

**18PYB103J**

**SEMICONDUCTOR PHYSICS**

**MODULE 4**

**LECTURE 1 – CONCEPT OF ELECTRICAL  
MEASUREMENTS, TWO PROBE METHOD**

# CONCEPT OF ELECTRICAL CONDUCTIVITY

## Electrical Measurements:

- **Measurements** of **electrical** quantities, such as voltage, impedance, current, AC frequency and phase, power, **electric** energy, **electric** charge, inductance, and capacitance
- **Electrical measurements** are among the most widely performed types of **measurement**.
- The resistivity measurements can be studied by different techniques

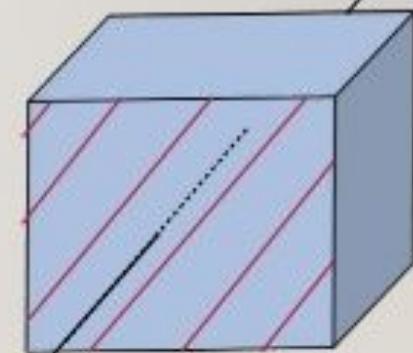
# Concept of Resistivity

## □ TO UNDERSTAND THE CONCEPT OF RESISTIVITY

- Measure of the resisting power of a specified material to the flow of an electric current.
- Resistivity is commonly represented by the Greek letter  $\rho$  (rho).
- The SI unit of electrical resistivity is the ohm-meter ( $\Omega \cdot m$ )

$$\text{Resistivity } \rho = R(A/L)$$

Material	Resistivity, $\rho$ ( $\Omega \cdot m$ )
Superconductors	0
Metals	$10^{-8}$
Semiconductors	Variable
Electrolytes	Variable
Insulators	$10^{16}$
Super insulators	$\infty$



# CONCEPT OF ELECTRICAL CONDUCTIVITY

- 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)
  - $V = IR$
- The constant of proportionality,  $R$ , is called resistance of the material.

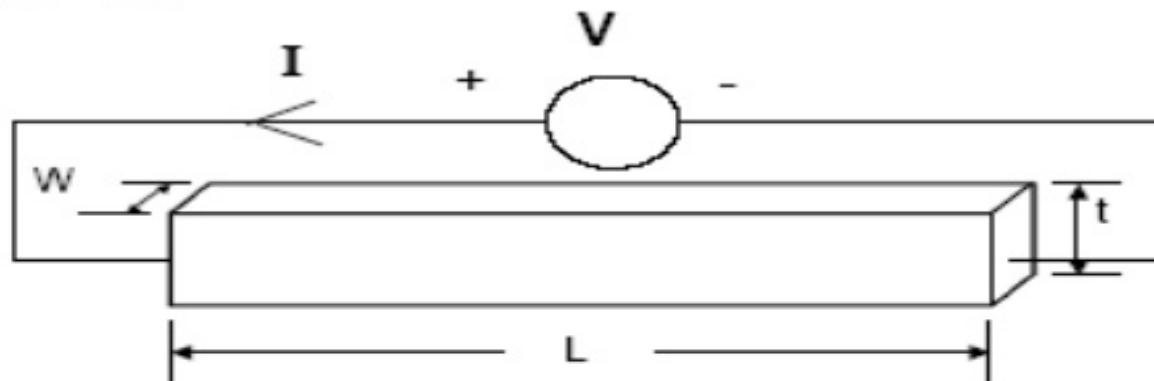
# CONCEPT OF ELECTRICAL RESISTIVITY

- Resistivity:
- 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) 
$$R = \rho L / A$$
- Resistivity is important for devices because it contributes to the device series resistance, capacitance, threshold voltage, hot carrier degradation of MOS devices, latch up of CMOS circuits, and other parameters.

# RESISTIVITY MEASUREMENTS

## Measurements

### Resistance:



$$R = \rho L / (W t) \text{ where } \rho = \text{resistivity}$$

***Sheet Resistance*** (in ohms/square)

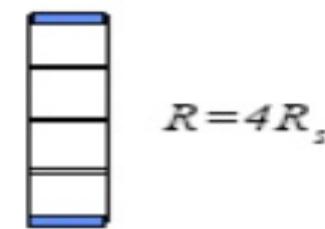
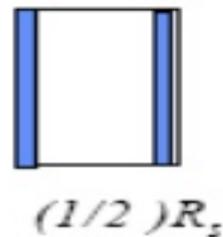
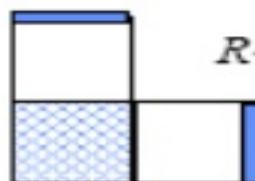
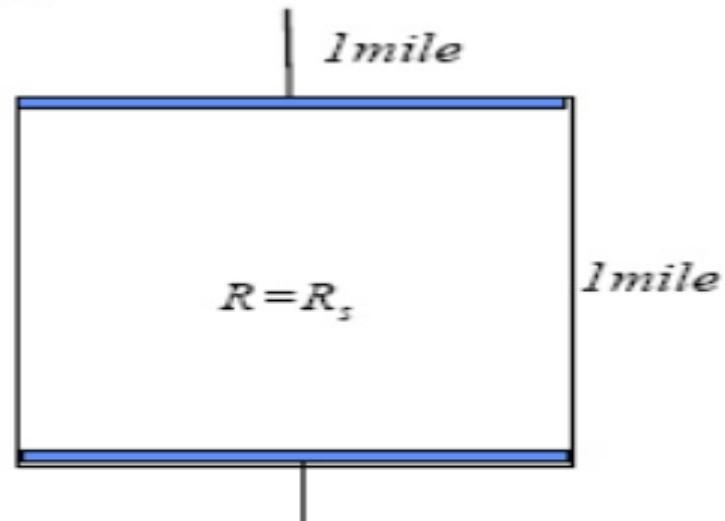
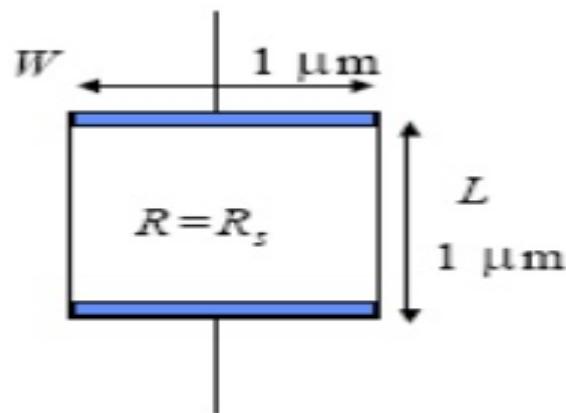
$R_s = \rho / t$  is the resistance when  $W = L$

# RESISTANCE AND SHEET RESISTANCE

## Measurements

### Resistance and Sheet Resistance:

$$R = R_s \cdot \frac{L}{W}$$



# RESISTIVITY MEASUREMENTS

## Measurements

**Resistivity of a semiconductor is given by**

$$\rho = \frac{1}{q\mu_n n + q\mu_p p} \text{ } \Omega\text{cm}$$

**In the case of four point probe,**

**When  $t \ll s$ , as in the case of diffusion or implant layer,**

$$\rho = 4.532 \frac{V}{I} x_j \text{ } \Omega\text{cm}$$

**Sheet Resistance,**

$$R_s = \frac{\rho}{x_j} = 4.532 \frac{V}{I} \text{ } \Omega/\text{square}$$

# METHODS FOR MEASURING RESISTANCE

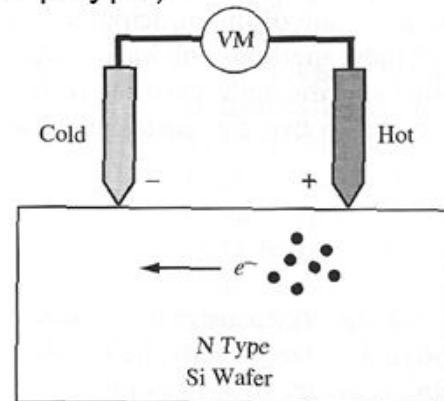
- Two general methods involved for measuring the resistance of the materials are:
  - (i) Two point probe method
  - (ii) Four point probe method
- linear method & Vander pauw method

# TWO PROBE METHOD

## ***2-point probe***

Useful to determine material type (n- or p-type)

- Apply two probes, one 25 – 100 °C hotter than other
- Thermally excited electrons flow away from hot probe, leaving holes and build up around cold electrode
- Measure Seebeck voltage using high impedance volt meter
- If material is p-type polarity will be reversed



We can measure either short circuit current or open circuit voltage. Current for an n-type material is:

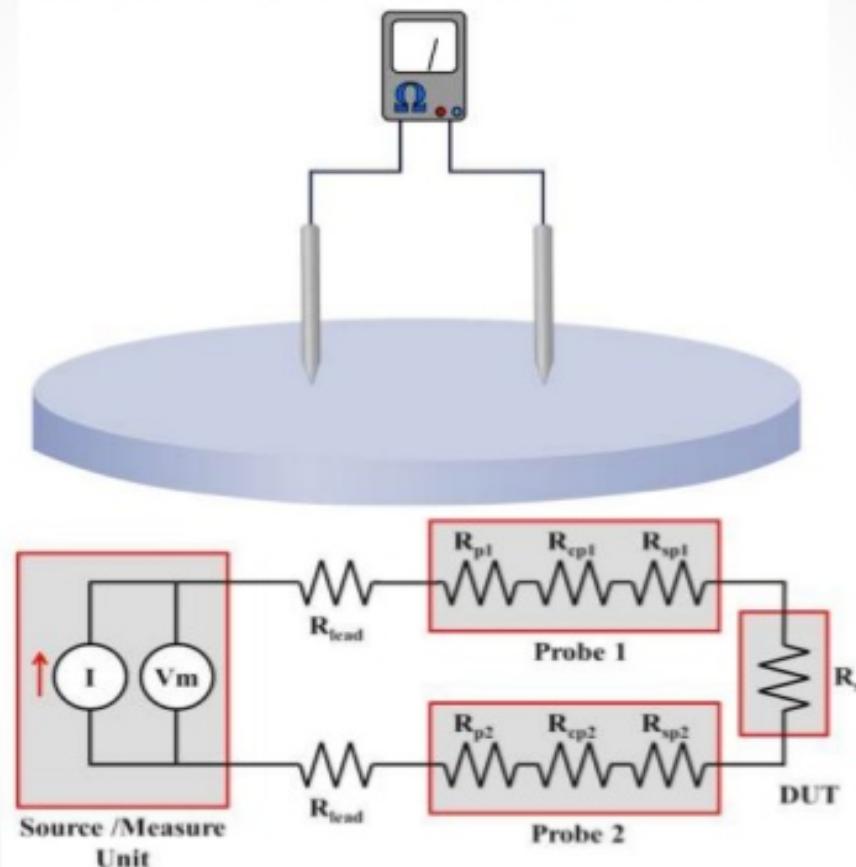
$$J_n = q\mu_n n P_n dT/dx$$

$P_n$  is thermoelectric power, either (-) for  $e^-$  or (+) for  $h^+$

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# TWO PROBE METHOD

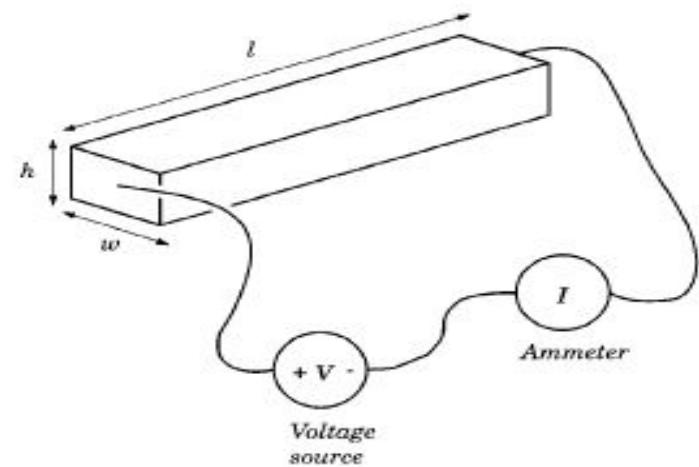
## Two Probe Measurement



# TWO PROBE METHOD

The resistivity of the bar can be measured by measuring voltage drop across the wire due to passage of known current supplied by the battery  $E$  through the probes 1 and 2. The potential difference ( $V$ ) between the two contacts at the ends of the bar can be measured by a voltmeter. Therefore, the resistivity of the wire is, i.e.,

$$\rho \equiv \frac{Rwh}{I}$$



# TWO PROBE METHOD

- While the two-probe method is a simple and advantageous method for measuring resistance above  $1\Omega$  directly, this method suffers from certain issues.
- Two-probe method:  
Error due to contact resistance of the measuring leads

# TWO PROBE METHOD

- 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.



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**SEMICONDUCTOR PHYSICS**

**MODULE 4**

**LECTURE 2 – FOUR POINT PROBE METHOD  
LINEAR METHOD, VAN DER PAUW METHOD**

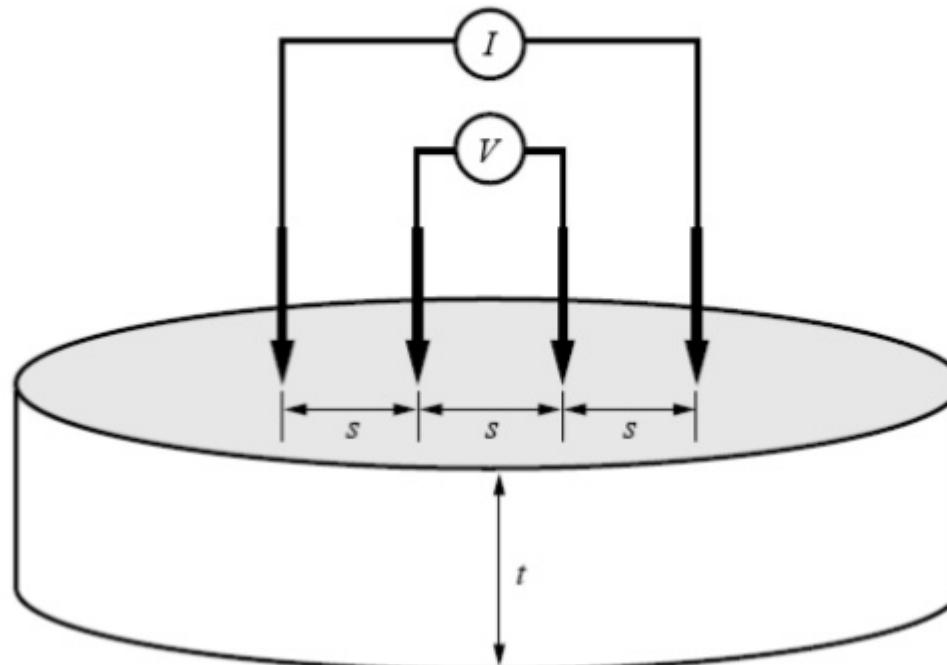
# FOUR POINT PROBE METHOD

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

## Measurements

### **Four Point Probe:**

**To determine the Resistivity / Sheet Resistance of semiconductors**



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

## 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, in contact with a materials of unknown resistance.
- This method can be used either in bulk or thin film specimen.

# Four-probe method:

- This method provides the measurement of the resistivity of the specimen having the wide variety of shapes but with uniform cross-section.
- The soldering contacts proposed in two-probe method are replaced by pressure contacts
- 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.

# FOUR PROBE METHOD-RESISTIVITY

- Current is most commonly passed between the outer two probes, and the voltage difference is measured between the two inner probes. Resistivity in a four-point probe measurement is given by

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

- Where

s is the distance between two probe

F represents the correction factor

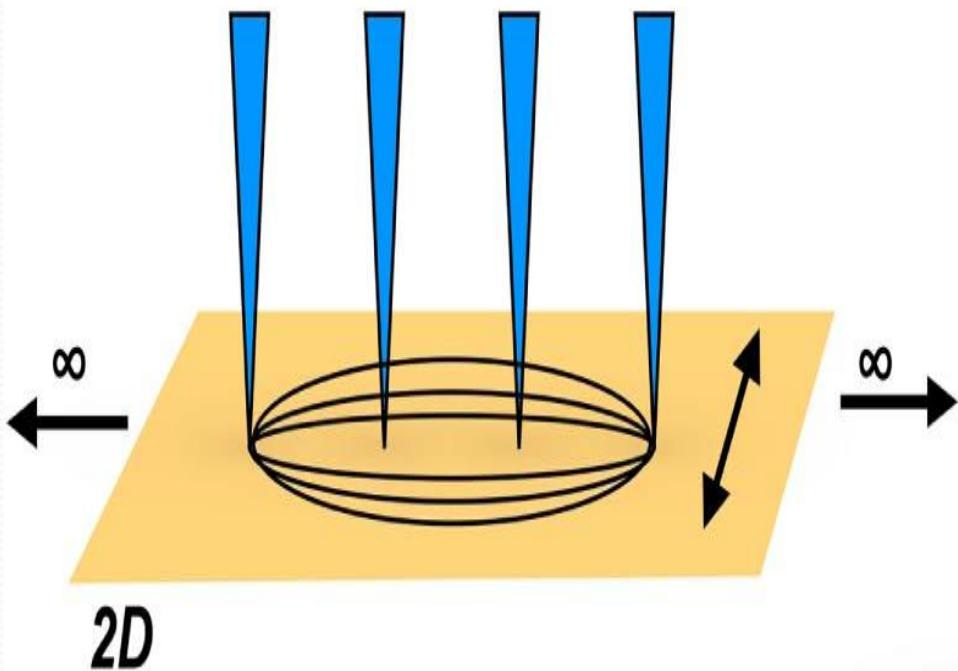
- $F = F_1 F_2 F_3$
- $F_1$  corrects for sample thickness,
- $F_2$  for lateral sample dimensions,
- $F_3$  for placement of the probes relative to the sample edges.

# Four-probe method

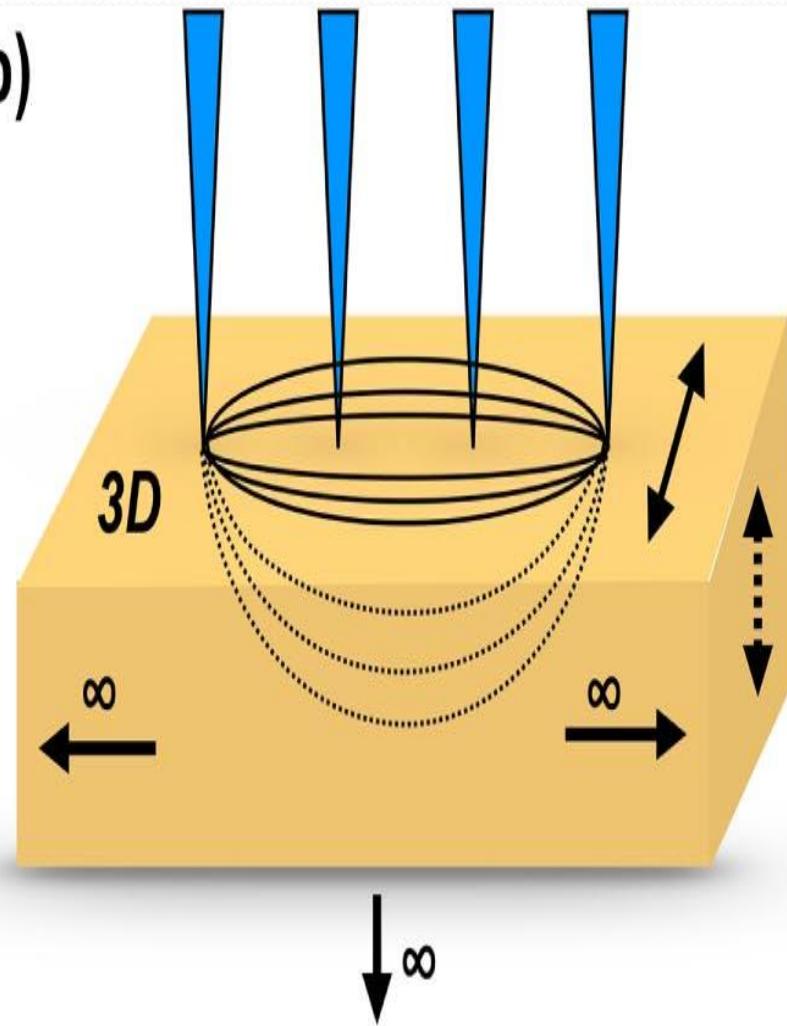
- In this method, four probes are utilized to measure the resistance of the samples. For example, two of the outer probes are used to send the current from the source meter and other two inner probes are used to measure the voltage drop across the sample.
- The typical set up of the four-probe method is shown in Figure. There are four equally spaced tungsten metal tips supported by springs at one end to mount the sample surface without any damage.

# FOUR PROBE MEASUREMENT IN 2D AND 3D MATERIALS

(a)



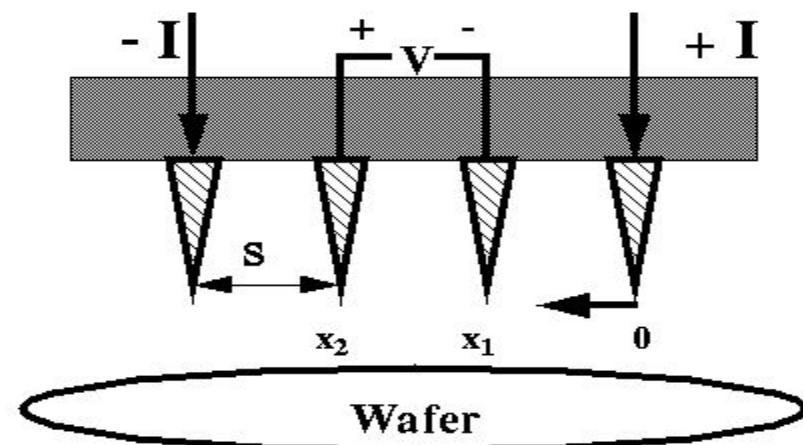
(b)





# How the system works

- In order to measure the resistivity of a substance, four points of contact must be made with the probe and the substance.
- Current goes through the two outer probes, and the difference in voltage is measured between the two inner probes.
- Through this process the resistance can be calculated.



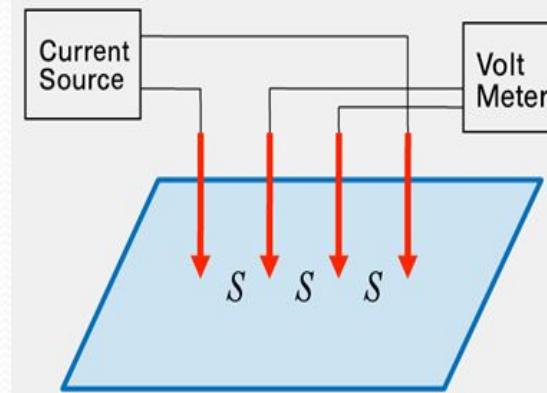
# Four-probe method: For Thin sheet:

## Four-probe method: For Thin sheet:

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

where probe spacing is uniform. Due to the superposition of current at outer tips,  $R = V / (2I)$ .  
Therefore,

$$\rho = \frac{Vt\pi}{I \ln 2}$$



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

# FOUR PROBE EXPERIMENTAL METHOD

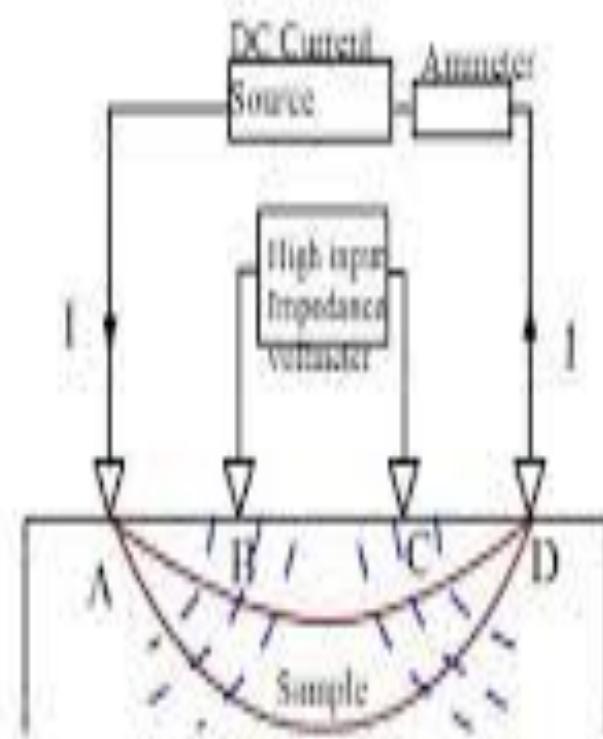
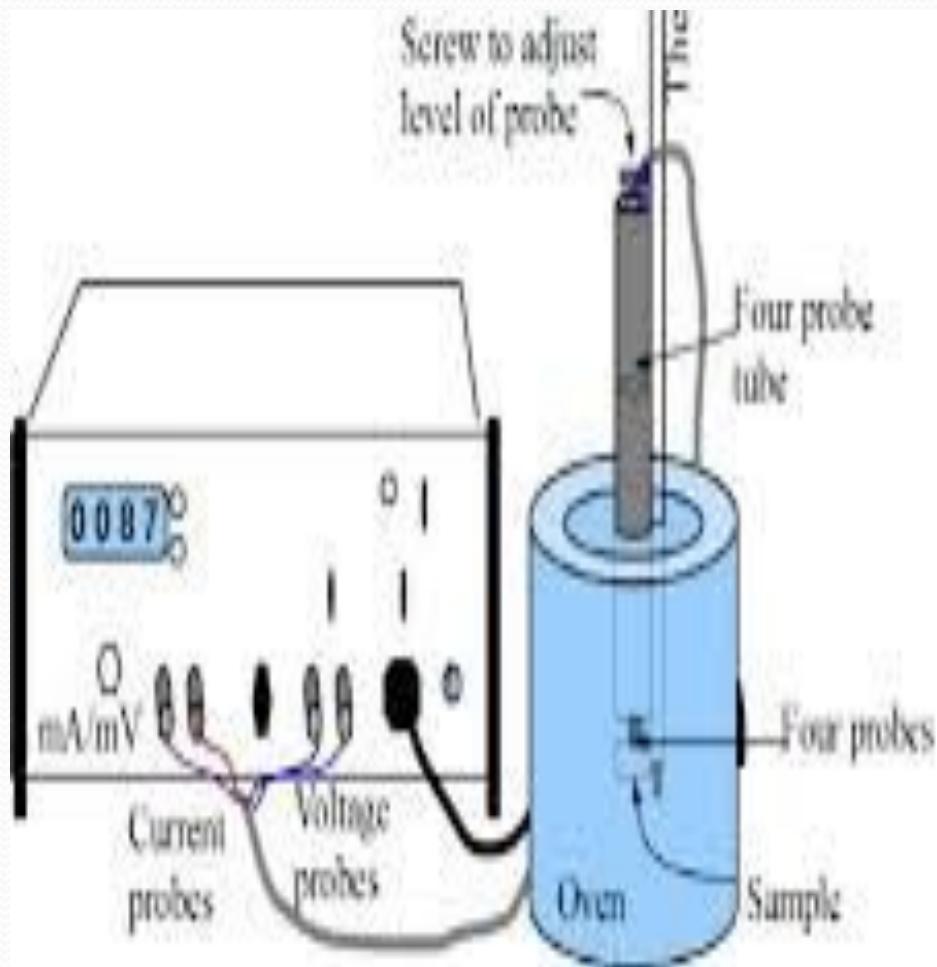
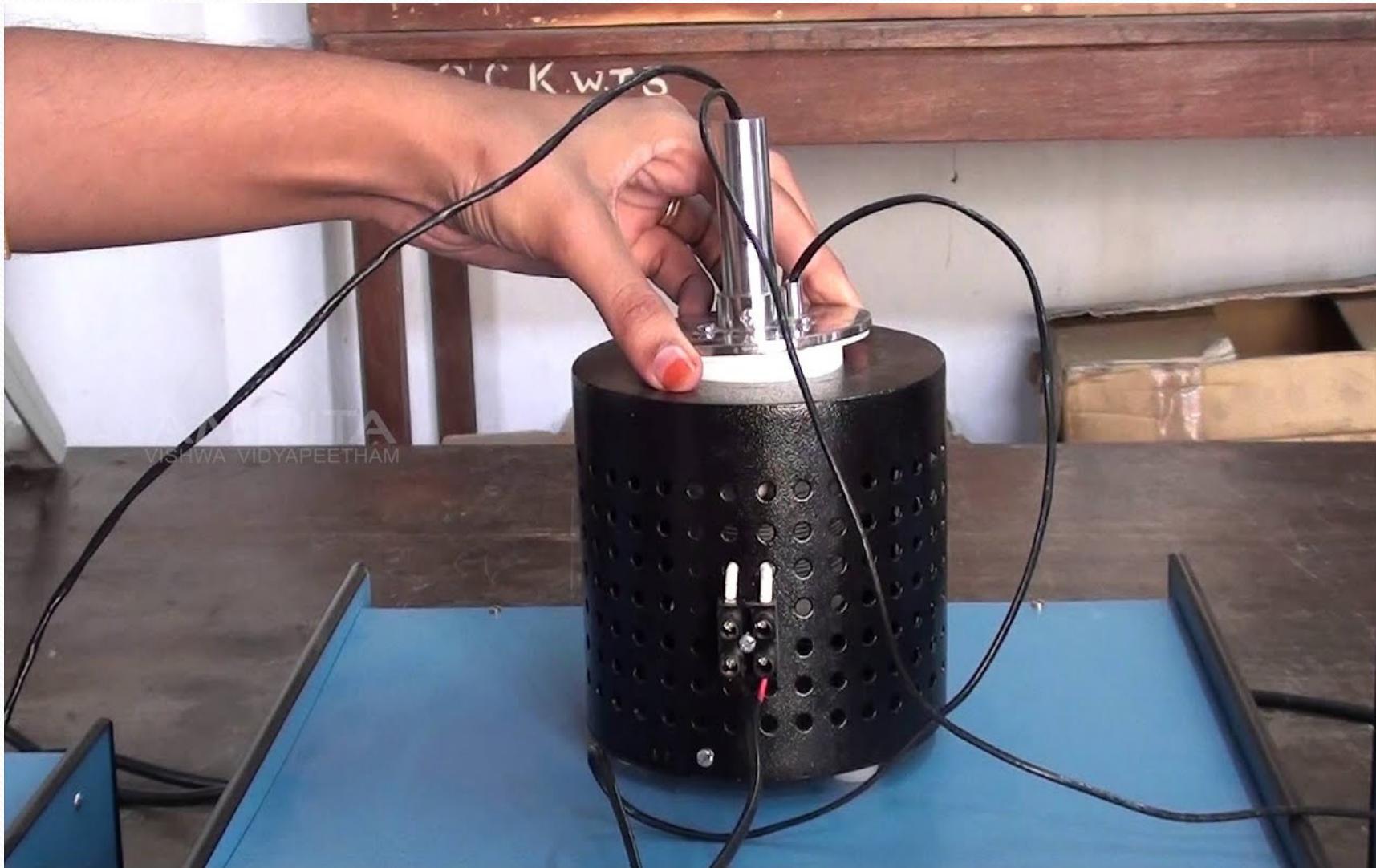


Fig.II

# FOUR PROBE METHOD



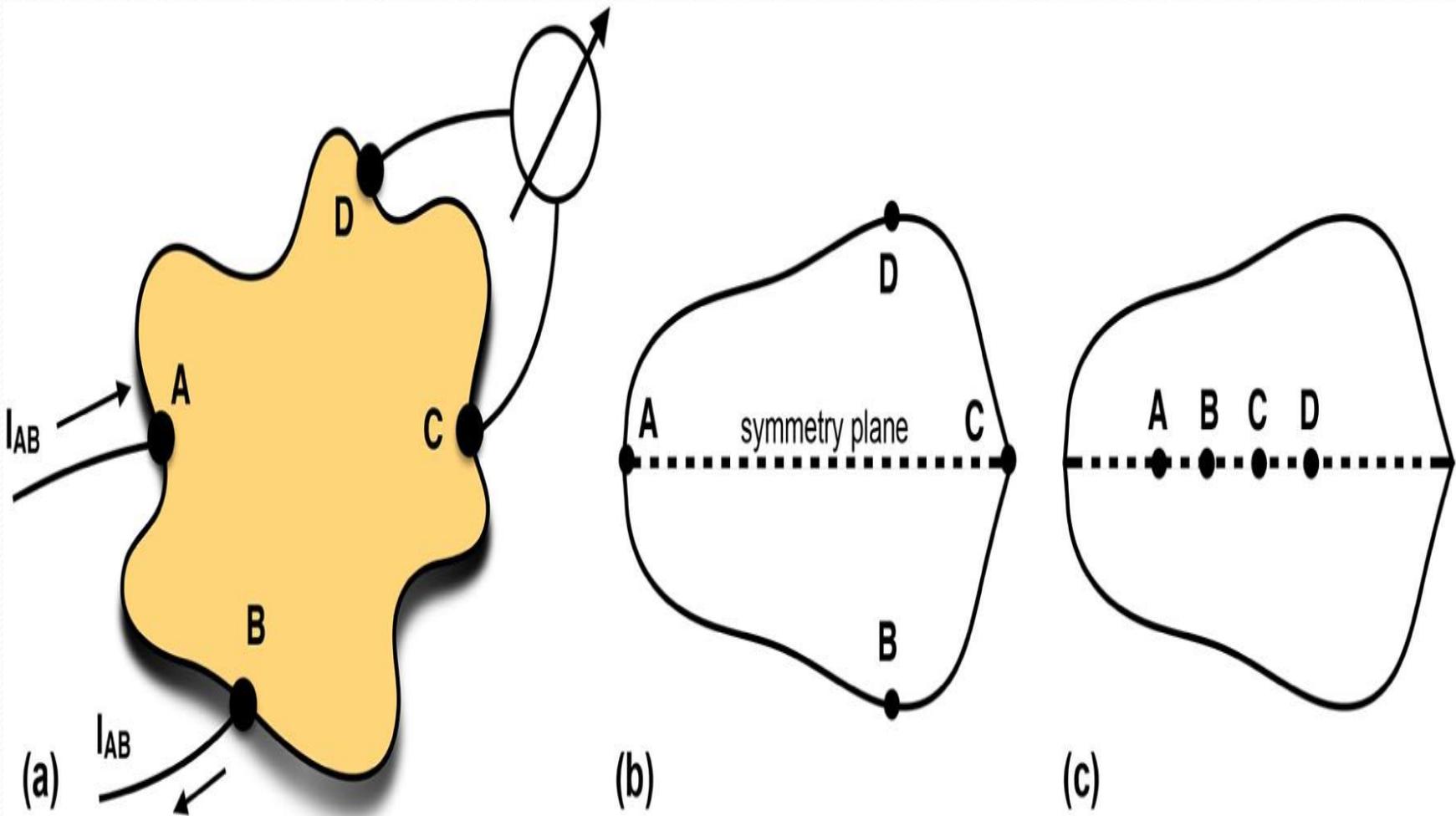
# Vander Pauw method

First propounded by Leo J. van der Pauw in 1958 [van der Pauw, Philips Research Reports, 13, 1958]

To measure specific resistivity and Hall-coefficient of arbitrarily shaped sample

From the measurements we can measure  
-specific resistivity  
-doping type  
-- majority carrier density  
-- mobility of majority carriers

# VAN DER PAUW METHOD



# Vander Pauw method

- The van der Pauw method is a technique commonly used to measure the resistivity and the Hall coefficient of a sample. There are five conditions that must be satisfied to use this technique:
- The sample must have a flat shape of uniform thickness. The sample must not have any isolated holes.
- The sample must be homogeneous and isotropic.
- All four contacts must be located at the edges of the sample. The area of contact of any individual contact should be at least an order of magnitude smaller than the area of the entire sample.

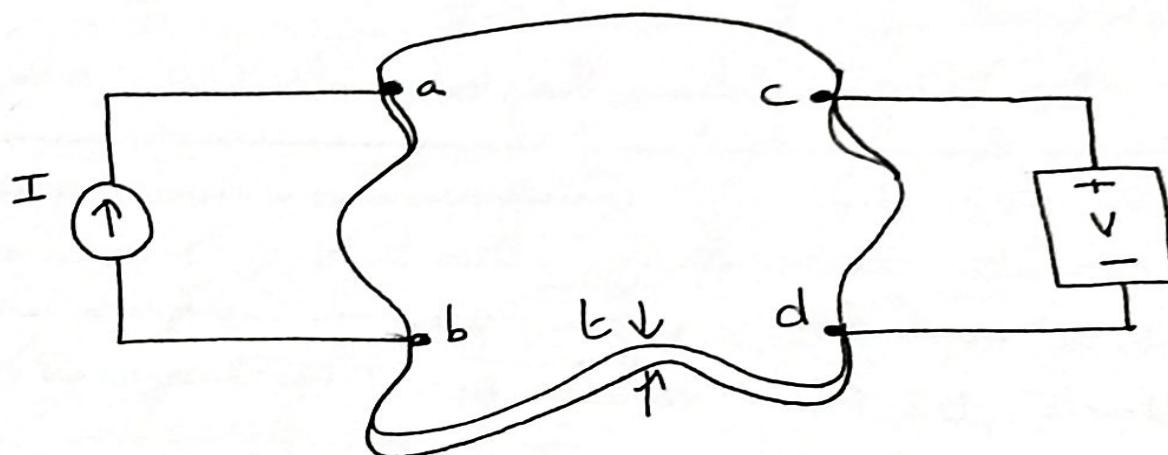
# Vander Pauw method

- In order to use the van der Pauw method, the sample thickness must be much less than the width and length of the sample.
- In order to reduce errors in the calculations, it is preferable that the sample be symmetrical. There must also be no isolated holes within the sample.

# Vander Pauw method

## Experiment

- The Vander Pauw method can determine the resistivity of small, arbitrarily shaped layers and generally requires less surface area than the four point probe method.
- It is often used in integrated circuit processing.



Vander Pauw measurement of an arbitrarily shaped sample uses a known current and a high-impedance Voltmeter.

# Vander Pauw method

- The method considers four small contacts placed around the periphery of a homogeneous, uniform thickness "L" sample,
- The resistance  $R_{ab,cd}$  is determined by driving a current from point "a" to "b" and measuring the voltage from point "c" to "d"

$$R_{ab,cd} = \frac{|V_c - V_d|}{|I_{ab}|}$$

- The resistivity is given as,

$$\rho = \frac{\pi L}{\ln 2} \frac{R_{ab,cd} + R_{bc,da}}{2} F$$

# Vander Pauw method

- for the case of a material with a uniform thickness, homogenous film with identical contacts,  $F=1$ , then

$$\rho = \frac{\pi t}{\ln 2} R_{ab,cd} = 4.532 t R_{ab,cd}$$

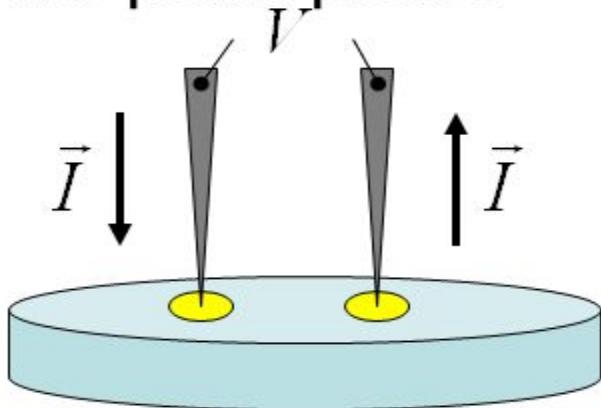
- In Van der Pauw measurements, it is common to calculate resistivity from two sets of measurements ( $R_{ab,cd}$  and  $R_{bc,da}$ ). For uniform samples with good contacts, the same result should be measured.

## ADVANTAGES AND DISADVANTAGES

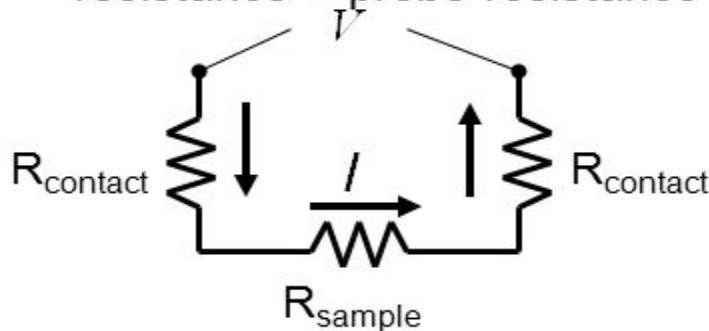
- The **Advantages** of this method are simple, inexpensive and suitable for dual or multiple point control.
- The **Disadvantages** are probe cannot become contaminated with grease or other deposits and has limited suitability for products of varying conductivity.

# Resistivity

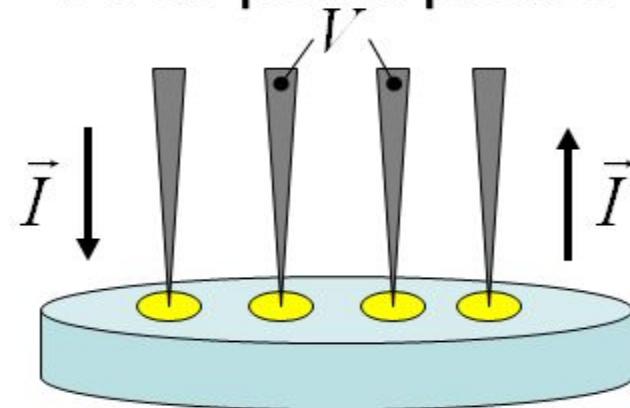
Two-point probe



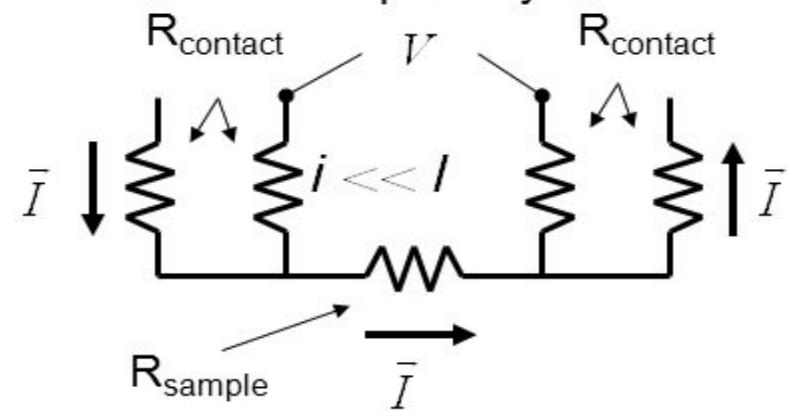
Measures sample + contact resistance + probe resistance



Four-point probe



Measures sample only



In four-point probe, negligible current flows through the voltmeter, the only voltage drop measured is across  $R_{\text{sample}}$ .

# **Advantage of four probe method over two probe method**

- Four point probe is preferred than two-point probe as the contact and spreading resistances in two point probe are large and the true resistivity cannot be actually separated from measured resistivity.
- In the four probe method, contact and spreading resistances are very low with voltage probes and hence accuracy in measurement is usually very high.

## **Advantage of four probe method over two probe method**

- To measure very low resistance values, four probe method is used.
- The resistance of probe will be not be added to that of sample being tested.
- It uses two wires to inject current in the resistance and another two wires to measure the drop against the resistance.





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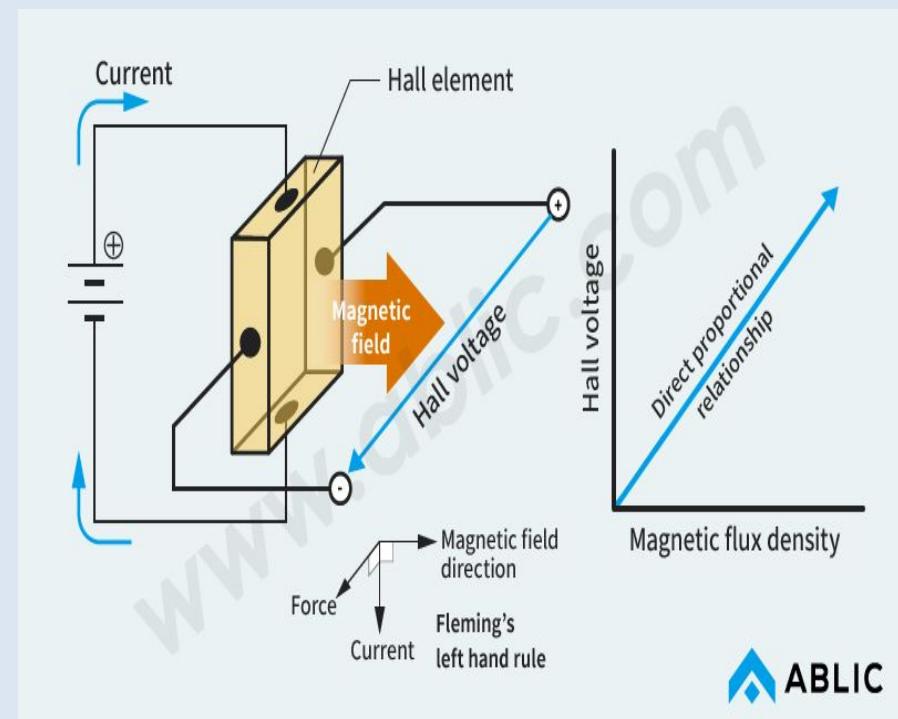
**18PYB103J –Semiconductor Physics**

**MODULE IV- LECTURE 3**

**HALL EFFECT**

## Definition

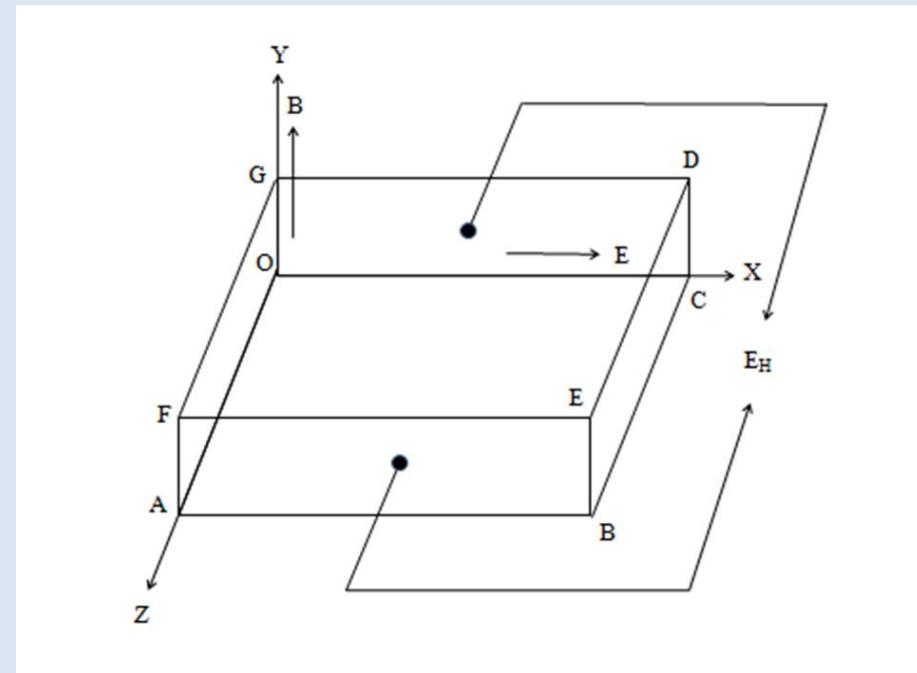
When a piece of conductor (metal or Semiconductor) carrying current is placed in a transverse magnetic field, an electric field is produced inside the conductor in a direction normal to both the current and the magnetic field. This phenomenon is known as the Hall Effect and the generated voltage is called the Hall voltage.





## Explanation:

Consider a conventional current flow through the strip along OX and a magnetic field if induction  $B$  is applied along axis OY.





## Case – I If the Material is N-type Semi-Conductor (or) Metal

- If the strip is made up of metal or N-type semiconductor, the charge carriers in the strip will be electrons.
- As conventional current flows along OX, the electrons must be moving along XO. If the velocity of the electrons is ‘v’ and charge of the electrons is ‘-e’, the force on the electrons due to the magnetic field is,
- $F = -Bev$ , which acts along OZ. This causes the electrons to be deflected and so the electrons accumulate at the face ABEF.



- Thus, face ABEF will become negative and the face OCDG becomes positive. A potential difference is therefore established across faces ABEF and OCDG., causing a field  $E_H$ .
- This field gives rise to a force of ‘ $-eE_H$ ’ on the electrons in the opposite direction (i.e, in the negative Z direction).



$$\text{At equilibrium, } eE_H = Bev \text{ (or) } E_H = Bv \quad (1)$$

$$\text{If } J \text{ is the current density, then, } J = -nev \quad (2)$$

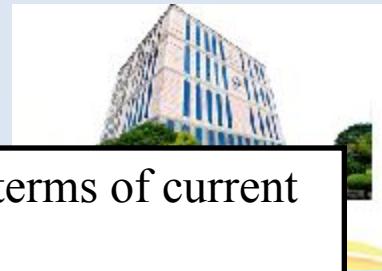
Where 'n' is the concentration of current carriers,

From equ. (2)

$$v = J/-ne \quad (3)$$

Substituting the value of v in equ. (1) we get,

$$E_H = BJ/-ne \quad (4)$$



- The Hall Effect is described by means of the Hall coefficient ‘ $R_H$ ’ in terms of current density ‘ $J$ ’ by the relation,

$$E_H = R_H B J$$

$$(or) R_H = E_H / B J \quad (5)$$

By substituting the value of  $E_H$  from equ. (4) we get,

$$R_H = B J / -neBJ = - 1/ne \quad (6)$$

- Since all the three quantities  $E_H$ ,  $J$  and  $B$  are measurable , the Hall coefficient  $R_H$  and hence the carrier density ‘ $n$ ’ can be found out.



### Case – (ii) If the material is a P-type semiconductor

If the strip is a P- type semiconductor, the charge carriers in the strip will be holes i.e., positively charged particles. The holes will constitute current in the direction of conventional current. Therefore, holes move along the direction of the conventional current itself i.e., along OX. If ‘e’ is the charge of the hole, the force experienced by the holes due to magnetic field is ,  $F = Bev$ , which acts along OZ. This causes the holes to accumulate on the face ABEF- making it positive and leaving the face OCDG as negative.

Therefore , for a P-type semiconductor,  $R_H = 1/pe$  (7)\

Where p= the density of holes.



## Determination of Hall Coefficient

The Hall coefficient is determined by measuring the Hall voltage that generates the Hall field.

If 'w' is the width of the sample across which the Hall voltage is measured, then

$$E_H = V_H / w \quad (8)$$

$$\text{We know that } R_H = E_H / BJ \quad (9)$$

Substituting the value of  $E_H$  in the above equation, we get,

$$R_H = V_H / wBJ$$

(or)

$$V_H = R_H w BJ \quad (10)$$



If the thickness of the sample is ‘t’ , then its cross sectional area  $A = wt$ , and the current density,

$$J = I/A = I/wt \quad (11)$$

Substitute the value of ‘ J’ in equation (11) , we get

$$V_H = R_H w B J / wt = R_H I B / t$$

$$(or) R_H = V_H t / IB \quad (12)$$

$V_H$  will be opposite in sign for P and N type semiconductors

## Experiment



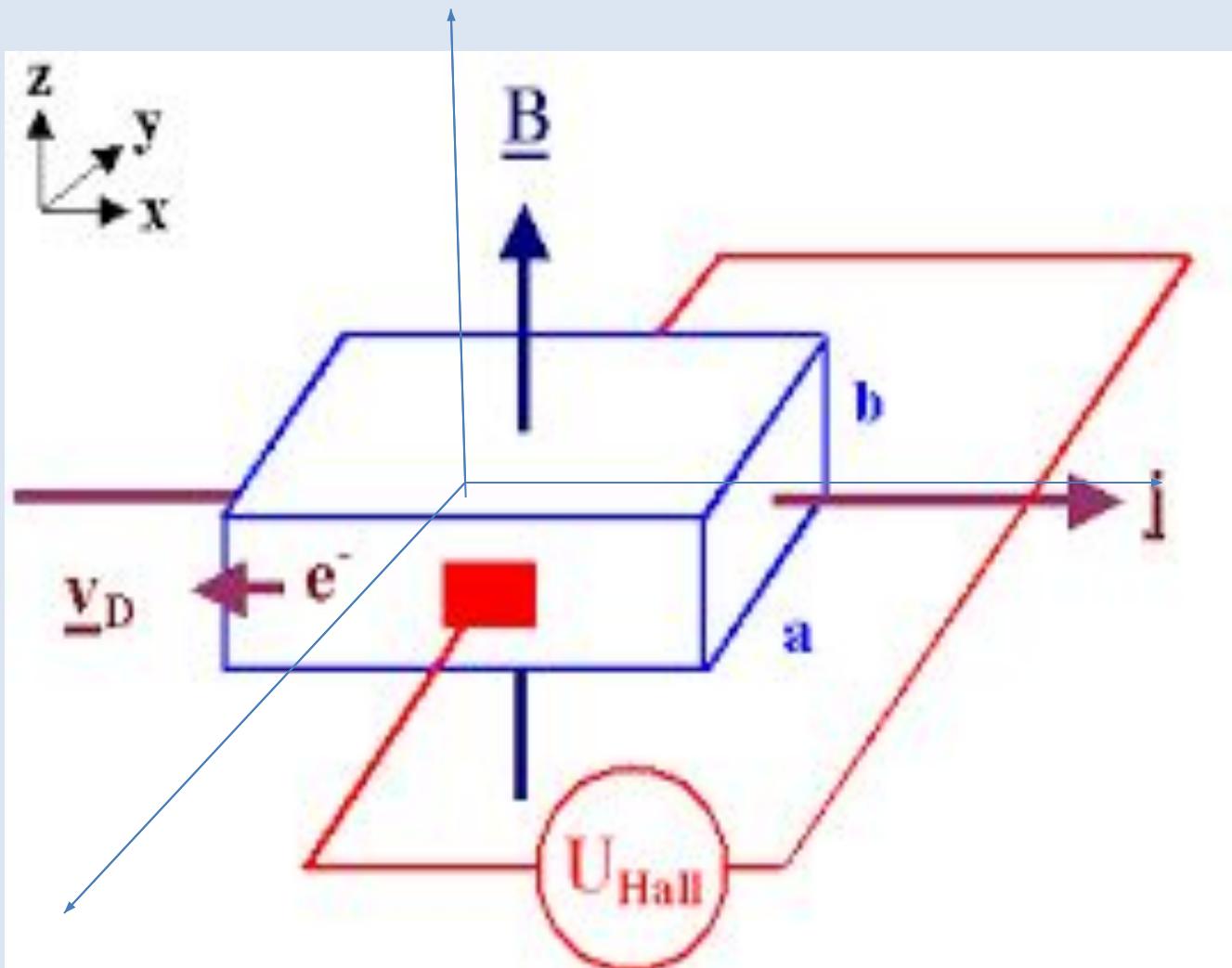
A rectangular slab of the given material having thickness ‘t’ and width ‘w’ is taken . A current of ‘I’ amperes is passed through this sample by connecting it to a battery, ‘Ba’. The sample is placed between two pole pieces of an electromagnet such that the field ‘B’ is perpendicular to I as shown in the experimental setup.

The Hall voltage ‘ $V_H$ ’ is then measured by placing two probes at the two side faces of the slab. If the magnetic flux density is ‘B’ and ‘ $V_H$ ’ is the hall voltage, then the Hall coefficient.

$$R_H = V_H t / IB \quad (\text{m}^3 / \text{coulomb})$$

For n-type material,  $\sigma_n = ne\mu_e$  (or)  $\mu_e = \sigma_n / ne = - \sigma_n \cdot R_H$

For p-type material,  $\sigma_p = pe\mu_e$  (or)  $\mu_p = \sigma_p / pe = - \sigma_p \cdot R_H$





## Applications of Hall effect:

### (1) Determination of type of semiconductor

For a N-type semiconductor, the Hall coefficient is negative whereas for a P-type semiconductor, it is positive. Thus from the direction of the Hall voltage developed, one can find out the type of semiconductor.

### (2) Calculation of carrier concentration

Once Hall coefficient  $R_H$  is measured, the carrier concentration can be obtained from,

$$n = 1/eR_H \text{ or } p = 1/eR_H$$



### (3). Determination of mobility

We know that, conductivity,  $\sigma_n = ne\mu_e$  (or)  $\mu_e = \sigma_n / ne = -\sigma_n R_H$

Also  $\sigma_p = pe\mu_h$  or  $\mu_h = \sigma_p / pe = \sigma_p R_H$ . Thus by measuring  $\sigma$  and  $R_H$ ,  $\mu$  can be calculated.

### (4) Measurement of magnetic flux density:

Using a semiconductor sample of known ' $R_H$ ' the magnetic flux density can be deduced from  $R_H = V_H t / BI$  or  $B = V_H t / R_H I$



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**18PYB103J –Semiconduuctor Physics**

**Module IV & Lecture 4**



## Problem 1:

**Compute the resistivity of the given material whose resistance is  $2\Omega$ ; area of cross-section and length are  $25\text{cm}^2$  and  $15\text{cm}$  respectively?**

**Answer:**

Given

$$R = 2\Omega$$

$$l = 15\text{cm} = 0.15\text{m}$$

$$A = 25\text{cm}^2 = 0.25\text{m}^2$$

Resistivity formula is

$$\rho = \frac{RA}{l} \quad \rho = \frac{2 \times 0.25}{0.15} = 3.333\Omega\text{m}$$

## Problem 2:

**The length and area of wire are given as  $0.2\text{ m}$  and  $0.5\text{ m}^2$  respectively. The resistance of that wire is  $3\ \Omega$ , Calculate the resistivity?**

**Ans:  $7.5\ \Omega\text{m}$**



### Problem 3:

**Calculate the resistivity of a rectangular Germanium crystal of area  $S= 100 \text{ cm}^2$  connected through Four probe if a current of 2 mA passed through it generates a voltage of 180 mV at 35 °C.**

$$\begin{aligned}\rho &= (V/I) \times 2\pi S \\ &= (180/2) \times 2 \times 3.14 \times 10^{-2} \\ &= 565.2 \times 10^{-2} = 5.652 \Omega \cdot \text{m}\end{aligned}$$



4. A silicon plate of thickness 1 mm, breath 10mm and length 100mm is placed in a magnetic field of  $0.5 \text{ Wb/m}^2$  acting perpendicular to its thickness. If  $10^{-2} \text{ A}$  current flows along its length, calculate the Hall voltage developed if the Hall coefficient is  $3.66 \times 10^{-4} \text{ m}^3 / \text{coulomb}$ .

**Given Data:**

$t = 1\text{mm}$ ;  $w = 10\text{mm}$  ;  $L = 100 \text{ mm}$  ;  $B = 0.5 \text{ Wb/m}^2$  ;  $I = 10^{-2} \text{ A}$  ;  $R_H = 3.66 \times 10^{-4} \text{ m}^3 / \text{coulomb}$ .

**Solution:**

$$\text{Hall coefficient } R = V_H t / IB$$

$$V_H = R_H IB/t$$

$$= (3.66 \times 10^{-4} \times 10^{-2} \times 0.5) / 1 \times 10^{-3}$$

$$= 1.83 \times 10^{-3} \text{ V} = 1.83 \text{ mV}$$



## Exercise:

1. A semiconducting crystal 12mm long, 5mm wide and 1mm thick has a magnetic flux density of 0.5 Wb/m<sup>2</sup> applied from front to back perpendicular to largest faces. When a current of 20mA flows lengthwise through the specimen , the voltage measured across its width is found to be 37  $\mu$ V . What is the Hall coefficient of this semiconductor? Ans:  $R_H = 3.7 \times 10^{-6} \text{ C}^{-1}\text{m}^3$



2. A n-type semiconductor has Hall coefficient =  $4.16 \times 10^{-4} \text{ m}^3\text{C}^{-1}$ . The conductivity is  $10^8 \text{ ohm}^{-1}\text{m}^{-1}$ . Calculate its charge carrier density  $n_e$  and electron mobility at room temperature.

$$\text{Ans : } n_e = 1.77 \times 10^{22} \text{ m}^{-3}; \mu_e = 0.0038 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$$



# DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

**18PYB103J –Semiconductor Physics**

**Module –IV ; LECTURE - 7**

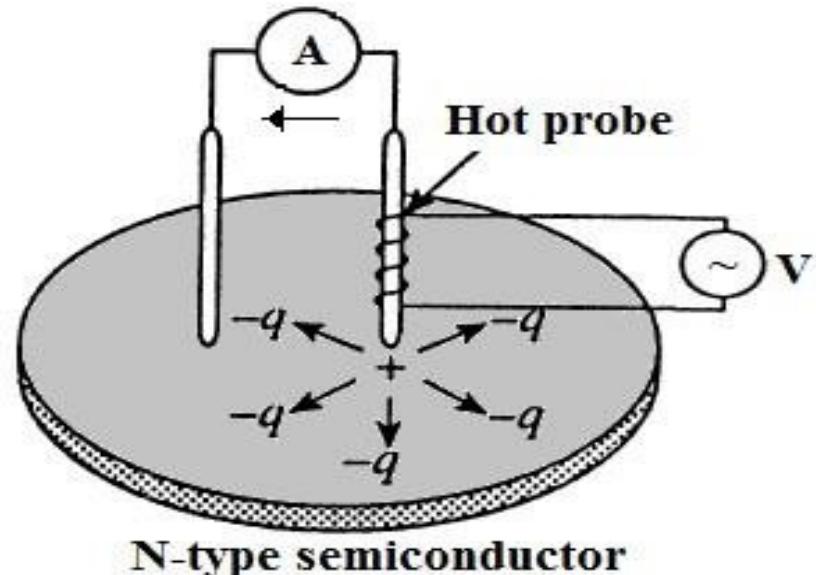
**HOT PROBE METHOD FOR SEMICONDUCTOR THIN FILM**

- Physical properties of thin films significantly differ from those of bulk material
- There are various parameters such as a thickness, crystal structure, composition and other, which characterize a semiconductor film
- The parameters of charge carriers are
  - (a) Type of semiconductor,
  - (b) Impurities concentration,
  - (c) Mobility of charged carriers,
  - (d) Diffusion coefficient.

Define the possibility to apply material for various electronic devices

### Principle:

- 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.
- While applying the cold and hot probes to an n-type semiconductor, positive voltage readout is obtained in the meter, whereas for a p-type semiconductor, negative voltage is obtained.





## Experiment:

- A couple of a cold probe and a hot probe are attached to the semiconductor film surface.
- The hot probe is connected to the positive terminal of the multimeter while the cold probe is connected to the negative terminal.
- The thermally excited majority free charged carriers are translated within the semiconductor from the hot probe to the cold probe.
- 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 multimeter

- The Hot-Probe measurement may be described as a three-step process:
  - (1) the heated probe excites additional free charged carriers of two types
  - (2) The hot majority carriers begin to leave the heated part of the semiconductor surface by a diffusion mechanism. Simultaneously, a built-in electrical field is created between the electrodes and the second (cold) electrode is warmed as well. This warming and the built-in electrical field tend to prevent the diffusion process up to a halt at a steady state. This steady state condition exists until the heated source is switched off.
  - (3) The third process is actually a recombination of the excited additional charged carriers.

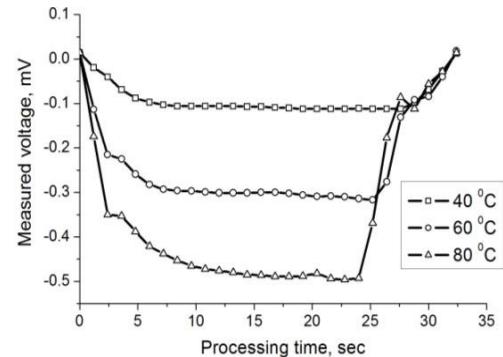


- This three-step process may be described, in general, by the continuity and Poisson's equations

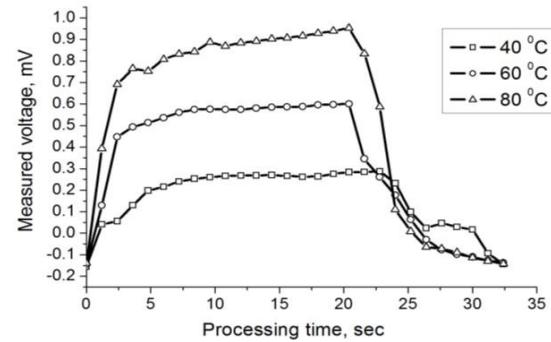
$$\nabla J + \frac{\partial Q}{\partial t} = 0$$

$$\nabla E = \frac{Q}{\epsilon_0 \epsilon_r}$$

- Here  $Q$  is the uncompensated charge density excited by the heated electrode,  $J$  is the current density,  $\epsilon_0$  and  $\epsilon_r$  are the absolute and relative permittivity, and  $E$  is the built-in electrical field.



(a) As deposited film of P-type-



(b) thermally treated film of N-type

Hot-probe characteristics for vanadium oxide thin films deposited on the oxidized silicon surface by thermal evaporation.

## Capacitance-Voltage measurements



- Hillibrand and Gold (1960) first described the use of capacitance –voltage (C-V) methods to determine the majority carrier concentration in semiconductors.
- C-V measurements are capable of yielding quantitative information about the diffusion potential and doping concentration in semiconductor materials.
- The technique employs PN-junctions, metal- semiconductor junctions (Schottky barriers), electrolyte –semiconductor junction MIS field effect semiconductors.
- C-V measurements yield accurate information about the doping concentrations of majority carriers as a function of distance (depth) from the junction.

# CAPACITANCE – VOLTAGE MEASUREMENT

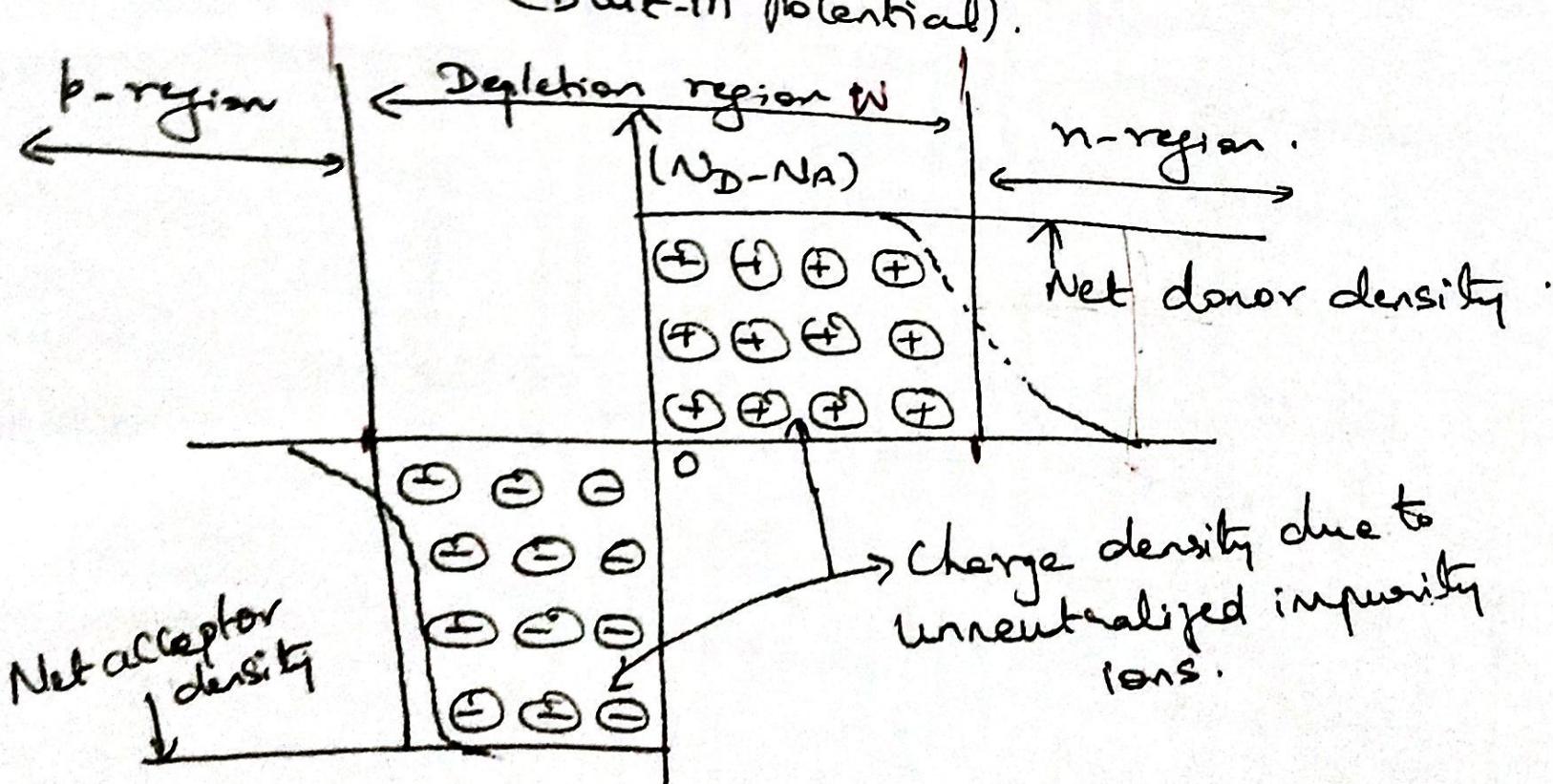
## Principle

- The Capacitance at an p-n or metal-Semiconductor junction depends on the properties of the charge-depletion layer formed at the junction.
- The depletion region is the vicinity of the pn junction and is "depleted" of free carriers due to the drift field required to maintain charge neutrality.

## Experiment:

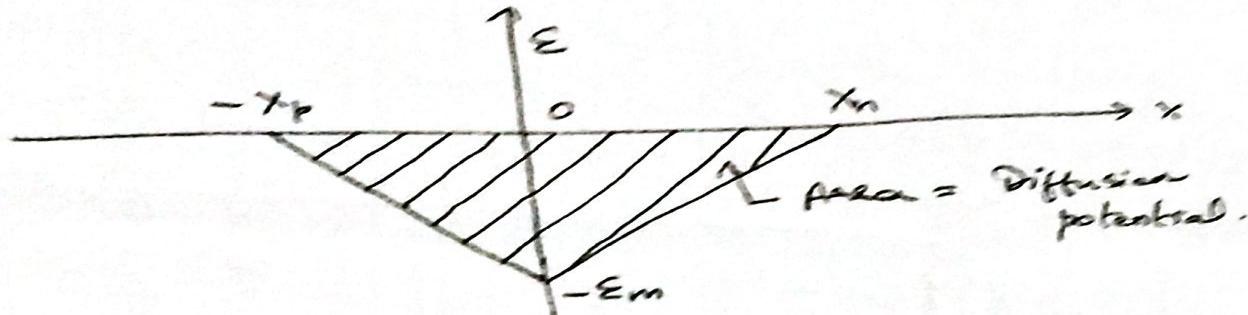
- As shown in figure, an abrupt pn junction is considered.
- The bandgap of the semiconductor  $E_{Gn} = E_c - E_v$  is defined by the difference between the Conduction band energy  $E_c$  and the Valence band energy,  $E_v$ .
- The Fermi energy  $E_f$  defines the equilibrium condition for charge neutrality.

→ The difference in energy between the conduction band as one leaves the p-n junction is called the diffusion potential,  $V_{bi}$  (built-in potential).

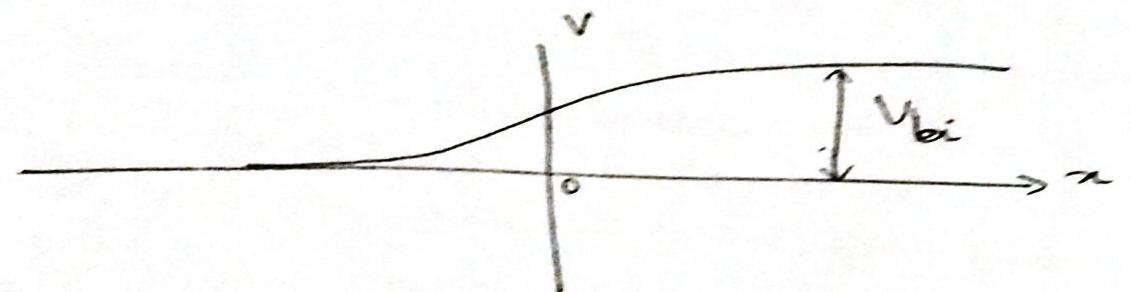


# CAPACITANCE – VOLTAGE MEASUREMENT

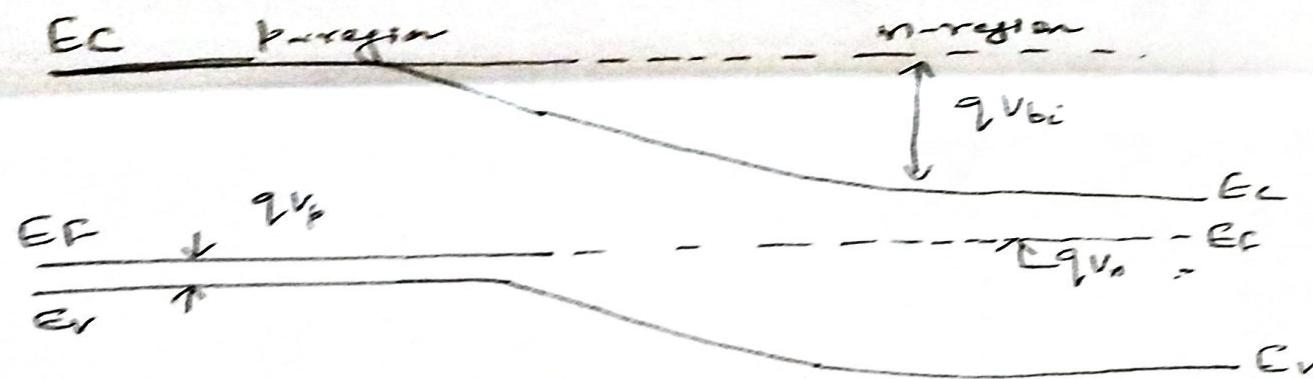
B



C



D



# CAPACITANCE – VOLTAGE MEASUREMENT

## Diagram Explanation:

Abrupt pn junction in thermal equilibrium (no bias).

- A. Space charge distribution in the depletion approximation.  
The dashed lines indicate the majority carrier distribution tails.
- B. Electric field across the depletion region.
- C. Potential distribution due to the electric field where  $V_{bi}$  is the (built-in) diffusion potential.
- D. Grey band diagram.

# CAPACITANCE – VOLTAGE MEASUREMENT

- Consider the pn junction, where the regions denoted by  $\oplus$  and  $\ominus$  indicate the junction region depleted of free carriers, leaving behind ionized donors and acceptors. In this region, from Poisson's equation

$$-\frac{\partial^2 V}{\partial x^2} = \frac{\partial E}{\partial x} = \frac{q(x)}{\epsilon} = \frac{1}{\epsilon} [p(x) - n(x) + N_D^+(x) - N_A^-(x)]$$

for predominantly doped p-type

$$-\frac{\partial^2 V}{\partial x^2} \approx \frac{q}{\epsilon} N_D^+ \quad \text{for } 0 < x \leq x_n$$

and for n-type

$$-\frac{\partial^2 V}{\partial x^2} \approx \frac{q}{\epsilon} N_A^- \quad \text{for } (-x_p \leq x \leq 0)$$

where,  $V \rightarrow$  voltage,  $E \rightarrow$  electric field.

$q \rightarrow$  electronic charge,

$p(x), n(x) \rightarrow$  the hole and electron concentrations (electric potential) comprising the mobile carriers.

# CAPACITANCE – VOLTAGE MEASUREMENT

$N_D(x) \& N_A(x) \rightarrow$  the donor and acceptor doping concentrations

$\epsilon = k_s \epsilon_0 \rightarrow$  the permittivity with dielectric coefficient  $k_s$

- The Spatial dependence,  $x$ , is measured relative to the physical location of the p-n junction.
- The solution of these equations is a form useful for C-V measurement is

$$V(x) = V_{bi} \left[ 2 \left( \frac{x}{w} \right) - \left( \frac{x}{w} \right)^2 \right]$$

where,  $V_{bi} = \frac{2\pi\epsilon}{q} \ln \left( \frac{N_D N_A}{n_e n_h} \right)$



# **DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY SRM INSTITUTE OF SCIENCE AND TECHNOLOGY**

**18PYB103J –Semiconductor Physics**

**Module-IV Lecture-8**

**Extraction Parameters & I-V Characteristic of PN Junction Diode**

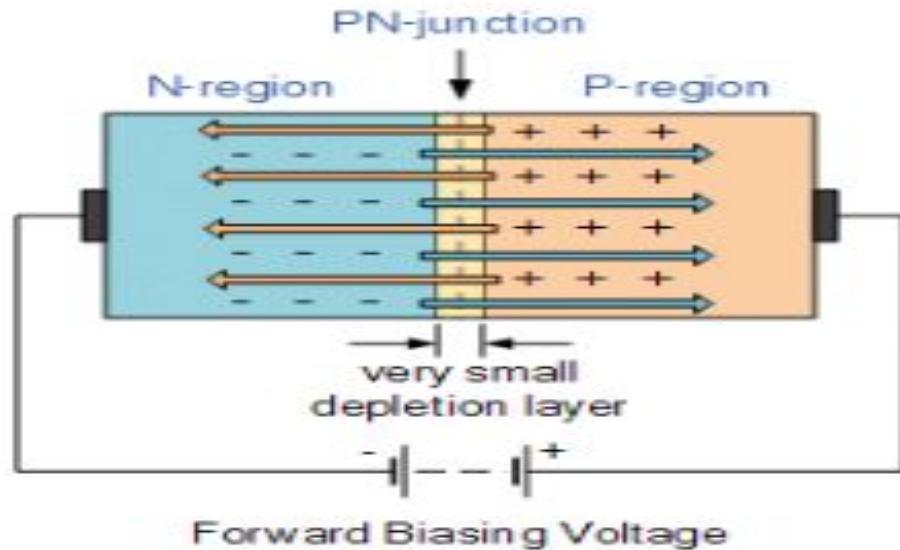
## PN Junction Diode

- if we join P-type and N-type semiconductor materials together they behave in a very different way and producing what is generally known as a “**PN Junction**“.
- The charge transfer of electrons and holes across the PN junction is known as **diffusion**. The width of these P and N layers depends on how heavily each side is doped with acceptor density  $N_A$ , and donor density  $N_D$ , respectively.
- Due to diffusion processes **potential barrier** is formed around the area of the junction as the donor atoms repel the holes and the acceptor atoms repel the electrons.
- At room temperature the voltage across the depletion layer for silicon is about 0.6 – 0.7 volts and for germanium is about 0.3 – 0.35 volts. This potential barrier will always exist even if the device is not connected to any external power source, as seen in diodes.

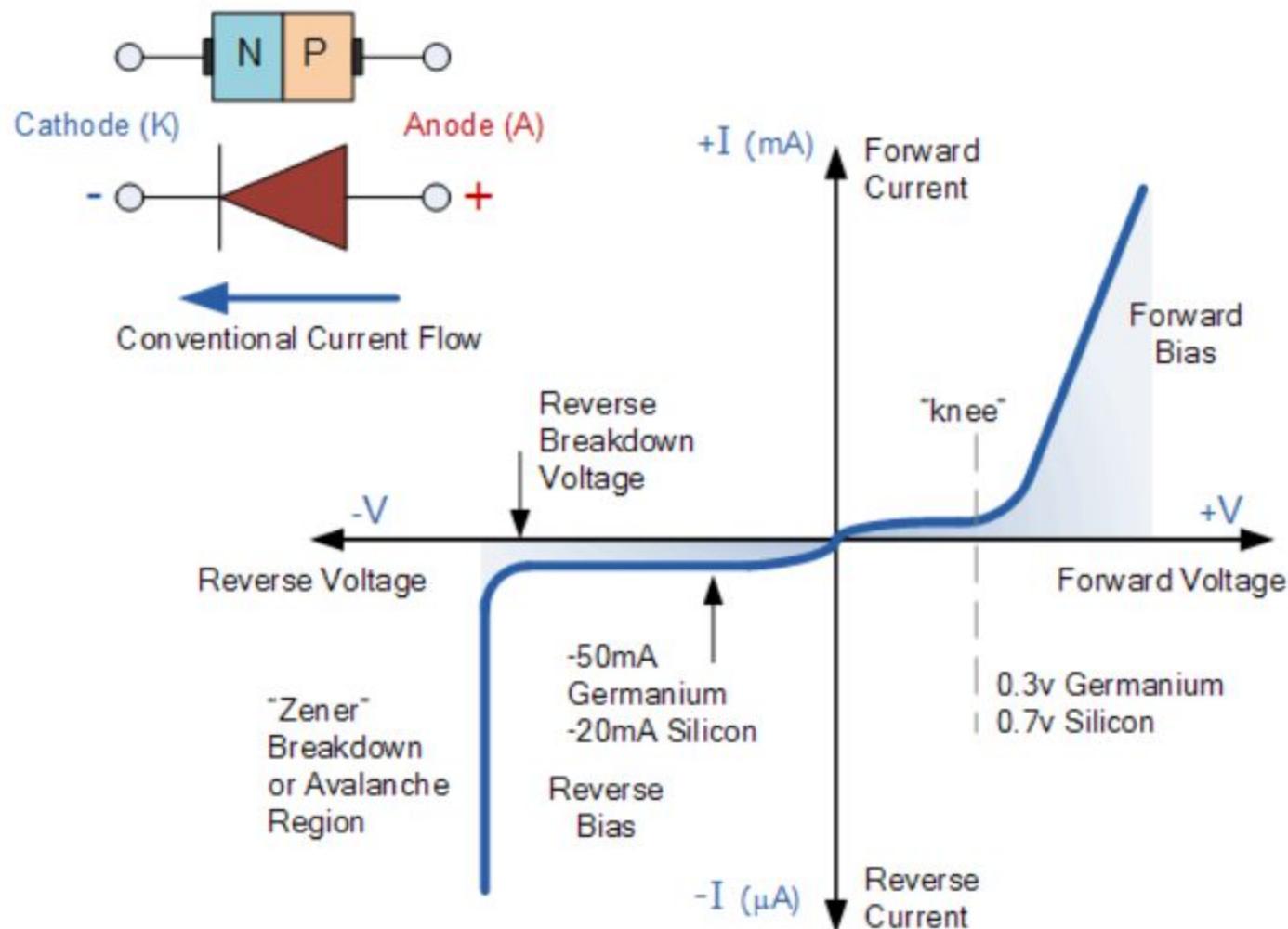


## I-V Characteristics in a Diode

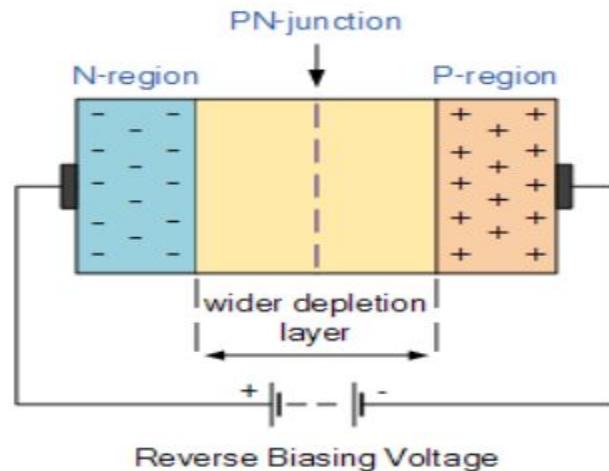
- A *PN Junction Diode* is one of the simplest semiconductor devices around, and which has the characteristic of passing current in only one direction only. However, unlike a resistor, a diode does not behave linearly with respect to the applied voltage as the diode has an exponential current-voltage ( I-V ) relationship and therefore we can not described its operation by simply using an equation such as Ohm's law.
- If a suitable positive voltage (forward bias) is applied between the two ends of the PN junction, it can supply free electrons and holes with the extra energy they require to cross the junction as the width of the depletion layer around the PN junction is decreased.
- By applying a negative voltage (reverse bias) results in the free charges being pulled away from the junction resulting in the depletion layer width being increased. This has the effect of increasing or decreasing the effective resistance of the junction itself allowing or blocking current flow through the diode.



- When a diode is connected in a **Forward Bias** condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow.



- Due to forward biasing the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the “knee” on the static curves and then a high current flow through the diode with little increase in the external voltage.
- The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the “knee” point.
- Since the diode can conduct “infinite” current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.



- When a diode is connected in a **Reverse Bias** condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.
- The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.



- This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small **leakage current** does flow through the junction which can be measured in micro-amperes, (  $\mu\text{A}$  ).
- if the reverse bias voltage applied to the diode is increased to a sufficiently high enough value, it will cause the diode's PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below.
- When the reverse voltage is increased beyond the limit, then the reverse current increases drastically. This particular voltage that causes the drastic change in reverse current is called **Reverse Breakdown voltage**. Diode breakdown occurs by two mechanisms: Avalanche breakdown and Zener breakdown.



# **DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY SRM INSTITUTE OF SCIENCE AND TECHNOLOGY**

**18PYB103J –Semiconductor Physics**

**Module-IV Lecture-9**

**Deep Level Transient Spectroscopy(DLTS)**

## Deep-level transient spectroscopy(DLTS)

### DLTS Principle:

- Emission of trapped charge carriers change the depletion capacitance of a pn-junction or Schottky diode. The transient measurement provides information on the defect levels in the band gap.
- Deep-level transient spectroscopy is a method of determining the concentration and thermal emission rate of semiconductor deep levels by measuring capacitance transients as a function of temperature.
- A Schottky or p-n diode is first forward biased to fill the traps, then the capacitance transient caused by carrier emission from filled traps in the depletion region is measured at the quiescent reverse bias.

- A DLTS peak is generated when the thermal emission rate of the trap is the same as that of the rate window. Because of the strong temperature dependence of the trap emission rates, it is possible to resolve the emission from different traps using an appropriate emission rate window.
- When voltage across a p-n junction is changed, there is a corresponding change in the depletion region width. This change in width causes a change in the number of free charge carriers on both sides of the junction, resulting in a change in the capacitance.
- This change has two contributions; a) the contribution due to change in depletion width known as the junction capacitance and b) the contribution due to change in minority carrier concentration called the diffusion capacitance.
- Junction capacitance is dominant under reverse biased conditions while diffusion capacitance is dominant under forward biased conditions.



□ Consider a p-n junction with a deep level present having its energy as  $E_T$ . In steady state there is no net flow of charge carriers across the trap. Also the electron and hole densities within the depletion region are negligible. Thus from **Shockley and Reed & Hall** the relationship between the total density of deep states  $N_T$  and density of filled traps is given by

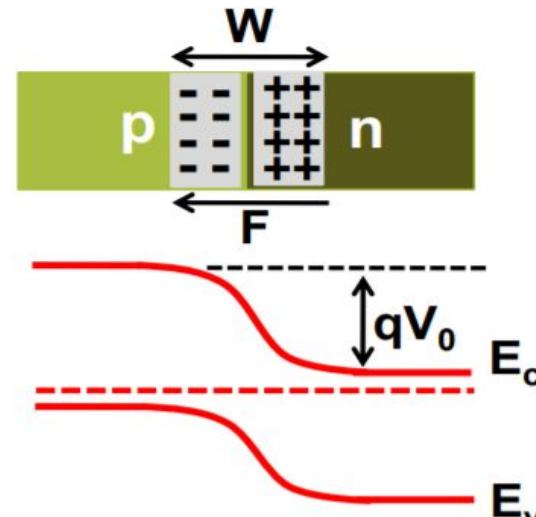
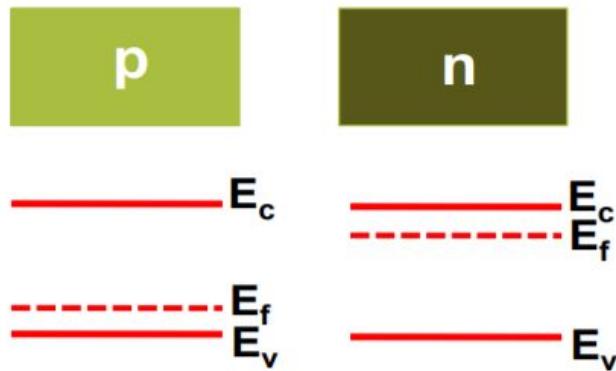
$$e_p n_T = (e_n + e_p) N_T$$

where  $e_p$  is the hole emission rate,  $e_n$  is the electron emission rate,  $n_T$  is the density of filled traps, and  $N_T$  is the total density of deep states.



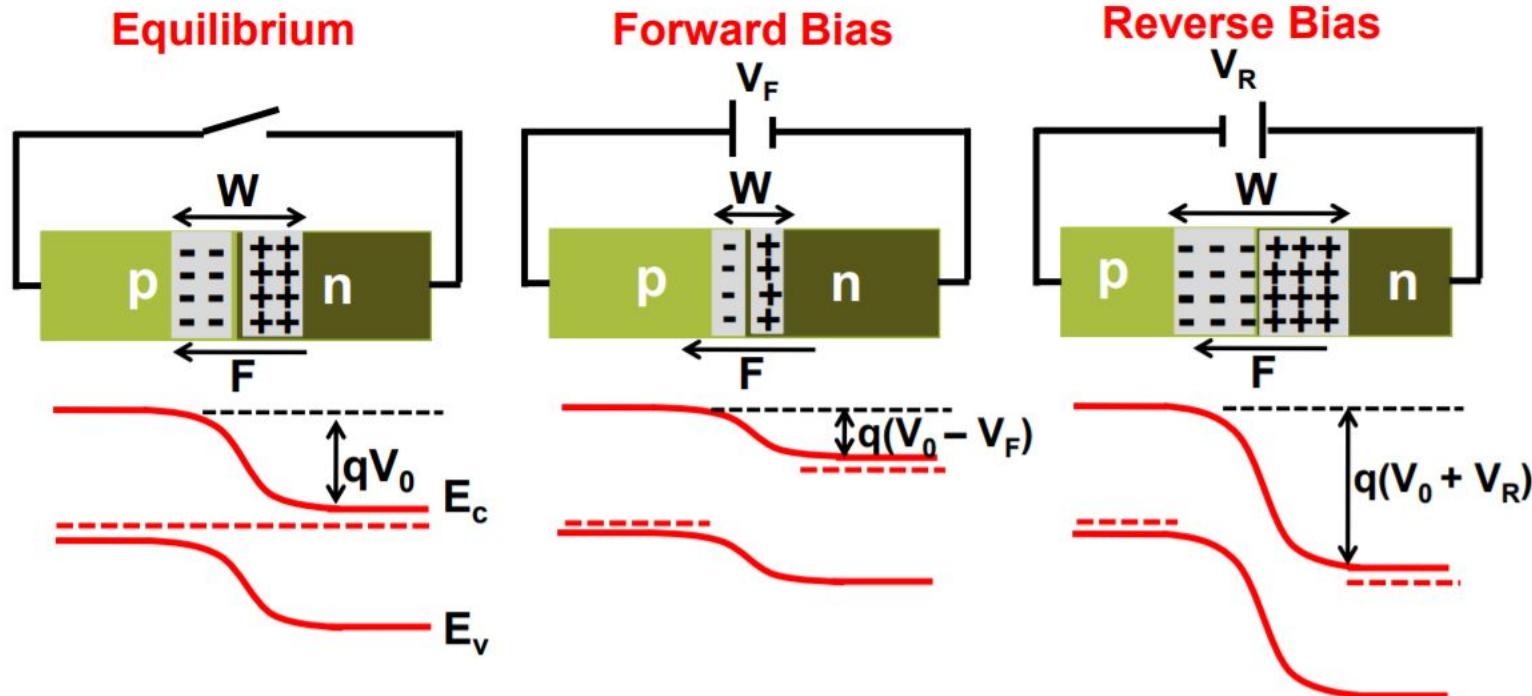
## Semiconductor Basics

### ❖ pn-junction



$$C = \frac{\epsilon A}{W}$$

- Connection of p- and n-type regions:
  - Diffusion of charge carriers into the opposite regions.
  - This will give rise to an electric field across the depletion region ( $W$ ), with a capacitance  $C$
  - No free charge carriers in  $W$  as the field will sweep them across the junction



- The SCR width ( $W$ ) Changes with applied voltage and doping concentration
  - High doping  $\rightarrow$  small  $W$
  - Low doping  $\rightarrow$  large  $W$
- The depletion region width ( $W$ ) will extend mostly into low-doped material in order to keep charge balance



## Point Defects

- **Substitution impurity:** extra impurity atom in an origin position
- **Vacancy:** missing atom at a certain crystal lattice position
- **Interstitial impurity atom:** extra impurity atom in an interstitial position
- **Self-interstitial atom:** extra atom in an interstitial position;

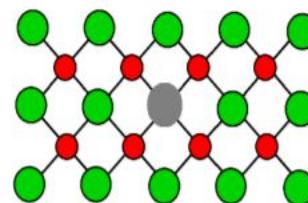
**Introduce energy level in the band structure**

**•Shallow level**

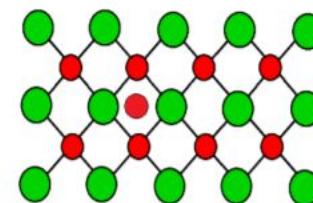
- Close to the edges of the bandgap
- Use mainly as a dopant

**•Deep level**

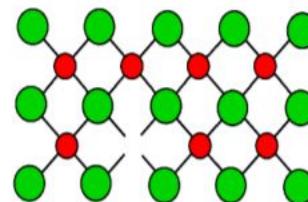
- Close to the middle of the bandgap
- Act as generation/recombination or trap center.



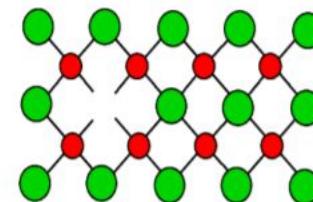
(a) Substitutional



(b) Self-interstitial



(c) Carbon Vacancy



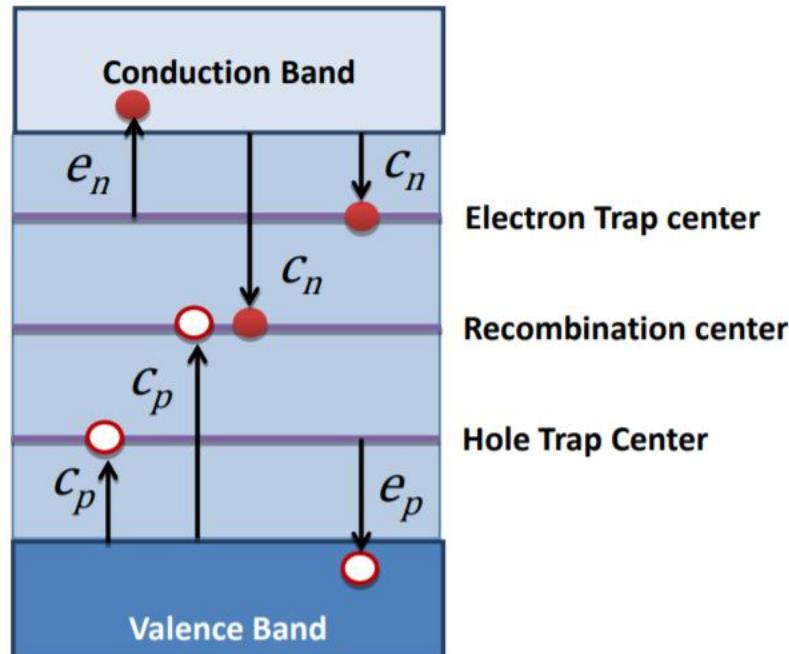
(d) Silicon Vacancy



## Capture & Emission Processes

Deep levels in the band gap act as

- **Recombination centers:** can interact with both edges of bandgap  $c_n = c_p$ .
- **Electron traps:** If they mostly interact with the conduction band  $c_n \gg c_p$ .
- **Hole traps:** If they mostly interact with the valence band  $c_n \ll c_p$ .





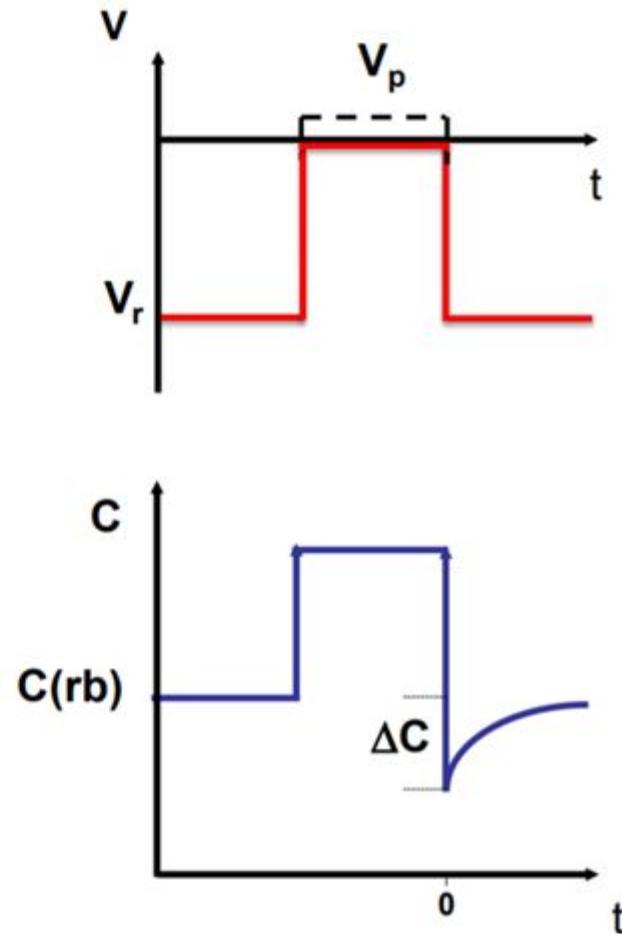
## DLTS Theory

### Principle of measurement

- Diode kept at fixed reverse bias.
- Filling Pulse to fill the traps.
- Return to the reverse bias:
  - Change of the W
  - Emission of charge carriers changes the capacitance of the depletion region as a function of time

$$C(t) = C_{rb} - \Delta C_o \exp(-e_n t)$$

- Repeated through a temperature scan





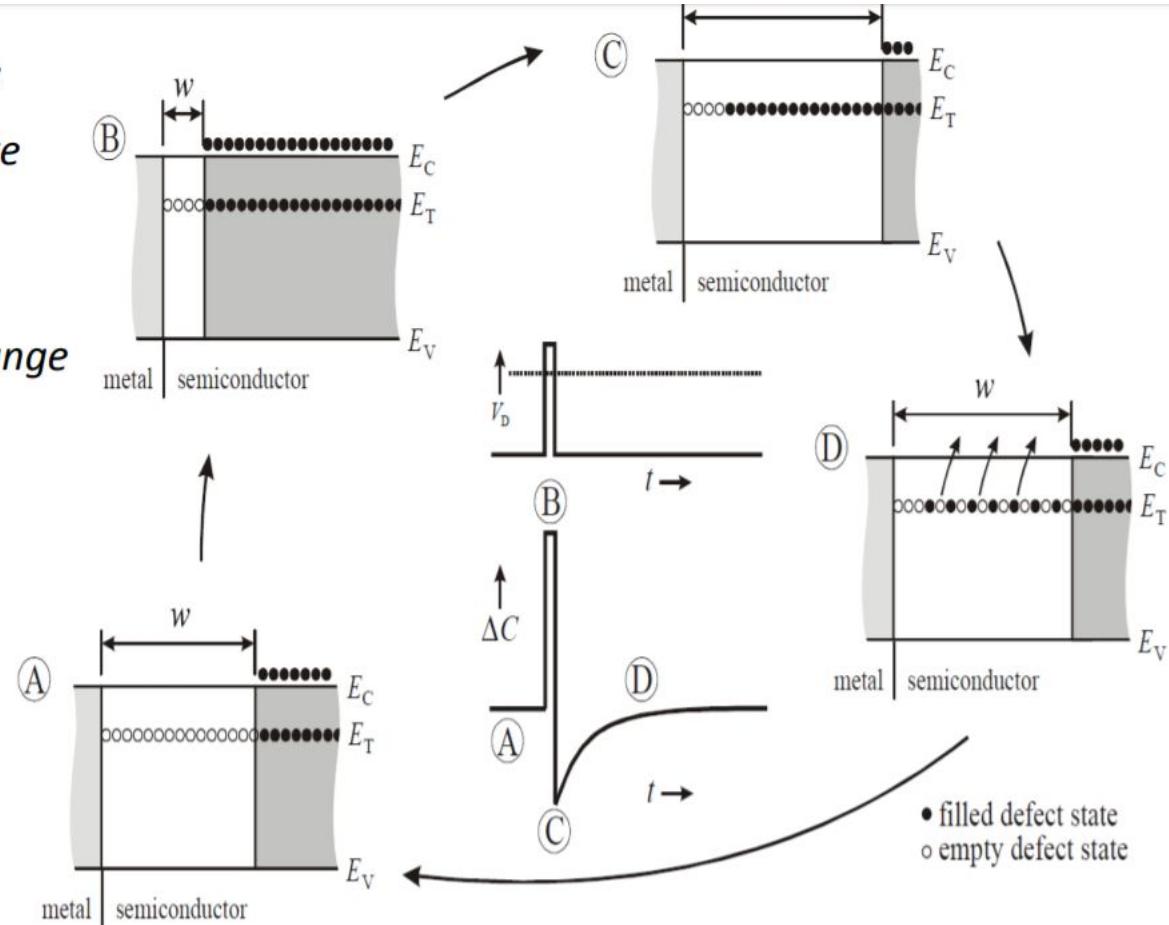
### DLTS Measurement:

(A) Equilibrium state

(B) Filling pulse

(C) Return to the reverse bias with change in the capacitance

(D) Emission case.



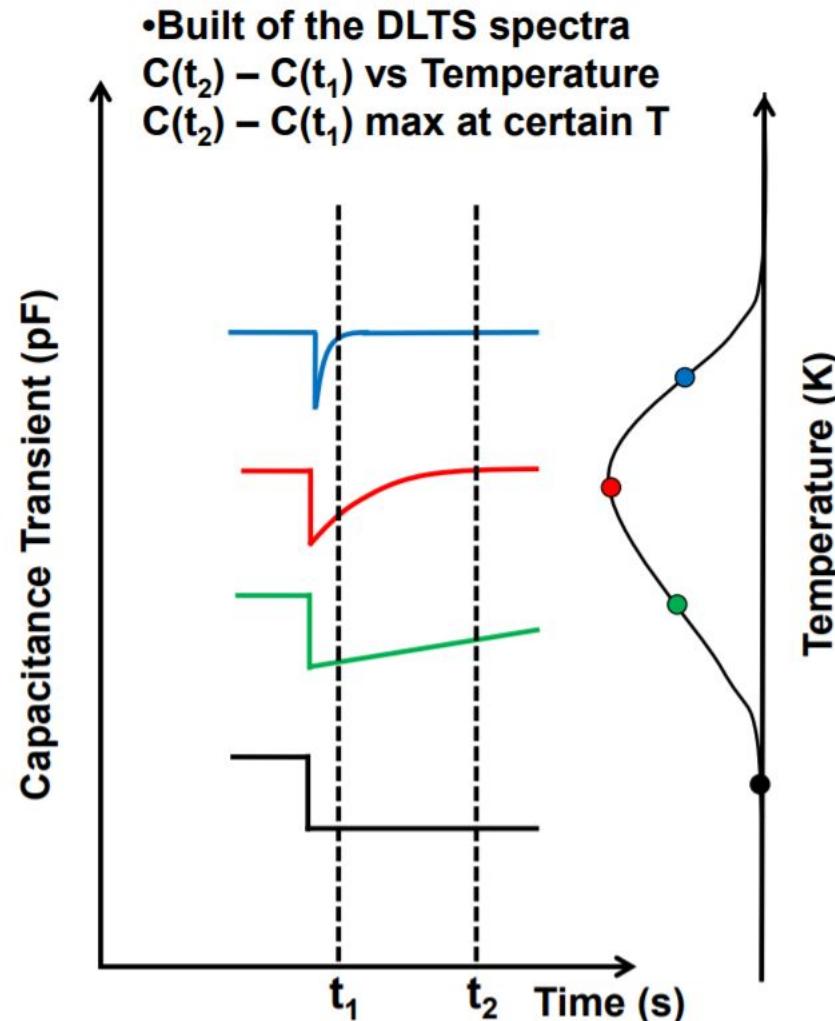


- The carrier concentration of the traps is changed exponentially

$$n_T(t) = N_T \exp(-e_n t)$$

- The trap concentration can be deduced from the maximum amplitude of the transient

$$\Delta C_o = \frac{N_T}{2N_d} C_{rb}$$



# **DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY SRM INSTITUTE OF SCIENCE AND TECHNOLOGY**

**18PYB103J –Semiconductor Physics**

**Module-IV Lecture-14**

**FUNDAMENTAL LAWS OF ABSORPTION &  
INSTRUMENTATION OF UV-VIS**



- The light source is passed through the setup, measurements are recorded for incident and transmitted radiations.
- These measurements are used to calculate the transmission and absorption spectra of the material.
- While many modern instruments perform Beer's law calculations by simply comparing a test sample with a reference sample which have a negligible absorbance.
- The graphing method assumes a straight-line relationship between absorbance and concentration, which is valid only for dilute solutions.

$$\text{Transmittance, } T = I/I_0$$

$$\text{Absorbance, } A = -\log(\%T)$$

I – Transmitted radiation intensity

$I_0$  – Incident radiation intensity



- When the light beams are passed through a dilute sample, the absorption will be less since there is only less number of absorbing particles presented.
- The light beam was passed through a concentrated sample.
- The intensity of the transmitted beam was considerably low, which leads to violation of Beer Lambert's law.
- The law thus states that for a dilute solution,  $A = Kcl$   
Where,

A – absorbance

K – molar absorbance coefficient

c – molar concentration

l - Path length



- Basic principle of spectroscopy is the Beer-Lambert's law (also known as beer's law) that relates the attenuation of light to the properties of the material through which the light is travelling.
- Lambert's law stated that absorbance of a material is directly proportional to its thickness (path length).
- Much later, August Beer discovered another attenuation relation in 1852. Beer's law stated that absorbance is proportional to the concentrations of the material sample.
- The modern derivation of the Beer–Lambert law combines the two laws and correlates the absorbance to both the concentrations and the thickness of the material.
- Absorption spectra of chemical samples are generated when a beam of electromagnetic radiation is passed through a sample, and the chemical sample absorbs a portion of the photons of electromagnetic energy passing through the sample.



**Spectrophotometry** is a method to measure how much a chemical substance absorbs light by measuring the intensity of light as a beam of light passes through sample solution. The basic **principle** is that each compound absorbs or transmits light over a certain range of wavelength.

The **Beer-Lambert law** is the linear relationship between **absorbance** and concentration of an **absorbing** species. The **Beer-Lambert law** implies that both the type and the concentration of the molecules are important in the process of radiation **absorption**.



- Spectroscopy is the measurement and interpretation of electromagnetic radiation absorbed or emitted when the molecules or atoms or ions of a sample moves from one energy state to another energy state.
- UV spectroscopy is type of absorption spectroscopy in which light of ultra-violet region (200-400 nm) is absorbed by the molecule which results in the excitation of the electrons from the ground state to higher energy state.
- Most of the organic molecules and functional groups are transparent in the portion of the electromagnetic spectrum that we call the uv and visible regions
- In that region where wavelengths range from 190nm to 800nm
- This information, when combined with the detail provided by infrared and nuclear magnetic resonance (NMR) spectra, can lead to valuable structural proposals.

## Principle of UV Spectroscopy

- Basically, spectroscopy is related to the interaction of light with matter.
- As light is absorbed by matter, the result is an increase in the energy content of the atoms or molecules.
- When ultraviolet radiations are absorbed, this results in the excitation of the electrons from the ground state towards a higher energy state.
- Molecules containing  $\pi$ -electrons or non-bonding electrons ( $n$ -electrons) can absorb energy in the form of ultraviolet light to excite these electrons to higher anti-bonding molecular orbitals.
- The absorption of ultraviolet light by a chemical compound will produce a distinct spectrum which aids in the identification of the compound.

## Instrumentation of UV Spectroscopy

### Light Source

- Tungsten filament lamps and Hydrogen-Deuterium lamps are most widely used and suitable light source as they cover the whole UV region.
- Tungsten filament lamps are rich in red radiations; more specifically they emit the radiations of 375 nm, while the intensity of Hydrogen-Deuterium lamps falls below 375 nm.



## Sample and reference cells

- One of the two divided beams is passed through the sample solution and second beam is passé through the reference solution.
- Both sample and reference solution are contained in the cells.
- These cells are made of either silica or quartz. Glass can't be used for the cells as it also absorbs light in the UV region.
- Generally two photocells serve the purpose of detector in UV spectroscopy.
- One of the photocell receives the beam from sample cell and second detector receives the beam from the reference.
- The intensity of the radiation from the reference cell is stronger than the beam of sample cell. This results in the generation of pulsating or alternating currents in the photocells.



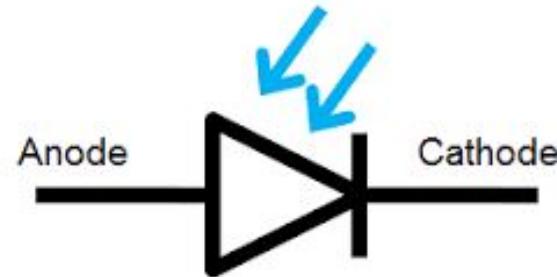
## Monochromator

- Monochromators generally is composed of prisms and slits.
- Most of the spectrophotometers are double beam spectrophotometers.
- The radiation emitted from the primary source is dispersed with the help of rotating prisms.
- The various wavelengths of the light source which are separated by the prism are then selected by the slits such the rotation of the prism results in a series of continuously increasing wavelength to pass through the slits for recording purpose.
- The beam selected by the slit is monochromatic and further divided into two beams with the help of another prism.



## Detector

### Photo-diode symbol



- A photo detector is a semiconductor device which converts light energy to electrical energy.
- It consists of a simple P-N junction diode and is designed to work in reverse biased condition.
- The photons approaching the diode are absorbed by the photodiode and current is generated.
- It can be made by diffusing a p-type impurity into a n-type bulk silicon wafer or vice versa.

- The defused area is called active photodiode area which is coated by an anti reflecting thin film for maximum detection and is covered by an illumination window.
- Non active area is deposited by thick layer of silicon oxide. Some photodiodes are manufactured with built-in filters and lenses having different surface areas.
- Response time of the photodiode is inversely proportional to the surface area. Solar cell is one of the best examples for photodiode.
- To increase the speed of response, a PIN junction is used instead of P-N junction

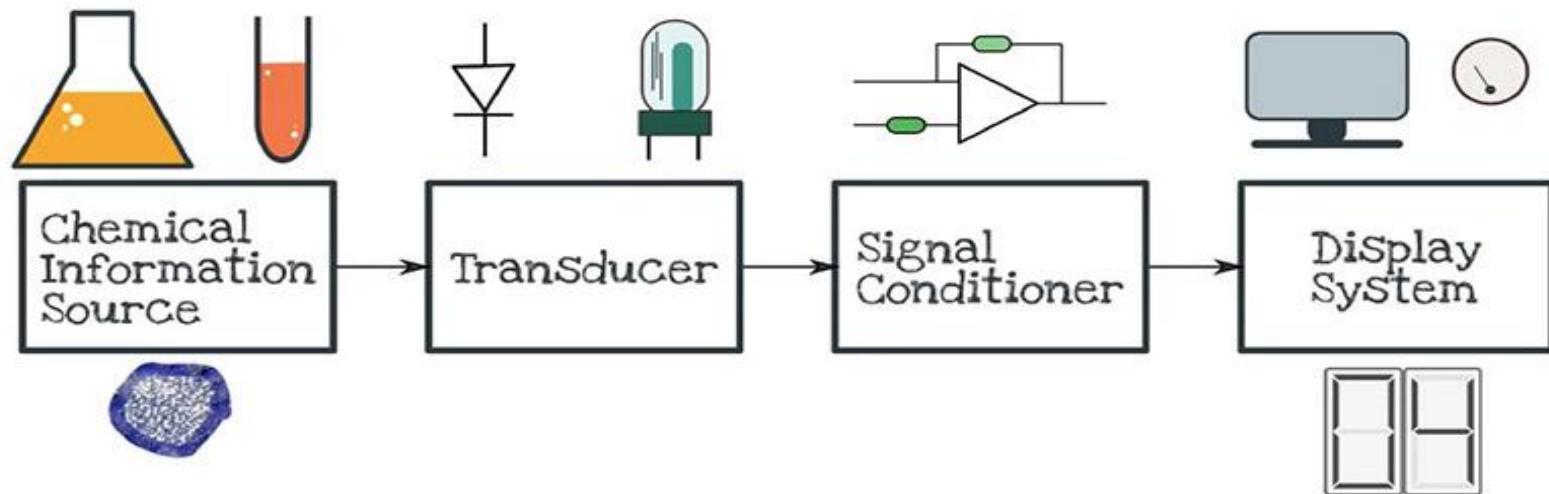


## Amplifier

- The alternating current generated in the photocells is transferred to the amplifier.
- The amplifier is coupled to a small servometer.
- Generally current generated in the photocells is of very low intensity, the main purpose of amplifier is to amplify the signals many times so we can get clear and recordable signals.

## Recording devices

- Most of the time amplifier is coupled to a pen recorder which is connected to the computer.
- Computer stores all the data generated and produces the spectrum of the desired compound.



## UV-VISIBLE SPECTROSCOPY



## Applications of UV Spectroscopy

### Detection of Impurities

- Best methods for determination of impurities in organic molecules.
- Additional peaks can be observed due to impurities in the sample and it can be compared with that of standard raw material.
- By also measuring the absorbance at specific wavelength, the impurities can be detected.

### Structure elucidation of organic compounds

- It is useful in the structure elucidation of organic molecules, such as in detecting the presence or absence of unsaturation, the presence of hetero atoms.
- UV absorption spectroscopy can be used for the **quantitative determination of compounds** that absorb UV radiation.



## Applications of UV Spectroscopy

- UV absorption spectroscopy can characterize those types of compounds which absorbs UV radiation thus used in qualitative determination of compounds. Identification is done by comparing the absorption spectrum with the spectra of known compounds.
- This technique is used to detect the presence or absence of functional group in the compound. Absence of a band at particular wavelength regarded as an evidence for absence of particular group.
- Kinetics of reaction can also be studied using UV spectroscopy. The UV radiation is passed through the reaction cell and the absorbance changes can be observed.



- Many drugs are either in the form of raw material or in the form of formulation. They can be assayed by making a suitable solution of the drug in a solvent and measuring the absorbance at specific wavelength.
- Molecular weights of compounds can be measured spectrophotometrically by preparing the suitable derivatives of these compounds.
- UV spectrophotometer may be used as a detector for HPLC.

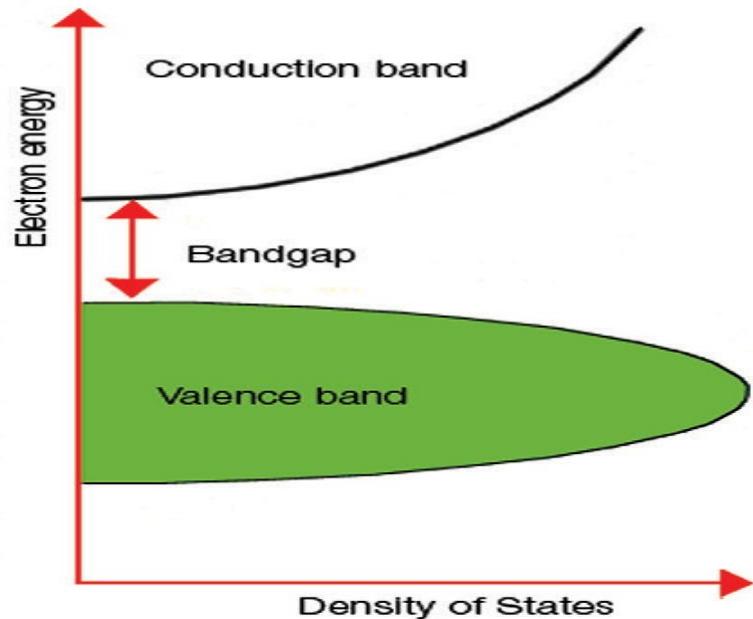


# DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

**18PYB103J –Semiconductor Physics**

## Determination of band gap by Uv-Vis spectroscopy

The measurement of the band gap of materials is important in the semiconductor, nanomaterial and solar industries. This note demonstrates how the band gap of a material can be determined from its UV absorption spectrum.



**Figure 1. Explanation of band gap.**



The term “band gap” refers to the energy difference between the top of the valence band to the bottom of the conduction band (See Figure 1); electrons are able to jump from one band to another.

In order for an electron to jump from a valence band to a conduction band, it requires a specific minimum amount of energy for the transition, the band gap energy.

A diagram illustrating the band gap is shown in Figure 1.

Measuring the band gap is important in the semiconductor and nanomaterial industries.

The band gap energy of insulators is large ( $> 4\text{eV}$ ), but lower for semiconductors ( $< 3\text{eV}$ ).

The band gap properties of a semiconductor can be controlled by using different semiconductor alloys such as GaAlAs, InGaAs, and InAlAs [1].

## Tauc plot



A **Tauc plot** is used to determine the optical **band gap**, or Tauc gap, in **semiconductors**.

The Tauc gap is often used to characterize practical optical properties of **amorphous materials**. While investigating the optical and electronic properties of amorphous germanium, Tauc et al, proposed and substantiated a method for determining the band gap using optical absorbance data plotted appropriately with respect to energy [2].

This was further developed in Davis and Mott's more general work on amorphous semiconductors [3,4]. They show that the optical absorption strength depends on the difference between the photon energy and the band gap as shown in (Eq. 1):

$$(\alpha h\nu)^{1/n} = A(h\nu - E_g) \quad (1)$$

where  $h$  is Planck's constant,  $\nu$  is the photon's frequency,  $\alpha$  is the absorption coefficient,  $E_g$  is the band gap and  $A$  is a proportionality constant.

2. Tauc, J., R. Grigorovici and A. Vancu, *Optical properties and electronic structure of amorphous germanium*. *Physica Status Solidi*, 1966. **15**: p. 627-637.

3. Davis, E.A. and N.F. Mott, *Conduction in non-crystalline systems V. Conductivity, optical absorption and photoconductivity in amorphous semiconductors*. *Philosophical Magazine*, 1970. **22**: p. 903.

4. Mott, N.F. and E.A. Davis, *Electronic processes in non-crystalline materials*. 2nd ed. 1979: Clarendon Press (Oxford and New York).



## Tauc plot

The value of the exponent denotes the nature of the electronic transition, whether allowed or forbidden and whether direct or indirect:

For direct allowed transitions  $n=1/2$

For direct forbidden transitions  $n=3/2$

For indirect allowed transitions  $n=2$

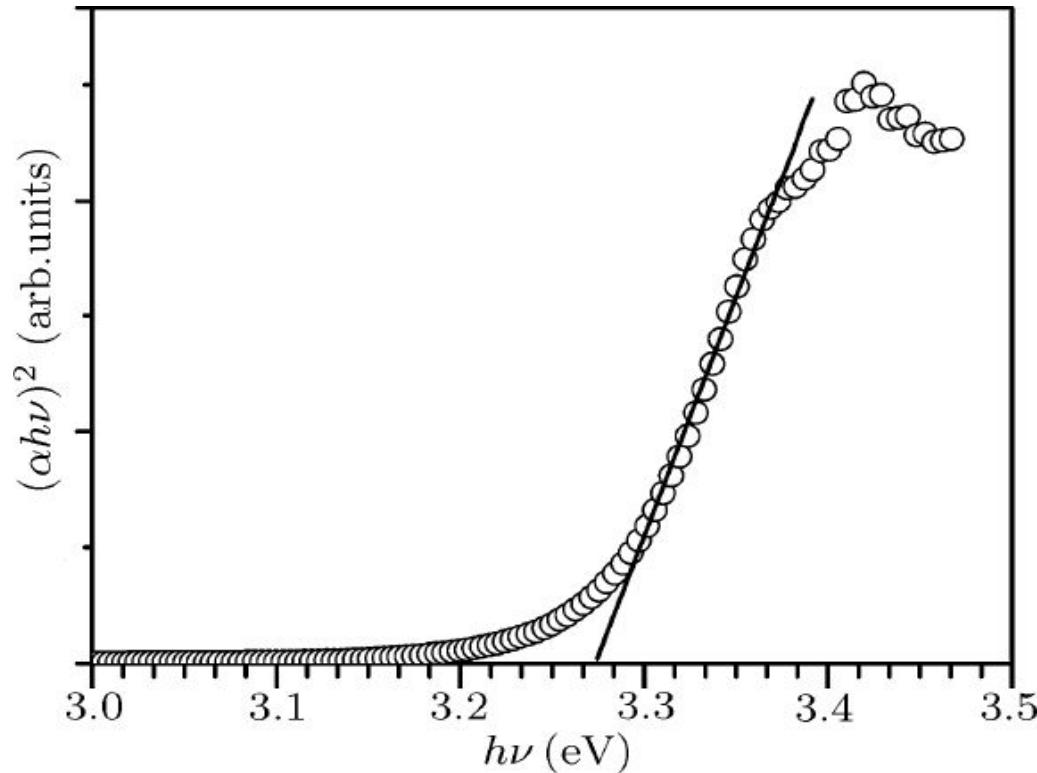
For indirect forbidden transitions  $n=3$

Typically, the allowed transitions dominate the basic absorption processes, giving either  $n=1/2$  or  $n=2$ , for direct and indirect transitions, respectively.

The resulting plot has a distinct linear regime which denotes the onset of absorption. Thus, extrapolating this linear region to the abscissa yields the energy of the optical band gap of the material.



### Tauc plot



**Figure 2: Example Tauc Plot from UV-Vis analysis of a ZnO thin film that illustrates the method of fitting the linear region to evaluate the band-gap at the X-axis intercept, here about 3.27 eV [5].**

5. Wang, M.D., D.Y. Zhu, Y. Liu, L. Zhang, C.X. Zheng, Z.H. He, D.H. Chen and L.S. Wen, *Determination of thickness and optical constants of ZnO thin films prepared by filtered cathode vacuum arc deposition*. Chinese Physics Letters, 2008. **25**(2): p. 743-746.



## Tauc plot

Figure 2 gives one example Tauc plot for ZnO where the absorption coefficient times the photon energy to the second power is plotted versus the incident photon energy[4].

The second power was used as zinc oxide is well known to have a direct allowed transition.

The characteristic features of Tauc plots are evident:

- at low photon energies the absorption approaches zero – the material is transparent;
- near the band gap value the absorption gets stronger and shows a region of linearity in this squared-exponent plot.
- This linear region has been used to extrapolate to the X-axis intercept to find the band gap value (here about 3.27 eV).
- At even higher energies the absorption processes saturate and the curve again deviates from linear.

## Tauc plot



To select and justify a linear region for extrapolation one must understand the reasons for these lower and upper deviations from linear behavior.

- On the low energy end, the deviation from linearity can be associated with defect absorption states that are near the band edge. This phenomenon has been investigated by Urbach [6] and in subsequent years, therefore, identified as an “Urbach Tail.” These states are usually described by an exponential function, corresponding to a typical distribution of density of states, evident in the absorption behavior seen in the example Tauc plot (Figure 2).
- On the high energy end, saturation of available transition states is responsible for a leveling out of absorption strength in most collected spectra [7].

6. Urbach, F., *The Long-Wavelength Edge of Photographic Sensitivity and of the Electronic Absorption of Solids*. Physical Review 1953. 92: p. 1324.

7. Brian D. Viezbicke., Shane Patel., Benjamin E. Davis, and Dunbar P. Birnie, III., *Evaluation of the Tauc Method for Optical Absorption Edge Determination: ZnO Thin Films as a Model System*. Physica Status Solidi, B 2015 252(8), 1700-1710.

## Concept of Photoluminescence

- Luminescence is an electromagnetic (EM) radiation phenomenon due to excessive thermal radiation or incandescence in physical system.
- With regard to luminescent semiconductors, when energy of incident photon is equal or beyond the energy band gap, it will excite the electron of valence band into conduction band through band gap.
- Semiconductors generate recombination radiation from excited state to ground state.
- Absorption will also happen when an electron is excited to higher energy level from neutral acceptor energy level and it can also transit to ionization donor energy level from valence band or transit to conduction band from ionization acceptor energy level. Those phenomena can explain the energy band or impurities in the semiconductor successfully.

## Concept of Photoluminescence

- Photoluminescence which inspects optical property of luminescent semiconductor materials is a strong and nondestructive technology.
- According to analytic data of photoluminescence, we can know the kind of impurities, band gap, and impurity activation energy etcetera from the spectra.
- We can estimate the composition of the compound from the peak intensity of PL spectra.
- Using photoluminescence can investigate the internal interface of hetero-structure that general physical or electronic measurements can not measure.

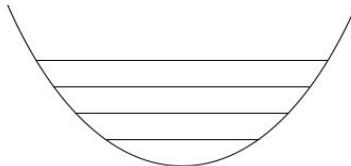


Fluorescent solutions under UV-light.  
Absorbed photons are rapidly re-emitted under longer electromagnetic wavelengths.

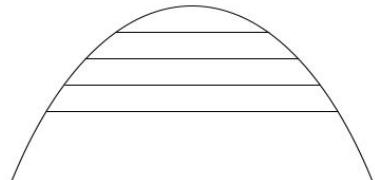


## Concept of Photoluminescence

- Luminescence process includes three procedures: (1) Excitation, (2) Heat balance, (3) Recombination.
- Incident light generates electron-hole pairs and recombines to generate photons after heat balance.
- Impurities and defects form various energy levels in the band gap and their corresponding energy will generate radiation by radiation recombination process or generate absorption by non-radiation recombination process.



Schematic for the excitation-relaxation processes of photoluminescence.



## Concept of Photoluminescence

Luminescence of semiconductors can divide two types:

### (1) Radiative transition

When an electron drops to lower energy state from higher energy state, it will probably occur radiative transition regardless of intrinsic state or energy state formed by impurities. Therefore, the system is not a balanceable condition and we assume that excited phenomena will generate electron-hole pairs in semiconductors. Firstly, we consider some basic transitions:

#### (a) Band-to-band transition:

Band-to-band transition is the relationship of free-electrons and holes. Those transitions usually occur in direct band gap materials such as III-V compounds where the electron-hole pairs will generate radiation recombination effectively between conduction band and valence band.



## Concept of Photoluminescence

### (b)Free exciton transition

If the material is very pure, an electron and a hole will attract each other to form exciton. Then, they will recombine to generate a very narrow spectrum. In III-V compounds, free exciton energy state usually describes Wannier-Mott approximation. The energy of free exciton can be expressed as Equation 1.

$$E_n = \frac{2\pi^2 m^* e^4}{h^2 \epsilon^2 n^2} \quad (1)$$

In this equation,  $m^*$  is effective mass,  $h$  is Planck constant,  $\epsilon$  is dielectric constant, and  $n$  is quantum number.

However, there are probably several mechanisms to result in non-radiative transition. Those transitions will compete with radiative transition to result in lower luminescence.

## Concept of Photoluminescence

### (c)Free-to-bound transition

The transition is free-to-bound transition between energy bands of materials and impurity energy level. This transition is between the impurity and one of energy bands such as from conduction band to acceptor or from donor to valence band. The energy of radiative photon is  $E_g - E_b$  and  $E_b$  is bound energy of shallow impurity energy level.

### (d)Donor-acceptor pair recombination

The transition is between donor and acceptor. After optical pumping, the electrons and holes will be bounded at D+ and A- locations to generate neutral  $D_0$  and  $A_0$  centers. Some neutral donor electrons will recombine with neutral acceptor holes radiatively.

## Concept of Photoluminescence

### Non-radiative transition

Some opportunities which cause non-radiative transition will compete with radiative recombination transition and influence luminescent efficiency negatively. They can describe as below:

- a) Because of thermal oscillation to generate phonons;
- a) Recombination on the surface state includes two dimensional dislocation, and agglomerative boundary et al. through step-wise transition which causes loss energy. It also calls cascade process;
- a) Impurity locations are often not radiative recombination centers;
- a) Loss energy of trapped carriers will excite other carriers in the lattice and emit non-radiative loss energy by Auger process.