Module 4: Semiconductor Measurements

Introduction:

• Electrical property of the materials is one of the most important properties, which helps to classify the materials. For instance, solids may be classified in terms of their resistivity or conductivity as conductors, semiconductors or insulators.

• The electrical resistivity, an intrinsic property that quantifies how strongly a given material opposes the flow of electrical current, can be measured using several ways depending on the magnitude of the resistance involved in the materials. Two general methods involved for measuring the resistance of the materials are:

• Two-probe method

• Four-probe method

General Introduction:

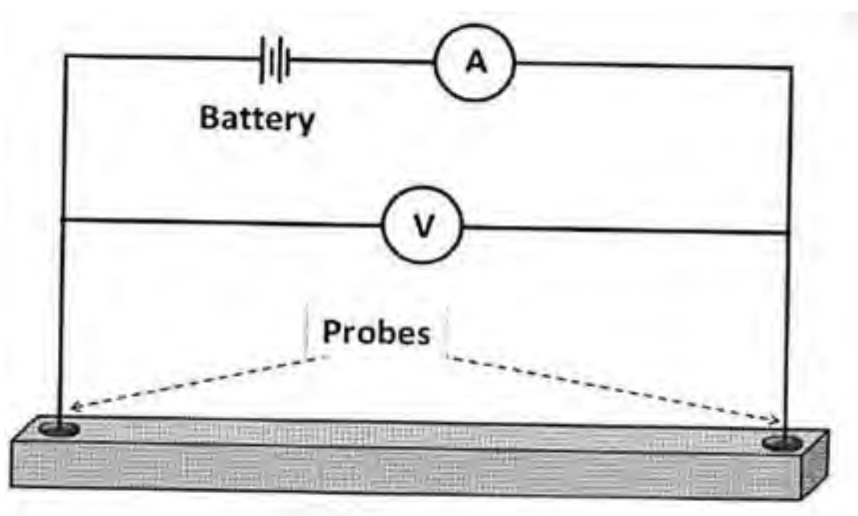
Ohm's law: If physical conditions such as temperature, stress, strain remains unchanged in the materials, then potential difference *(V)* across two ends of a conductor is proportional to current *(I)*flowing through a conductor, i.e.,

$V \propto I$ (or)

$V = I R$

The constant of proportionality, *R*, is called resistance of the material.

1.Two probe Method



For a long sample having uniform cross section, resistivity is generally determined by measuring the potential drop across the sample by passage of known current as shown in figure.Battery supplies current (in through probe 1 and out through probe 2).Let I be the current passing through the sample. Potential difference between two contacts (probe 1 and probe 2)at the end of the sample"V".Then resistance of the sample will be R=V/I.

At a given constant temperature, the resistance *R* of the conductor is (i) proportional to its length *(L)* and (ii) inversely proportional to its area of cross-section *(A)*, i.e.,

$R \propto L / A$ (or)

$R = \rho L / A$

The constant of proportionality, ρ, is called resistivity of the material, which is defined as the resistance offered by a wire of this materials of unit length and unit cross-sectional area.

Units of resistance and resistivity are Ohm (Ω) and Ohm-meter (Ω -m), respectively.

Drawbacks of two probe method.

1. Error due to contact resistance of measuring leads.

2. Above method can be used for material having random shapes.

3. For some of the materials soldering of test leads is difficult.

4. In case of semiconductors, heating of samples due to soldering results in injection of impurities in to the materials thereby affecting intrinsic electrical resistivity.

5. In case of semiconductors, contact between metallic probes and semiconducting samples are not ohmic in nature9rather they are of schottky nature) works as barrier.

2.Four-probe method:

In this method, four probes are utilized to measure the resistance of the samples. For example, two of the outer probes are used to send the current from the source meter and other two inner probes are used to measure the voltage drop across the sample.

The typical set up of the four-probe method is shown in Figure 1. There are four equally spaced tungsten metal tips supported by springs at one end to mount the sample surface without any damage.

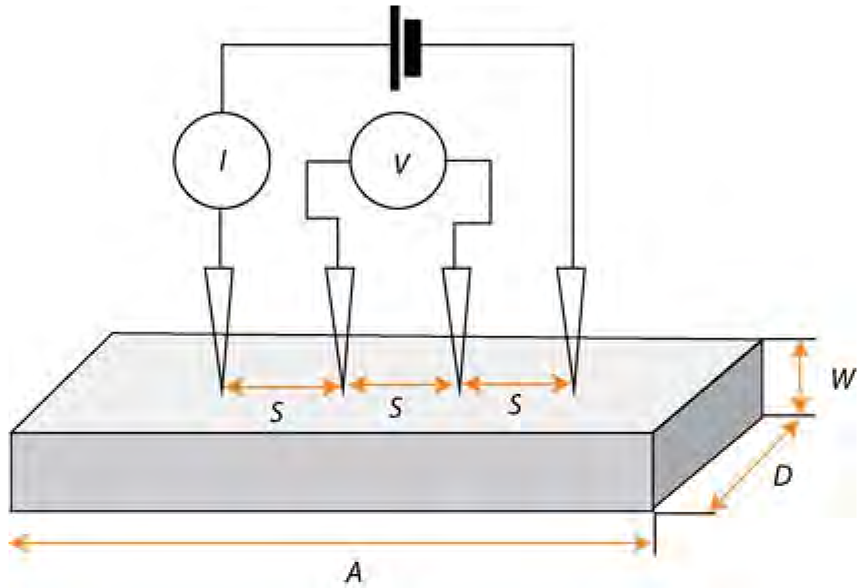


Figure 1: Schematic of four-probe setup.

Four-probe method:A high impedance current source is used to supply current through the outer two probes, which sets up an electric field in the sample. The potential difference developed across the inner probes, which draw no current due to the high input impedance voltmeter in the circuit, is measured through two inner probes.

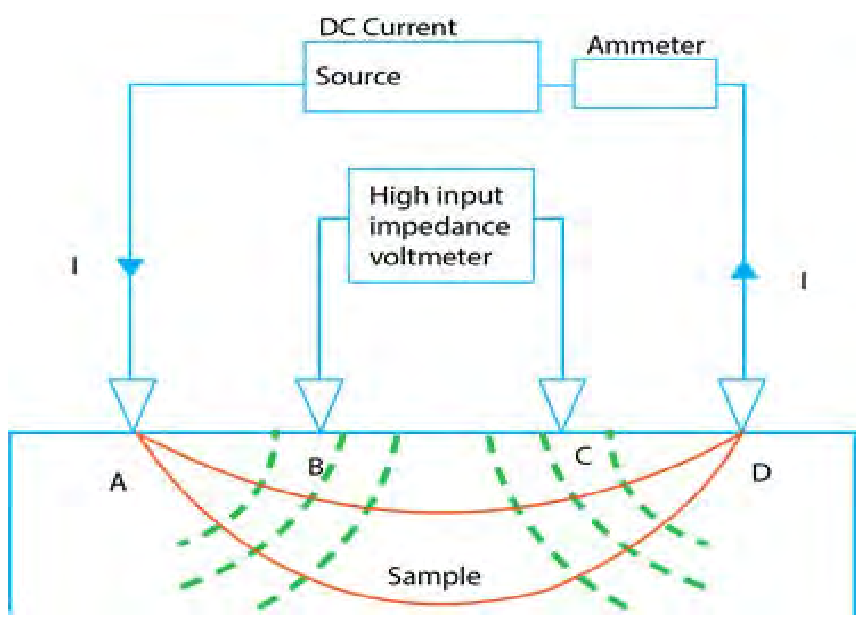


Figure 2: Electric field and equipotential lines in four-probe method

Four-probe method:

Two common techniques used in four-probe method are (i) Four-point collinear probe method and (ii) van der Pauw method.

Four-point collinear probe method:

This is the most common way of measuring the resistivity of a material, which involves four equally spaced probes as shown in Figure 3 in contact with a materials of unknown resistance.

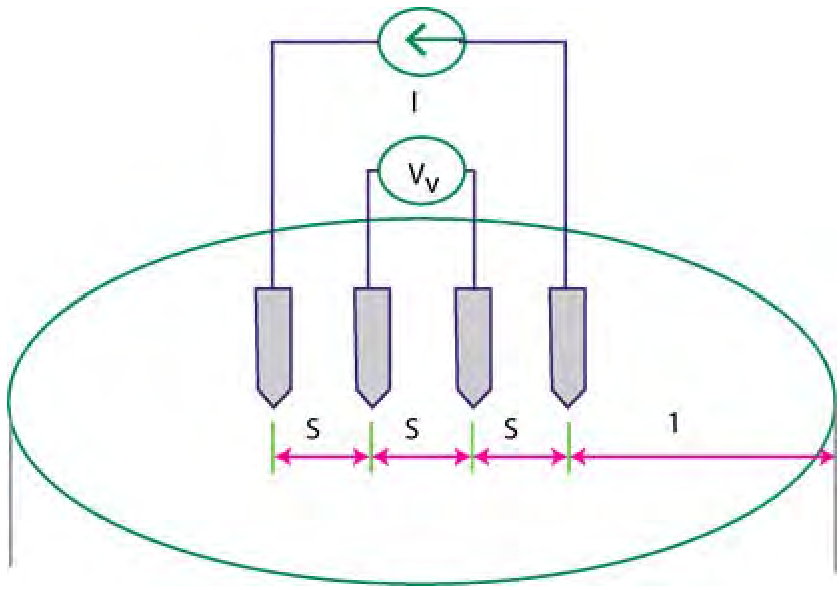


Figure 3: Schematic of four-point collinear probe method.

This method can be used either in bulk or thin film specimen.

Four-point collinear probe method:

For Bulk:

Consider a bulk material as shown in Figure 4, where the thickness (*t*) of the materials is much higher than the space between the probes (s), then the differential resistance due to spherical protrusion of current emanating from the outer probe tips is

$$\Delta R = \rho \left(\frac{dx}{A}\right)$$

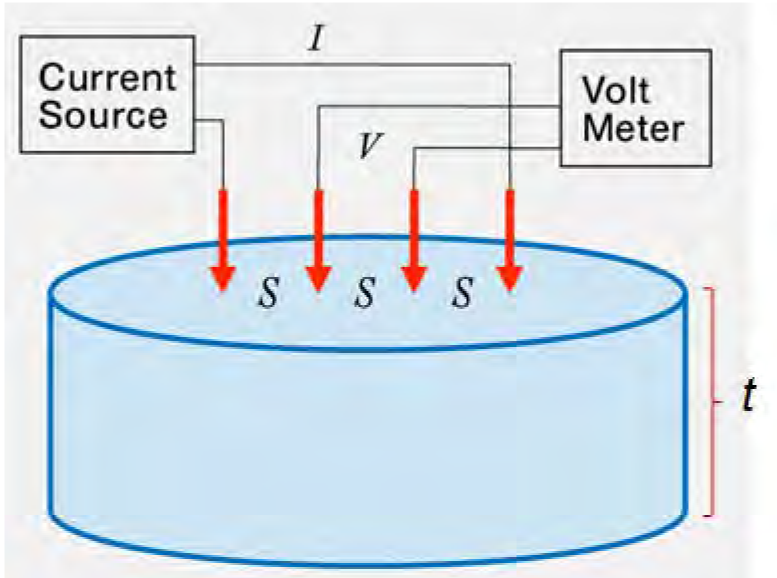


Figure 4: Schematic of four-point collinear probe method on bulk material.

Carrying out the integration between the inner probe tips,

$$R = \int_{v1}^{v2} \rho \frac{dx}{2\pi x^2} = \int_{s}^{2s} \rho \frac{dx}{2\pi x^2}$$

$$R = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Bigg|_{s}^{2s} = \frac{\rho}{2\pi}\frac{1}{2s}$$

where probe spacing is uniform.

Due to the superposition of current at outer tips, $R = V/(2I)$.

Therefore,

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

Four-probe method:

For Thin sheet:

For a very thin layer as shown in Figure 5, where the thickness of the sheet t << the space between the probes, s, we can get current rings instead of spheres. Therefore, the expression for the area is A = $2\pi x.t$. Therefore, the derivation for resistance turns out to be:

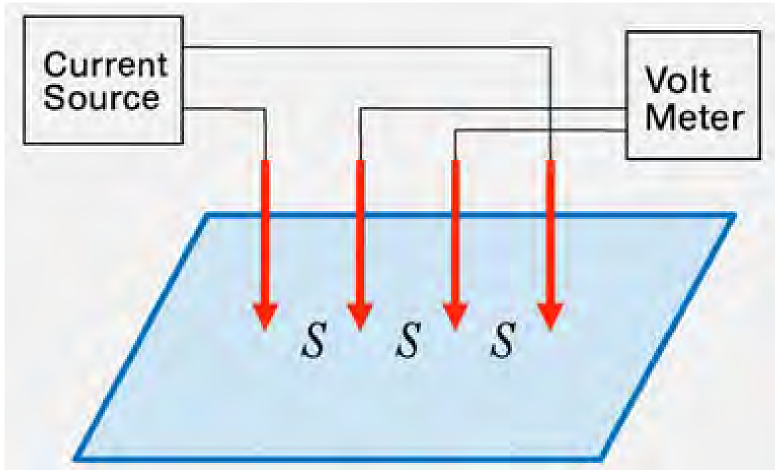


Figure 5: Schematic of four-point collinear probe method on thin sheet.

$$R = \int_{v1}^{v2} \rho \frac{dx}{2\pi x t} = \int_{s}^{2s} \frac{\rho}{2\pi t} \frac{dx}{x}$$

$$R = \frac{\rho}{2\pi t} ln(x)|_{s}^{2s} = \frac{\rho}{2\pi t} ln2$$

Due to the superposition of current at outer tips, $R = V / (2 I)$.

Therefore , the sheet resistivity for a thin sheet is

$$\rho = \left(\frac{V}{I}\right)\left(\frac{\pi t}{ln2}\right)$$

This expression is independent of probe spacing.

Van der Pauw four probe method:

This method involves applying a current and measuring voltage using four small contact on the circumference of a flat, arbitrarily shaped sample of uniform thickness.

The resistivity can be obtained from a total of eight measurements that are made around the periphery of the sample with the configurations as shown in Figure 6.

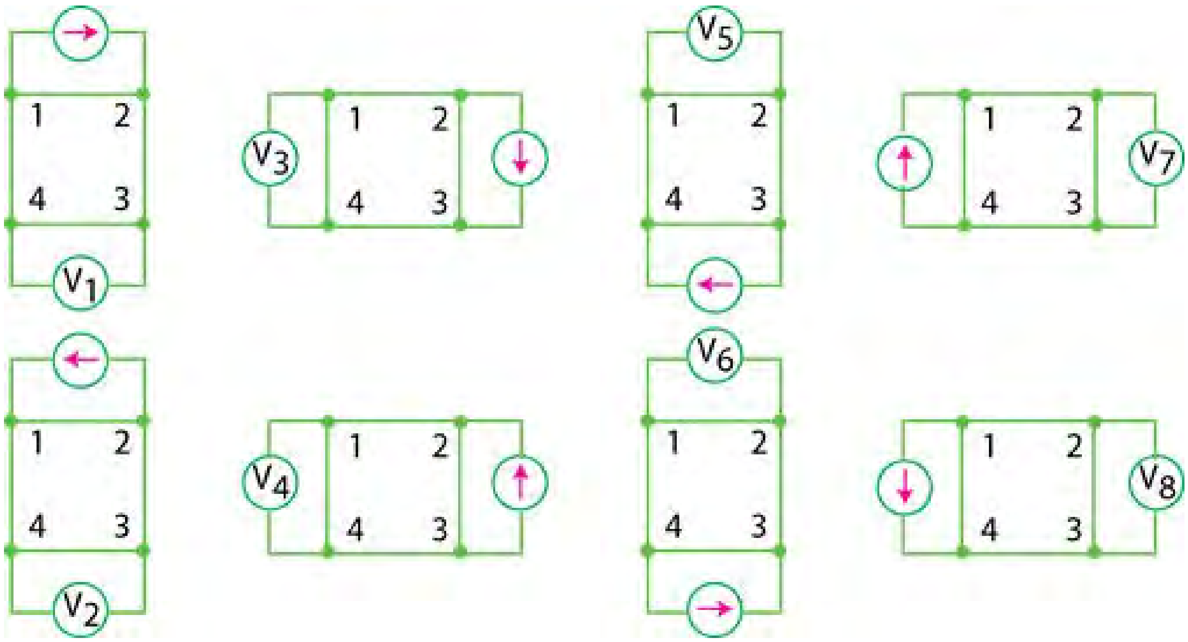


Figure 6: Schematic of different configurations involved in van der Pauw method.

Once all the voltages are taken, two values of resistivity ρ_A and ρ_B can be derived as follows:

Van der Pauw method:

$$\rho_A = \left(\frac{\pi}{ln2}\right) f_A t_s \left[\frac{(V_1 - V_2 + V_3 - V_4)}{4I}\right]$$

$$\rho_B = \left(\frac{\pi}{ln2}\right) f_B t_s \left[\frac{(V_5 - V_6 + V_7 - V_8)}{4I}\right]$$

where ρ_A and ρ_B are volume resistivity in Ohm-cm, t_s is the sample thickness in cm, V_1 to V_8represent the voltages measured by the voltmeter under eight geometrics respectively, I is the current through the sample in amperes.

For a perfect symmetry system, $f_A = f_B \approx 1$ and therefore, the average resistivity turns out to be

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

3.Hall effect:

• This effect discovered by Edwin Hall is the production of a voltage difference across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current.

• The Hall coefficient useful for the determination of the charge carriers and type is defined as the ratio of the induced electric field to the produce of the current density and the applied magnetic field.

• This effect is also useful for the determination of the magnetic field in most of the magnetometers.

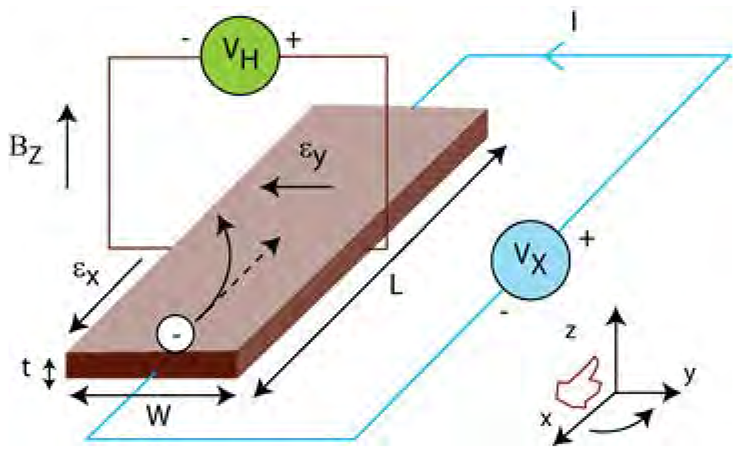


Figure 7 : Schematic of Hall effect set up.

Consider a rectangular bar with thickness, *t*, Length *L*, and width *W*, as shown in Figure 7, and the current *I* flows through the sample in the presence of magnetic field applied perpendicular to the current direction, i.e., along the thickness direction.

Hall effect:

• Under this situation, the magnetic field exerts a transverse force on the moving charge carriers, which tends to push them to one side of the sample as shown in the Figure 6.

• The buildup of the charges at the sides of the sample will eventually balance the magnetic influence, resulting in a measurable voltage difference between the two sides of the conductor. This is called the Hall Effect.

For a simple metal, where there is only one type of charge carrier, the Hall voltage V_H can be computed by setting net Lorentz force to zero.

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) = \boldsymbol{0} \Rightarrow q\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}$$

$$-\boldsymbol{B} \times \boldsymbol{E} = \boldsymbol{B} \times (\boldsymbol{v} \times \boldsymbol{B}) = \boldsymbol{v}B^2 - \boldsymbol{B}(\boldsymbol{v}.\boldsymbol{B})$$

The transverse components of this equation are

$$\boldsymbol{v} = \boldsymbol{E} \times \boldsymbol{B}/B^2 \Longrightarrow E/B$$

Using

$$E = \frac{V_H}{W}; v = \frac{L}{T}; I = \frac{q}{T}; q = nLWte$$

Hall effect:

We get

$$V_H = EW = \frac{vBIT}{nLte} = -\frac{IB}{nte}$$

The Hall coefficient can be found as

$$R_H = \frac{E_y}{J_x B} = \frac{V_H t}{IB} = -\frac{1}{ne}$$

The unit of R_H is expressed as m^3/C. This concludes that the type of charge carrier and its density can be estimated from the sign and the value of Hall co-efficient R_H. It can be obtained by studying the variation of V_H as a function of *I* for a given B.

The above equation also concludes that Hall effect differentiates between positive charges moving in one direction and negative charges moving in the opposite.

Hall effect: Application

Hall effect is also very useful as a means to measure the magnetic field as shown in Figure 8.

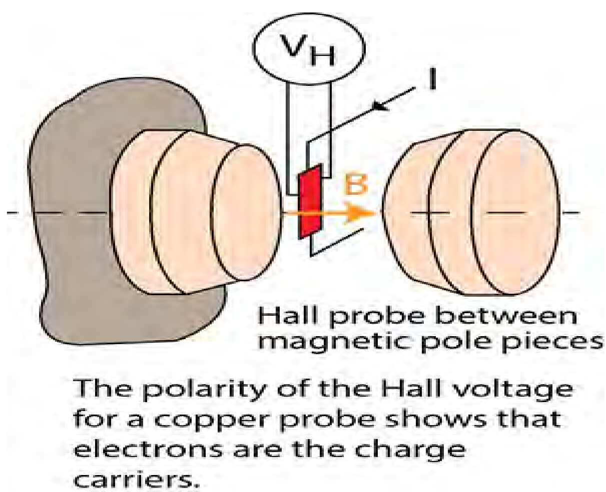


Figure 8 : Application of Hall effect in measuring magnetic field.

The measurement of large magnetic fields on the order of a Tesla in most of the magnetometers such as vibrating sample magnetometer, squid magnetometer is often done by making use of the Hall effect.

A thin film Hall probe as shown in Figure 8, is placed in the magnetic field and the transverse voltage (on the order of microvolts) is measured.

For a given hall probe of 2 μm thickness, the applied current of 1 ampere and magnetic field of 2 Tesla (n = 8.47e28 electrons/m^3) yields the Hall voltage of

$$V_H = \frac{1 \times 2}{8.47 \times 10^{28} \times 1.6 \times 10^{-19} \times 2 \times 10^{-6}}$$

$$V_H = 73.7\ \mu V$$

Hall probe applications:

Recently, the Hall effect has been used in portable electronics:

Open/Close detection:

Laptops, mobile phones, and other portable devices with a rotating hinge and clam-shell design (see Figure 9 ,had historically used mechanical switches to indicate an open or closed position. It is essential to the status of the device as opened or closed to apply power to the sleeping circuitry and for returning the device to the sleep mode to conserve power.

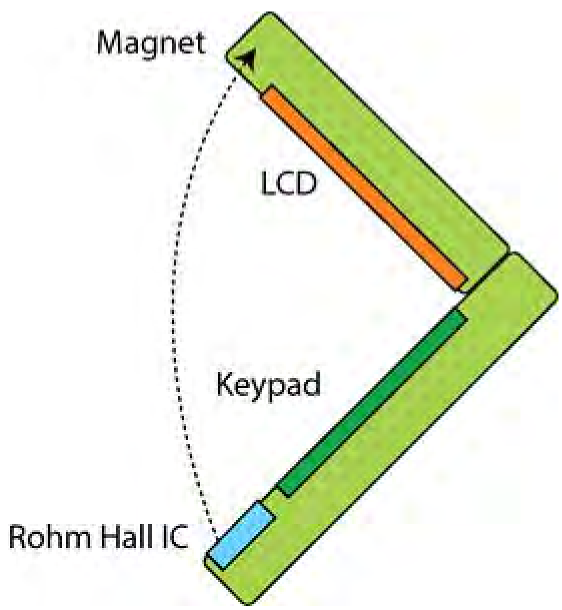


Figure 9 : Application of Hall effect in consumer electronics.

In recent cell phone, digital cameras and other portable instruments, a Hall effect integrated chip (IC) switch and magnet combination is used. The IC is often a unipolar Hall effect IC, which operates when a magnetic field of sufficient strength and polarity is detected.

Similarly, Omni polar Hall effect IC switches capable of detecting a magnetic field of either polarity can also be used. Unipolar devices typically require less power to operate but the magnet must be properly oriented, while Omni polar devices operate without regard to magnet orientation.

Detecting the Semiconductor Conductivity Type

Assume we have a piece of semiconductor and we want to detect whether it is n-type or p-type. This can be achieved by several techniques such as the hot probe method or the Hall coefficient measurement method.

4. Hot Probe Method

Thermoelectric power of a semiconductor is positive for p-type and negative for n-type. Using this property, we can determine the type of a semiconductor material by the hot probe method. The hot-probe experiment provides a very simple way to distinguish between n-type and p-type semiconductors using a simple soldering iron and a standard galvanometer.

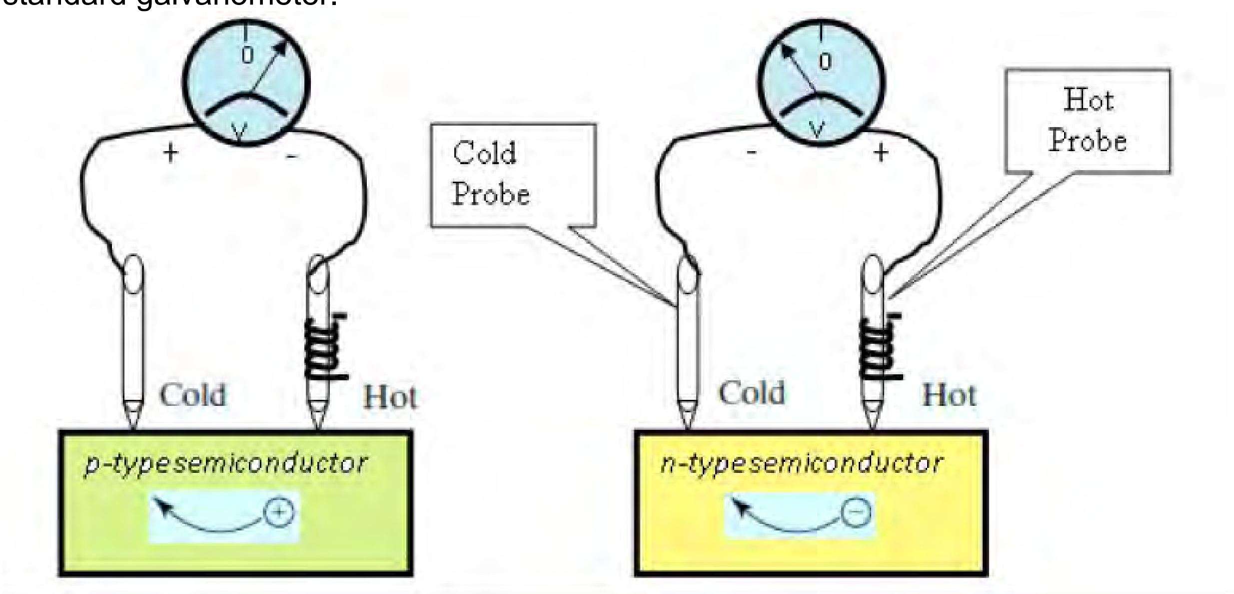


Figure 10: Schematic of the hot probe method

The experiment is performed by contacting the semiconductor wafer with a hot probe, such as a heated soldering iron, and another cold probe. Both probes are wired to a zero-centered galvanometer. The hot probe is connected to the positive terminal of the meter while the cold probe is connected to the negative terminal. The experimental set-up is illustrated in the figure 9. The hot probe heats the semiconductor beneath it so that the kinetic energy of free carriers in this region is increased. Therefore, the carriers diffuse out of the hot region faster than they diffuse into this region from the adjacent low-temperature regions. If the semiconductor is n-type, electrons will move from the hot probe leaving a positive charge region, and the hot probe becomes positive with respect to the cold probe. Then, the current will flow from the hot probe to the cold probe. In a *p-type* semi-conductor, the direction of the current flow is reversed. So, the polarity of the hot probe indicates whether the semiconductor is *n-* or *p-type.*

5.Capacitance-voltage Measurement.

The MOS capacitor structure is shown in Figure 10. The “metal” plate is a heavily doped p^+ - poly-silicon layer which behaves as a metal. The insulating layer is silicon dioxide and the other plate of the capacitor is the semiconductor layer which in our case is n-type silicon whose resistivity is 1-10 Ω-cm corresponding to a doping of 10^{15} cm^{-3}.

The capacitance of the MOS structure depends on the voltage (bias) on the gate. For the purposes of this discussion, we shall refer to the contact to the semiconductor as the body (B) while the poly-silicon is called the gate (G). Typically a voltage is applied to the gate while the body is grounded and the applied voltage is V_G but more accurately V_{GB}.

Capacitance-voltage (C-V) testing is widely used to determine semiconductor parameters, particularly in MOSCAP and MOSFET structures.

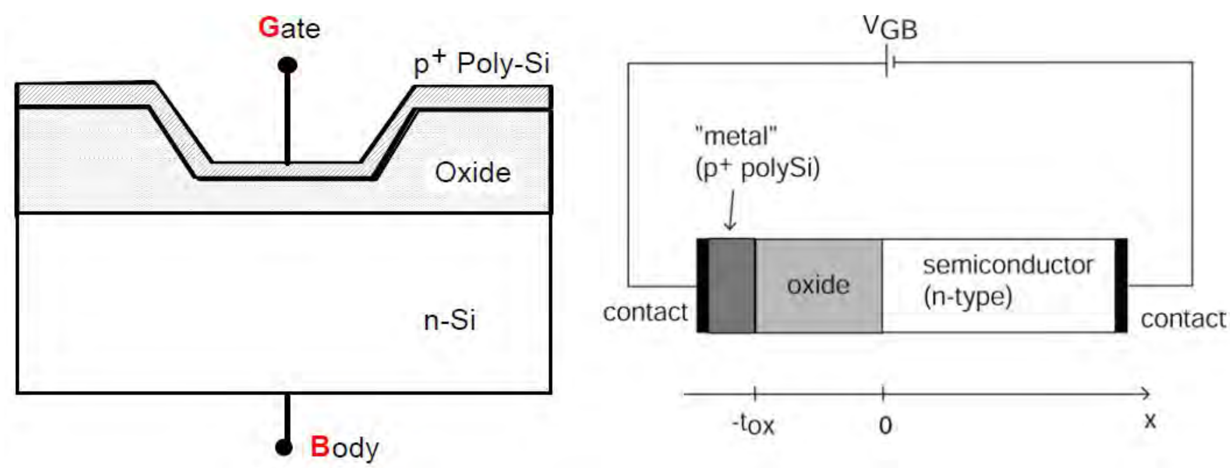


Figure 10: The MOS Capacitor structure. The substrate (body) is grounded and a voltage V_{GB} is applied to the poly-silicon gate.

The Physics of Semiconductor Capacitance

The metal/polysilicon layer shown in Figure 10 is one plate of the capacitor, and silicon dioxide is the insulator. Since the substrate below the insulating layer is a semiconducting material, it is not by itself the other plate of the capacitor. In effect, the majority charge carriers become the other plate. Physically, capacitance, C, is determined from the variables in the following equation:

$C = A (\kappa/d)$,

where A is the area of the capacitor,

κ is the dielectric constant of the insulator, and

d is the separation of the two plates.

Therefore, the larger A and κ are, and the thinner the insulator is, the higher the capacitance will be. Typically, semiconductor capacitance values range from nanofarads to picofarads, or smaller.

The capacitance depends on the voltage that is applied to the gate (with respect to the body). The dependence is shown in Figure 2 and there are roughly three regimes of operation separated by two voltages. The regimes are described by what is happening to the semiconductor surface. These are

(1) **Accumulation** in which carriers of the same type as the body accumulates at the surface

(2) **Depletion** in which the surface is devoid of any carriers leaving only a space charge or depletion layer, and

(3) **Inversion** in which carriers of the opposite type from the body aggregate at the surface to "invert" the conductivity type. The two voltages that demarcate the three regimes are (a) **Flatband Voltage** (V_{FB}) which separates the accumulation regime from the depletion regimes and (b) the **Threshold Voltage** (V_T) which demarcates the depletion regime from the inversion regime(figure 11).

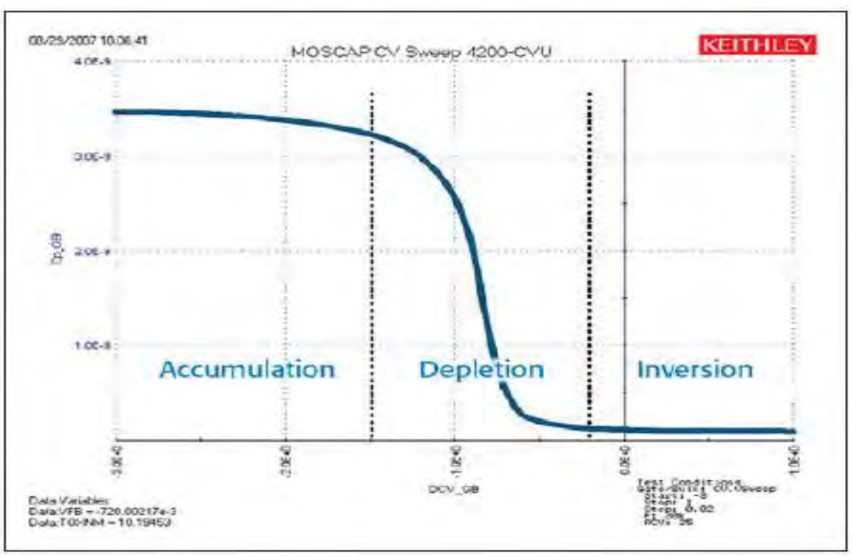


Figure 11. DC bias sweep of MOSCAP structure obtained during C-V testing.

6. Ultraviolet/ Visible Spectroscopy

The absorption spectroscopy employs electromagnetic radiations between 190 to 800 nm. Since the absorption of ultraviolet or visible radiation by a molecule leads transition among electronic energy levels of the molecule, it is also often called as electronic spectroscopy. When sample molecules are exposed to light having an energy ($E = h\nu$ where 'E' is energy in joules, 'h' is Planck's constant 6.62×10^{-34} J s and 'ν' is frequency in Hertz), that matches a possible electronic transition within the molecule, some of the light energy will be absorbed as the electron is promoted to a higher energy orbital. An optical spectrometer records the wavelengths at which absorption occurs, together with the degree of absorption at each wavelength. The resulting spectrum is presented as a graph of absorbance (A) versus wavelength (λ). The optical properties of materials can be studied with the help of UV - Vis spectra.

UV Absorption

UV-absorption can be analyzed when a beam of light is passing through the sample and it is reflected from the surface of the sample. UV-absorption forms at a single or a wide range of spectral wavelengths. During the transition of electrons the excitation takes place to higher energy levels. UV-Visible is used to identify inorganic complexation of molecules and their qualitative and quantitative measurements.

The main role for UV-Visible is to identify the properties of optical and electronic materials and to characterize the absorption, transmission, and reflectivity materials.

UV-Visible Spectra:

In a semiconductor material the charge carriers is generated by optical photons. The absorption takes in any material due to the fallowing aspects

i). Charge carriers electrons

ii). Valence band electrons

iii). Excitation of electrons

iv). Inner shell electrons

The valance band in a semiconductor is fills with electrons, such that the excitation takes place to higher energy levels during the absorption process. As the photon energy in a semi conducting materials the quantization of energy tends to transfer of electrons from valence band to conduction band.

The optical absorption takes place in semiconductors and depends on the important points which are given below.

i). The electronic transitions of elements are constant

ii). The absorption and emission process are under consideration.

UV-visible Spectroscopy is used for identify the energy band gap values of the materials in the transmitting radiation. In an energy level a photon is absorbed in its orbit. When an electron is jumps from lower energy level to higher energy level. Transitions takes place in a band gap energy as it rise in the absorption process called as absorption edge, where the optical band gap energies be determined.

<u>Working of UV - vis Spectrophotometer</u>

- UV - Vis spectrophotometer consists of five components namely source, monochromator, sample holder (cuvette), detector and signal processor.
- Figure 12 shows the functional block diagram of UV - Vis Spectrometer. The light source is usually a deuterium discharge lamp for UV measurements and a tungsten – halogen lamp for visible and NIR measurements.
- The instrument automatically lamp swaps when scanning between the UV and visible regions. UV and visible light from the source enters the monochromator through entrance slits. The beam is collimated to strike the dispersing element at an angle. The beam is split into its component wavelengths by the grating or prism. By moving the dispersing element or the exit slit, radiation of only a particular wavelength is allowed to leave through the exit slit.
- This monochromatic light passes through a set of mirrors resulting in splitting of monochromatic beam into two halves. One half of the beam passes through the sample and other half of the beam passes through the reference. Sample and reference are kept in a transparent quartz cuvette.

- The faces of these cuvettes through which the radiation passes are highly polished to keep reflection and scatter losses to a minimum. The two beams after passing through the sample and reference falls on the detector.
- Photomultiplier tube is the most commonly used detector, which amplifies the resulting spectrum. The detector is connected to a computer to obtain the desired output.

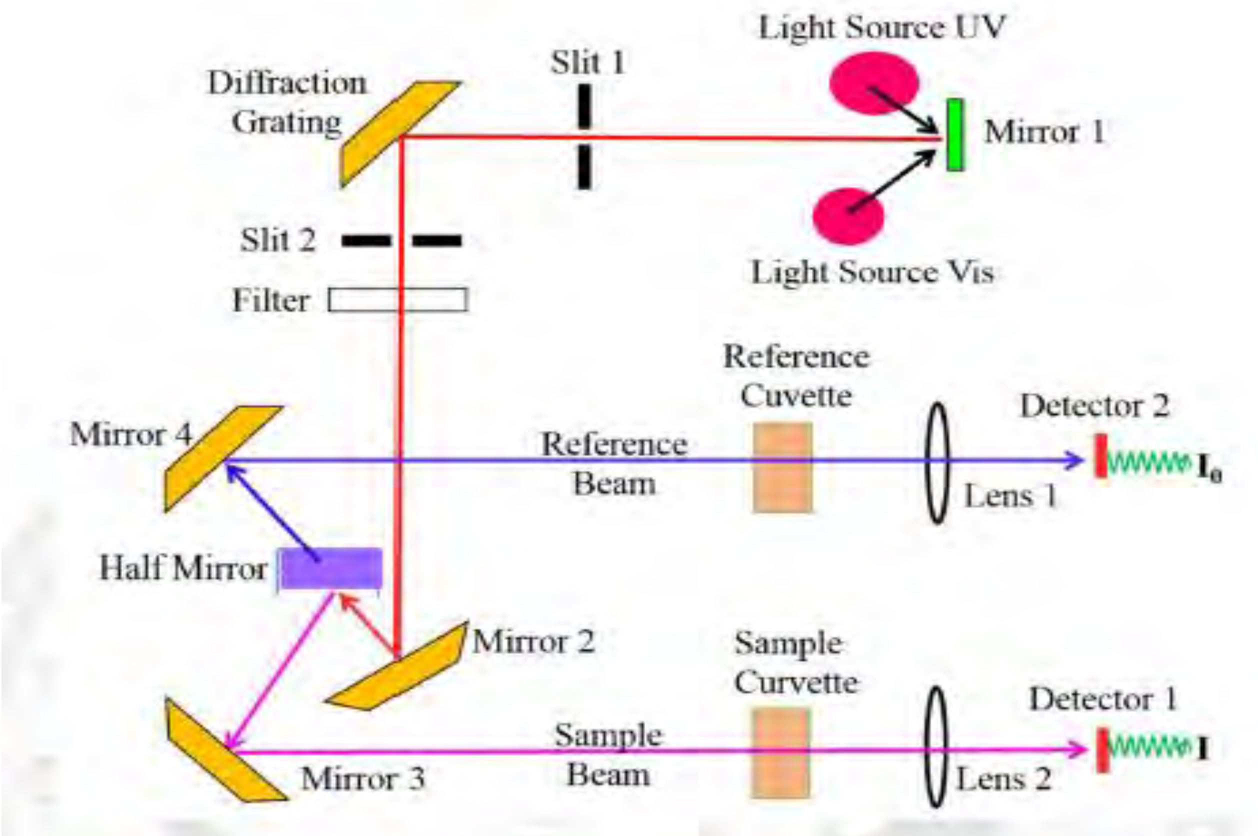


Fig 12. The working principal of UV-Visible spectra

7.Deep Level Transient Spectroscopy (DLTS)

- DLTS is an experimental tool for studying electrically active defects (for e.g charged carrier traps) in semiconductors.
- DLTS enables to establish fundamental defect parameters (some considered as defect “finger prints”) and measure their concentration in the material.
- DLTS has a higher sensitivity than almost any other semiconductor diagnostic technique.
- DLTS technique was pioneered by David Vern Lang of Bell Laboratories in 1974
- Semiconductor junction (p-n diode or Schottky diode) is a subject to the voltage pulse at different temperatures
- Capacitance transients are monitored and spectrum is generated which exhibits peaks for each deep levels
- The height of the peak is proportional to the trap density; sign distinguishes minority from majority traps; position of the peak determine the fundamental

parameters governing thermal emission and capture (activation energy and cross section)

- Application of the method has led to the discovery of new phenomena and has provided a unique tool for the understanding of materials processing for semiconductor devices.
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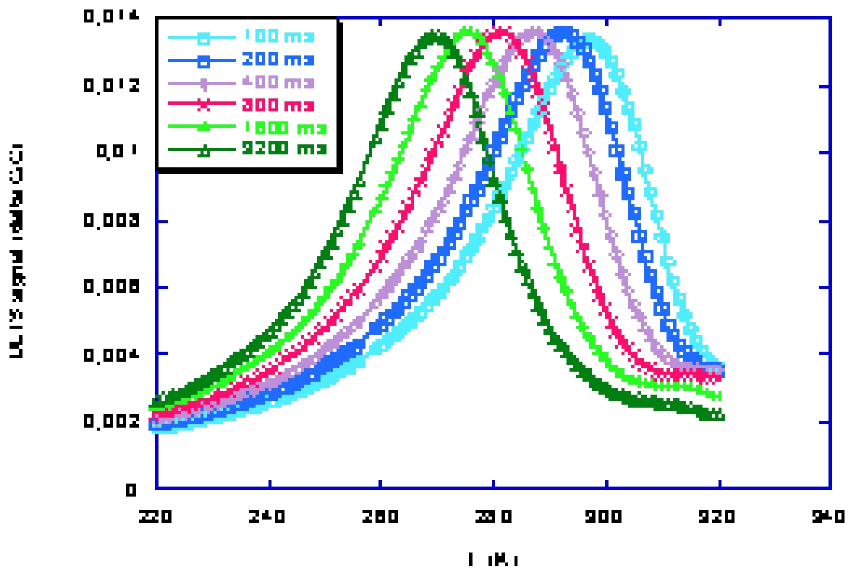
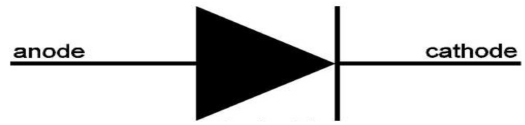


<u>8. Parameter extraction from diode I-V characteristics</u>

A semiconductor diode is a non-linear device whose most outstanding feature is the fact that, basically, current is only allowed to flow in one direction. The diode is built by joining together two semiconductor materials: an N-type material (rich in negative carriers or free electrons) and a P-type material (rich in positive carriers or holes). The area of contact is called the junction. For this reason the diode is commonly referred to as a **PN Junction**.

When an applied voltage forces the diode to conduct electrons from the anode to the cathode it is operating in a **forward bias** condition. When the applied potential does not allow for a sharp increase in current and only a minimal amount, practically zero, of current is observed across the junction, the diode is said to be in a **reverse bias** condition. When forward biased the diode behaves much like a closed switch, and when reverse biased the diode behaves like an open switch.

The following schematic symbol is used to represent a diode:



The anode represents the P-type material and the cathode is the N-type material of the junction.

Diode Operation

The operation of a diode is controlled by the diode's current-voltage (I-V) characteristics. A diode in a circuit with the positive potential (highest) connected to the P material and the negative potential connected to the N material is forward biased. A diode whose highest potential is connected to the N material and the lowest potential to the P material is reverse biased.

The following figure shows the forward and reversed biasing of a diode connected to a circuit.

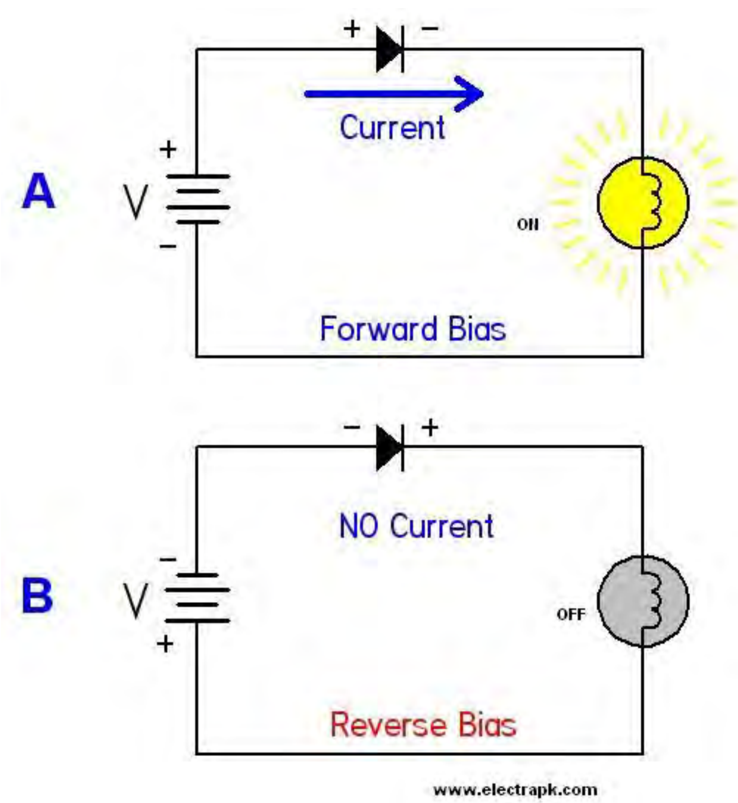
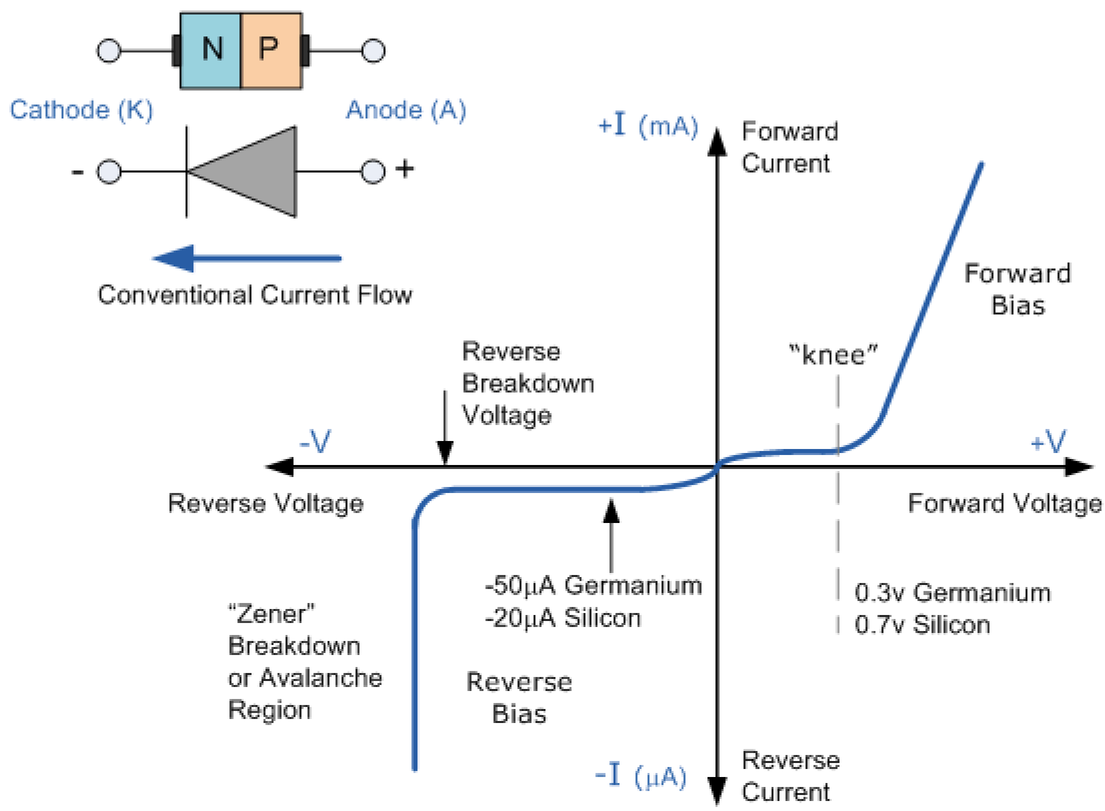


Image Credit: Electrapk

Diode Characteristics

The typical I-V characteristics of a diode are illustrated by the following figure. There are two operating regions that are clearly labeled: the forward bias region and the reverse bias region. Two scales are used along each axis to depict the varied response of the diode both in the positive and negative directions. A forward biased current in this particular I-V curve is expressed in milli-amps (mA), whereas in the reverse bias region the current is expressed in micro-amps (μA). The main features of these two operating conditions are explained below.



Forward Bias Region

In the forward bias region there exist two important areas to distinguish in relation to the amount of current observed through the diode. The first area is when there are low levels of diode voltage (V_D) and the associated current is very small. The second area is when the diode voltage (V_D) is greater than the threshold voltage (V_{thr}), and the current increases abruptly.

Diode Voltage is <V_{thr} - For any diode voltage (V_D) between zero and (V_{thr}) the current is very small. In general, as an approximation, we may consider this current to be zero.

This means that in this range the diode behaves like an open switch, or like a device with a very high resistance.

Diode Voltage is ≥ V_{thr} - For any diode voltage (V_D) greater than (V_{thr}) the current increases abruptly. In general, as an approximation, we may consider the resistance to be zero. This means that in this range the diode behaves like a closed switch.

The response to an applied voltage in the forward bias region is controlled by the diode's threshold voltage, which is dependent on the type of material the diode is built with. A silicon diode has an approximate value of V_{thr} = 0.7 V, and a germanium diode has an approximate value of V_{thr} = 0.3 V.

Reverse Bias Region

In the reverse bias region there also exists two important areas that can be distinguished in relation to the amount of the current observed through the diode. The current through the diode is very small, practically zero, when the diode voltage is between zero and the breakdown voltage (V_{BD}). Beyond the breakdown voltage (V_{BD}) there is an abrupt increase in current, which marks the second area of interest in the reverse bias region.

Diode Voltage is < V_{BD} - In this area the current is very small. We call this current the leakage current. In practical applications you may consider it to be zero. Thus, in this area the diode behaves like an open switch, or like a device with a very large resistance.

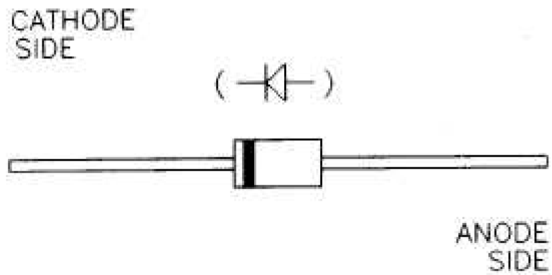
Diode Voltage is ≥V_{BD} - In the breakdown region the current increases very fast as a function of the diode voltage. The diode behaves like a closed switch, or like a device with a very small resistance. Notice that the diode voltage in this case is very close to V_{BD} for practical applications, for any source voltage.

The breakdown voltage is not a constant value like the threshold voltage in forward bias. V_{BD} is different for each diode. This value is a specification parameter given by the manufacturer.

Diode Identification

The schematic symbol used for the diode is typically an arrow with a short line across the tip. The cathode is the N-type material and is represented by the tip of the arrow. The anode is the P-type material and is indicated by the base of the arrow.

Manufacturers may use diverse methods to indicate the anode and the cathode of the diode. In the most common method the cathode (N-type material) is identified with a colored band. Thus, the end of the diode closest to this band is the cathode. The other end is the anode (P-type material.)



Diode Specifications

The important specifications of diodes depend on the type of diode and its applications. In what follows we list the most important specifications for all types of diodes.

Forward voltage (VF) is the voltage across the diode terminals resulting in a sharp increase of current in the forward direction.

Forward current (IF) is the current when the forward voltage is applied; it flows through the diode in the direction of lower resistance.

Reverse current (IR) or leakage current, is the current value when the reverse voltage is applied. This is the current that flows when reverse bias is applied to a semiconductor junction.

Reverse voltage (VR) is the maximum allowable reverse voltage that can be applied repeatedly.

Breakdown voltage (VBR) is the reverse voltage at which a small increase in voltage results in a sharp rise of reverse current.

Power Dissipation (PD) is the maximum permissible power dissipation per output (in W) of the diode at specified ambient temperature. Power dissipation is the power dissipated by the diode while in the ON state.

Junction operating temperature (Tj) is the range of temperatures at which a diode is designed to operate.