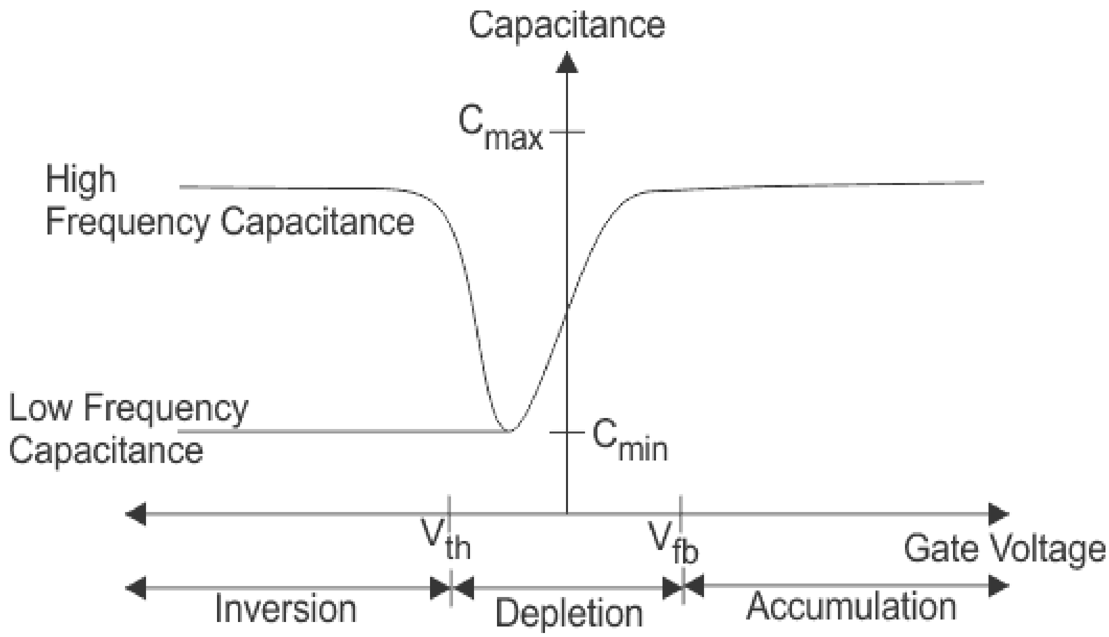


Figure 6: Capacitance Vs. Gate Voltage (C-V) diagram of a MOS Capacitor

The maximum measured capacitance C_{max} in the accumulation region gives the dielectric thickness *'d_i'*

$$d_i = \frac{A \in_i}{C_{\max}} \tag{30}$$

The minimum measured capacitance C_{min} at high frequency gives the doping concentration (assumed uniform) in the substrate.

Steps:

First, determine the depletion capacitance C_{dep} in the strong inversion region from

$$\frac{1}{C_{dep}} = \frac{1}{C_{\max}} \times \frac{1}{C_{\min}} \quad (31)$$

Then, obtain the depletion region thickness from

$$d_{dep} = \frac{\in_s A}{C_{dep}} \quad (32)$$

where, $\in_s$ is permittivity and A is gate area of MOS

All these kind of data can be obtained from C-V measurement systems available commercially and such system has many important qualities that make it a valuable support and a necessary tool in many activities related to the IC industry and nowadays increasingly also in the photovoltaic (PV) field. This type of electrical measurement is an effective way to gather information about materials and devices.

7. Deep level Transient Spectroscopy (DLTS)

DLTS was first introduced by D.V. Lang in 1974 and has developed many variations on the original capacitance transient method and also on the data analysis method. It is an experimental non destructive technique to identifying electrically active defects (known as charge carrier traps) in semiconductors. The basic principle of DLTS is emission of trapped charge carriers (defects) change the depletion capacitance of a p-n junction or Schottky diode and the transient measurement provides information of these defect levels in the band gap.

An energy level in the band gap of a semiconductor can be characterized by exploiting its emission behavior as a function of temperature and its activation energy, which is one of the most important parameters in describing the defect. The activation energy of a deep level, so called because its energy level falls deep in the gap and not near the edge of the gap, is the energy difference between the energy level and its respective band. Deep levels are also called traps.

8. Band gap determination by UV-Vis spectroscopy

The measurement of the band gap of materials is important in the semiconductors, nanomaterials and solar industries. This theory demonstrates how the band gap of a material can be determined from its UV absorption spectrum. For determination of band gap for suitable materials, absorption of incident photon by semiconducting material is an important technique. In this UV-Vis spectroscopic technique, photons of selected wavelength are bombarded on the sample and their relative transmission is observed. Since the photons with energies greater than the band gap are absorbed while photons with energies less than band gap are transmitted, the technique provides accurate measurements of the energy band gap. The ratio of transmitted to incident radiation intensities is expected to depend on photon wavelength and the thickness of the sample. The detector converts the incoming light into a current, the higher the current the greater the intensity. The chart recorder usually plots the absorbance against wavelength (nm) in the UV and visible section of the electromagnetic spectrum. Schematic of UV-Vis spectrometer is shown in figure 8.

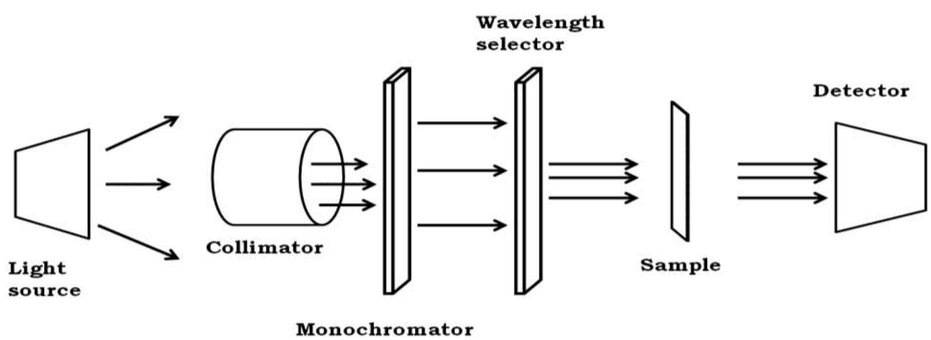


Figure 8:
Schematic of UV-Vis spectrometer

When a photon beam of intensity I_o (photon/cm^{2}sec) transmits through a slab of a medium of thickness x, the beam of photons attenuates in accordance with the exponential law,

$$I = I_0 e^{(-\alpha x)} \tag{34}$$

where, 'α' is called as the absorption coefficient and has units of cm^{-1}.

The transmittance 'T' of the sample can ne obtains as;

$$T = \frac{I}{I_0} \tag{35}$$

Absorbance 'A' of the sample can be calculated from the transmittance as;

$$A = -\log_{10} T \tag{36}$$

Absorption coefficient 'α' of the sample can be calculated from the absorbance and sample thickness 't' as;

$$\alpha = 2.303 \frac{A}{t} \tag{37}$$

The relationship that exists for possible transitions across the energy gap of semiconductor, the absorption coefficient 'α' is proportional as follow;

$$\alpha h\nu = A\left(h\nu - E_g\right)^r \tag{38}$$

Where, 'α' is the absorption coefficient, $h\nu$ is the energy of the incident photon, Eg is the band gap of material.

9. Parameter extraction from diode I-V characteristics

The current-voltage characteristics of an electronic component tell us much about its operation and can be a very useful tool in determining the operating characteristics of a particular device or component. It shows possible combinations of current and voltage, and as a graphical aid can help visually understand better what is happening within a circuit.

I-V characteristics of p-n junction diode:

When the p-n junction is connected in an external battery such that, the positive terminal of the battery is connected to the p region and negative terminal is connected to the n region of the diode, then the junction is said to be forward bias. The plot of the voltage across the diode versus the diode current gives the I-V characteristics and it is shown in figure 10. As shown in figure 10, when the forward voltage exceeds the junction's internal barrier voltage, which for silicon is about 0.6 volts and 0.3 volts for germanium, the abrupt change occurs and the forward current increases rapidly for a very small increase in voltage producing a non-linear curve. The "knee" point on the forward curve.

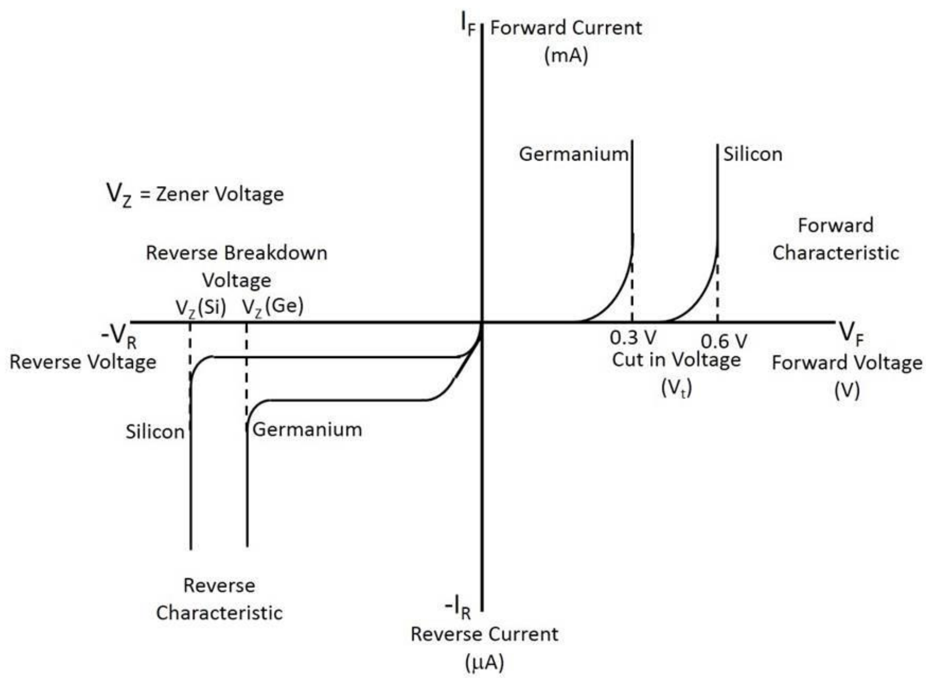


Figure 10: V-I characteristic of P - N junction diode

Likewise, when the diode is reversed biased, cathode positive with respect to the anode, the diode blocks current except for an extremely small leakage current, and operates in the lower left quadrant of its I-V characteristic curves. The diode continues to block current flow through it until the reverse voltage across the diode becomes greater than its breakdown voltage point resulting in a sudden increase in reverse current producing a fairly straight line downward curve as the voltage losses control.

Solved Examples:

Example 1: An n-type semiconductor material has Hall coefficient and the conductivity 1.19 × 10^{-3} m^3/C and 118 $(\Omega m)^{-1}$ respectively. Calculate charge carrier concentration and electron mobility.

Solution: Given data,

$R_H = 1.19 \times 10^{-3} \frac{m^3}{C}$

$\sigma_e = 118\ (\Omega m)^{-1}$

$n_e = ?$

Here we know that,

$$\mu_e = \sigma_e R_H$$

$$= 118 \times 1.19 \times 10^{-3}$$

$$= 140.42 \times 10^{-3} \frac{m^3}{volt \cdot \sec}$$

For charge carrier concentration

$$\mu_e = \frac{\sigma_e}{n_e e}$$

So,
$$n_e = \frac{\sigma_e}{\mu_e e}$$

$$n_e = 0.52 \times 10^{22} \text{ electrons } /m^3$$

Example 2: A semiconducting crystal with 12 mm long, 5 mm wide and 1 mm thick has a magnetic flux density of 0.5 Wbm^{-2} applied from front to back perpendicular to largest faces. When a current of 20 mA flows length wise through the specimen, the voltage measured across its width is found to be *37 μV*. What is the Hall coefficient of this semiconductor?

Solution:

Given Data,

VH = 37 μV = 37 × 10^{-6} V

Breath of material t = 1 mm = 1 × 10^{-3} m

Specimen current I = 20 mA = 20 × 10^{-3} A

Magnetic flux density B = 0.5 Wb·m^{-2}

Hall coefficient $R_H = \dfrac{V_H \cdot t}{I_H B}$

$$R_H = \frac{\mathbf{37 \times 10^{-6} \times 1 \times 10^{-3}}}{\mathbf{20 \times 10^{-3}} \times 0.5}$$

R_H = 3.7 × 10^{-6} C^{-1} m^3

Multiple Choice Questions

1. Four point probe method is used to determine

(A) Type of semiconductor (B) Hall coefficient (C) temperature

(D) resistivity

2 Type of semiconductor is obtained by ……….

(A) Four probe method (B) UV-Vis spectroscopy (C) two probe method (D) Hall Effect

3. To determine resistivity by van der Pauw method is preferred when sample has…………..

(A) Regular shape (B) rectangular shape (C) arbitrary shape

(D) all of these

4. Hall coeeficient for n-type semiconductor is…….

   (A) Positive (B) negative (C) zero (D) infinity

5. Optical bang gap is obtained by ………….method

   (A) Four probe (B) two probe (C) UV-Vis spectroscopic (D) C-V measurement

6. To obtain the proportion of impurity levels in semiconductor ……method is used

   (A) Four probe (B) DLTS (C) Hall Effect (D) C-V measurement

7. Type of optical transition and band gap can be identified by ……….method

   (A) UV-Vis spectroscopic (B) DLTS (C) Hall Effect (D) C-V measurement