

## Concept of Electrical Measurements

- Electrical and electronic measurements of materials are among the most powerful techniques available for materials characterization.
- The information that can be derived from these measurements are Conductivity (resistivity), Carrier Concentration, mobility, bandgap and other details about material transport properties.

### Conductivity Measurement.

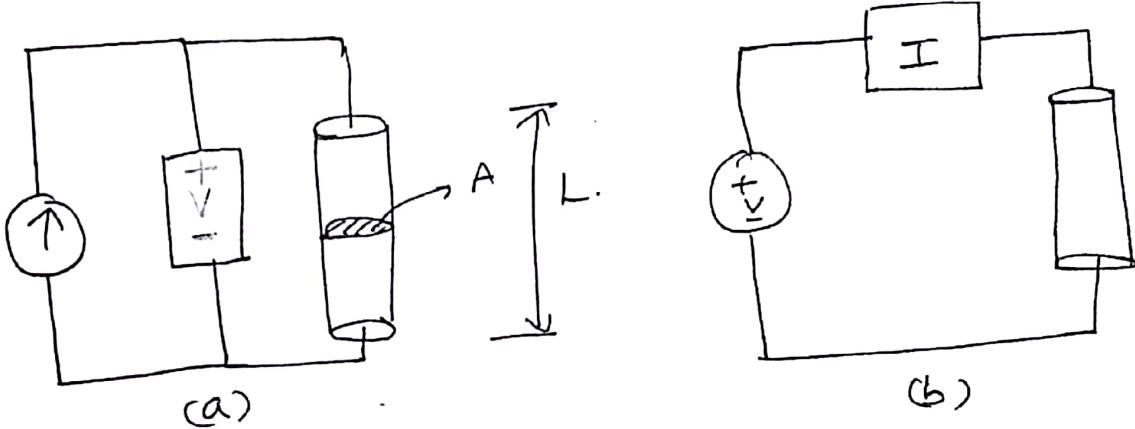
- A material's Conductivity,  $\sigma$ , relates its ability to conduct electricity.
- In metals, conduction of electricity is based on conduction of electrons whose density and scattering are important.
- In Semiconductors, Conductivity is determined by the number of available charge carriers and carrier mobilities.
- Since the mechanisms for conductivity are different, its dependence on temperature are also different.
- Conductivity increases with increasing temperature for Semiconductors (more carriers are generated) and it decreases with increasing temperature for metals (more scattering by the lattice).
- The Conductivity is also dependent on the physical structure, crystal type, orientation, crystallites (grain).
- The accurate determination of a material's conductivity can be critical for understanding material composition.
- The method used to determine Conductivity depends on whether the material is a bulk sample or a thin film.

## Two Point Probe Technique.

### Principle

- The Conductivity or resistivity of a bulk sample is based on accurate measurement of both resistance and the sample dimensions.
- The resistance is the ratio of the voltage measured across the sample to the current driven through the sample (Or) of the voltage applied across the sample to the measured current.

### Experiment.



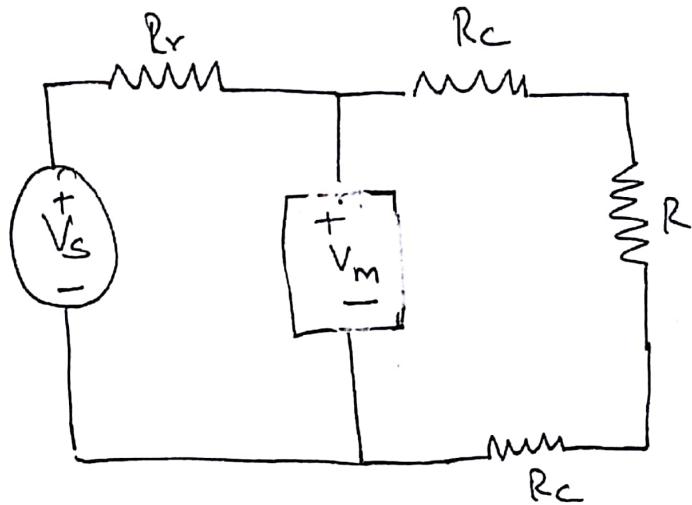
Two-point measurement of a resistive bar of length  $L$  and cross sectional area,  $A$  using (a) an ideal voltmeter in parallel with an ideal Current Source and (b) an ideal ammeter in Series with an ideal voltage Source

- For a homogenous bar of length  $L$ , and uniform Cross section  $A$  the resistance  $R$ , is related to the resistivity,  $\rho$  by .

$$R = \frac{\rho L}{A}$$

- The rod is connected in a "two-point" arrangement. The measurement apparatus is connected to the bar at the two end points.
- The measurement apparatus is represented by an ideal Current Source in parallel with a high-impedance voltmeter.

The apparatus can also be realised using an ideal voltage source in series with a low-impedance ammeter.



Two-point ohmmeter measurement circuit, which includes Contact and Cable resistance,  $R_c$

- This approach is a more realistic one.
- A Voltage Source and a variable range resistance ( $R_r$ ) supply the current, where  $R_r$  is adjusted to provide a convenient voltage across the voltmeter.
- Typical values of  $R_r$  from 100 to 10,000  $\Omega$ .
- $R_c$  represents Series resistance in Cable and the wire to Sample Contact resistance.
- The resistance in the bar is calculated as.

$$R = \frac{(R_r V_m / V_s)}{\left[1 - (V_m / V_s)\right]} - 2R_c$$

- A long bar of resistive material is desirable to minimize the effect of extra resistance in the measurement system or inaccurate length measurement.
- The two-point approach is most accurate for high-resistance measurements where usually small  $R_c$  term can be ignored.

# four Point Probe Technique - Linear Method. (1)

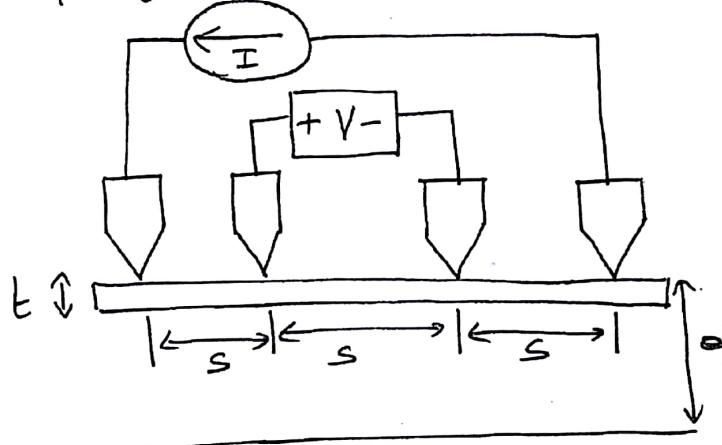
→ One of the most common approaches for measuring Sheet or Surface Conductivity is the four-point probe method.

## Principle

- The current is driven between a pair of probes or Connections and the voltage is measured across the other two.
- The four-point probe method is most often realised by Contacting a flat film surface with four equally spaced in-line probes.

## Experiment :

- The four-point probe method, has four equally spaced in-line probes with probe tip diameters small compared to the probe Spacing, "s".



In-line four-point probe measurement of a conductive film of thickness  $t$ , uses a known Current Source, high-impedance Voltmeter, Spacing loaded Sharp probes.

- An Ohmic Contact is assumed between the probe tip and the Sample.
- 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

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

where,  $F$  is a correction factor.

- for placement of probes near the center of a medium of area large relative to the probe spacing, and of a semi-infinite thickness, the correction factor  $F$  is unity.
- The correction factor  $F$  is dependent on the thickness of conducting layer, sample thickness, lateral dimensions of the sample (square, round, etc) and the conducting or semi-conducting nature of samples.
- Locating the probes closer than four probe spacings from the wafer edge can also result in measurement error.
- Separation of the current source from the high-impedance voltage meter avoids errors associated with contact resistance.
- At times of semiconductor measurements, sufficient separation between the current and voltage probes is required so that minority carriers injected near the current probes recombine before their presence can be felt at the voltage probes.

## Four Point Probe Method - Van der Pauw Method

→ One of the most common approaches for measuring Sheet or Surface conductivity is the Van der Pauw method.

Principle.

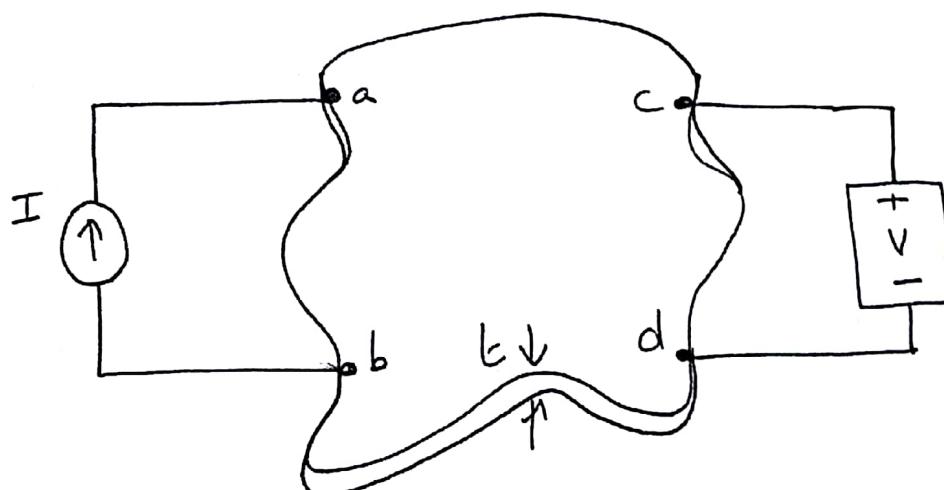
→ The current is driven between a pair of probes or connections and the voltage is measured across the two.

→ The Van der Pauw method can measure resistivity of small, arbitrarily shaped layers where the four contacts are typically placed around the periphery of the sample.

Experiment

→ The Van der 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.



Van der Pauw measurement of an arbitrarily shaped sample uses a known current and a high-impedance voltmeter.

- The method considers four small contacts placed on 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,

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

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

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

- 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.

①

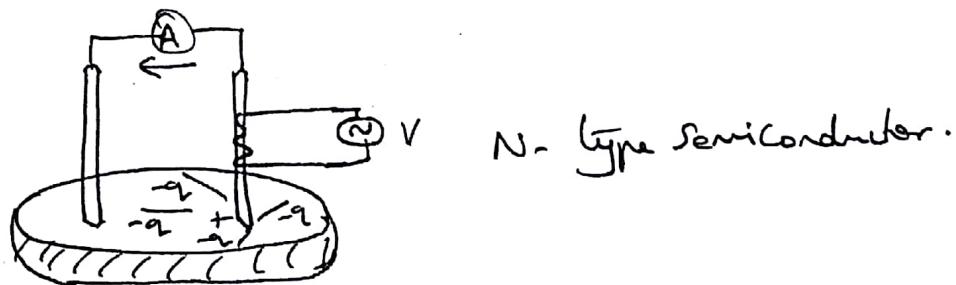
## Hot Probe Method for Semiconductor Thin films

- Physical properties of thin films significantly differs from those of bulk materials.
- There are various parameters such as thickness, crystal structure, composition and defects, which characterize a semiconductor film.
- The parameters or charge carriers like
  - (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-point probe experiment enables a simple and efficient way to distinguish between p-type and n-type semiconductors using a hot probe and a stand multimeter.



- While applying the cold and hot probes to an n-type semiconductor, positive voltage readout is obtained in meter, whereas for a p-type semiconductor, negative voltage readout 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 contact. Constant heating in the hot probe
- These translated majority charged carriers define the electrical potential sign of the measured current in multimeter.
- The hot-probe measurement may be describe 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 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 upto 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 excited additional charged carriers.

This three-step process may be described, in general, by the Continuity and Poisson's equation.

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

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

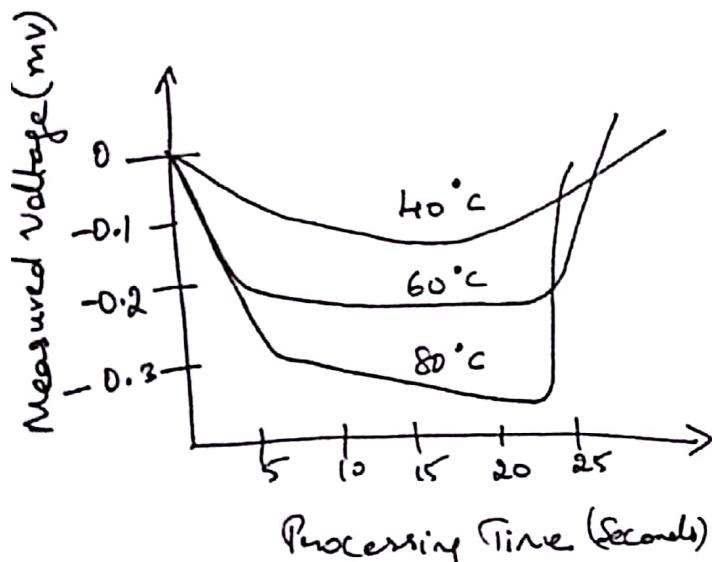
Where,  $Q \rightarrow$  uncompensated charge density excited by the heated electrode.

$J \rightarrow$  Current density.

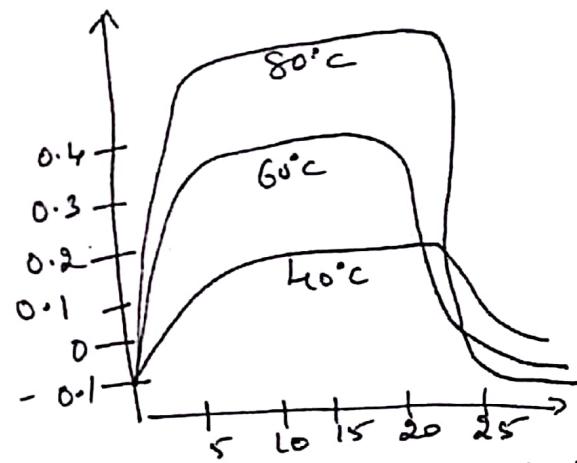
$\epsilon_0 \rightarrow$  absolute permittivity.

$\epsilon_r \rightarrow$  relative permittivity.

$E \rightarrow$  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 oxidised Silicon Surface by thermal evaporation.

# Capacitance - Voltage Measurements

⑪

- 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 p-n-junctions, metal-semiconductor junctions (Schottky barriers), electrolyte-semiconductor junctions, metal-insulator-semiconductor junctions, capacitors, and MIS field effect transistors.
- C-V measurements yield accurate information about the doping concentrations of majority carriers as a function of distance (depth) from the junction.

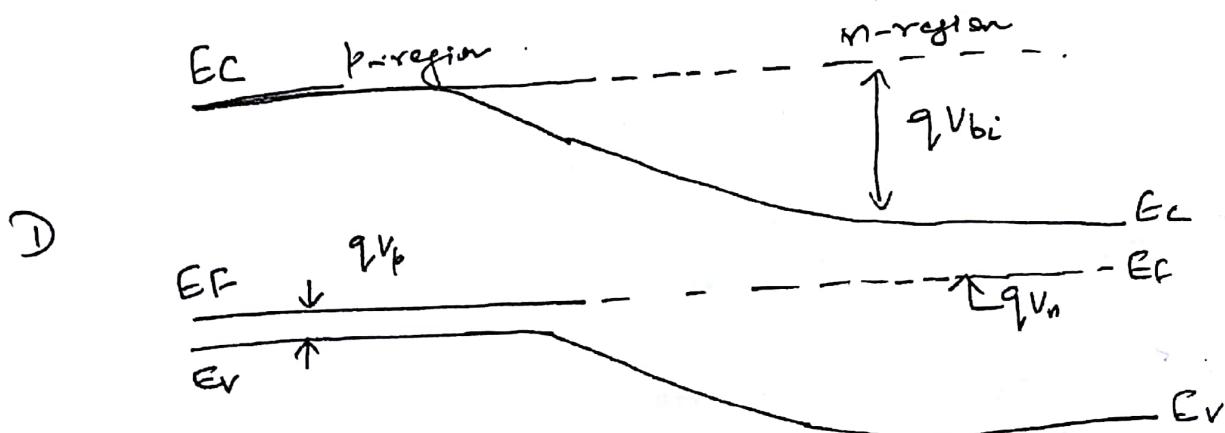
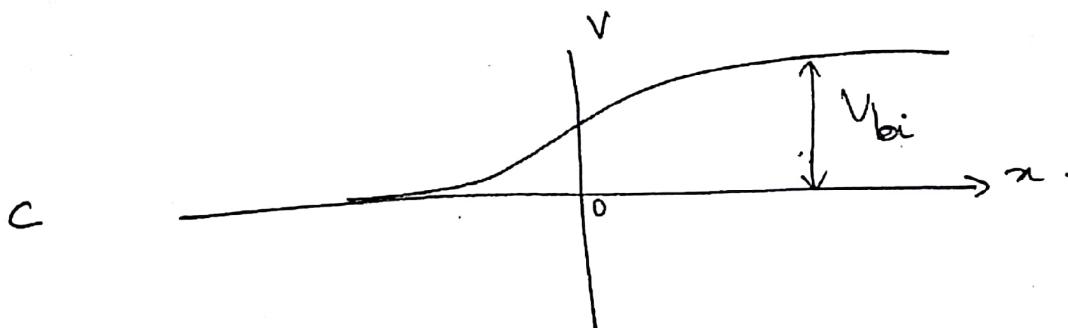
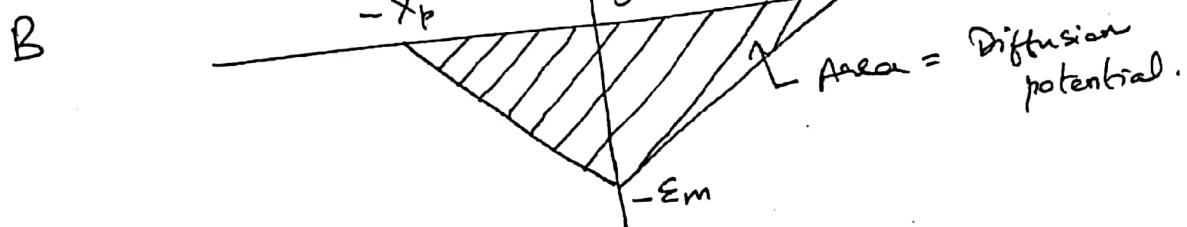
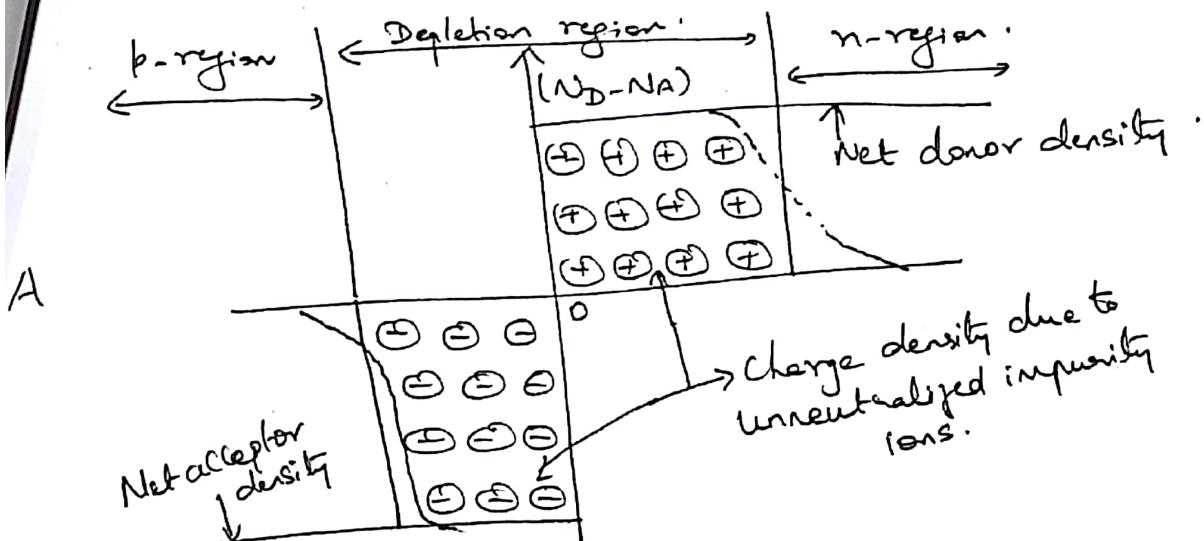
## Principle

- 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 in 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  $E_G = E_C - E_V$  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 crosses the  $p-n$  junction is called the diffusion potential,  $V_{bi}$  (built-in potential).



### 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. Energy band diagram.

→ 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

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

→ 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,

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

## Deep-Level Transient Spectroscopy (DLTS)

- Defects are responsible for many characteristic properties of a Semiconductor. They play a crucial role in determining the viability of a given material for device applications.
- The performance and reliability of devices can be significantly affected by only minute concentrations of undesirable defects.
- Deep-level transient Spectroscopy (DLTS) probes the temperature dependence of the charge carriers escaping from trapping centers formed by the point defects in the material.

### Principle.

- Deep-level transient Spectroscopy was first introduced in 1974, by Lang.
- The basis of this method is the dependence of the Capacitance of a Space-charge region on the occupancy of the traps within the Space-charge region in a Semiconductor.
- Under a non-equilibrium condition such as that existing in a Space-charge region, a trapped carrier can escape from a trapping center by thermal excitation to the nearest energy band.

### Experiment.

- To characterize a Semiconductor, it is necessary to fabricate a junction diode such as p-n- or Schottky barrier diode on material of interest.
- A Space-Charge region is formed by reverse biasing the p-n or schottky diode. The diode is initially reverse biased to empty the traps.

- When the bias across the junction is reduced (or even forward biased), the width of the space-charge region is reduced.
- An equilibrium condition is established in the neutralized region with the majority carriers populating the traps.
- When the reverse bias is restored, the space-charge region is again created as before, with only difference being that there are trapped carriers now residing in the defect centers within the space-charge region.
- The non-equilibrium condition thus created causes the trapped carriers to be thermally re-emitted to the relevant energy band.
- The rate of thermal emission, or "de-trapping", of a carrier is temperature dependent.
- The change of occupancy of these trapping centers is reflected in the capacitance of the junction producing a capacitance transient.
- Minority-carrier injection can also occur when the junction is forward biased during the bias pulse.
- Since both the majority and minority charge carriers are involved, which makes this method all more effective because emission of each type of carrier can be detected by monitoring the capacitance transients.
- The activation energy of the trap, or the depth of the trapping level from the nearest energy band edge, and the capture cross-section can be determined from the temperature dependence of emission rate.
- The trap concentrations can be determined from the intensity of the capacitance peak, and the polarity of the carriers can be found from the sign of the capacitance change.

## Instrumentation:

- As the trapped electrons are emitted into the conduction band following the termination of the bias pulse, the capacitance of the junction will decay exponentially with a time constant  $\tau_n$  according to the equation

$$C(t) = C(0) e^{-t/\tau_n}$$

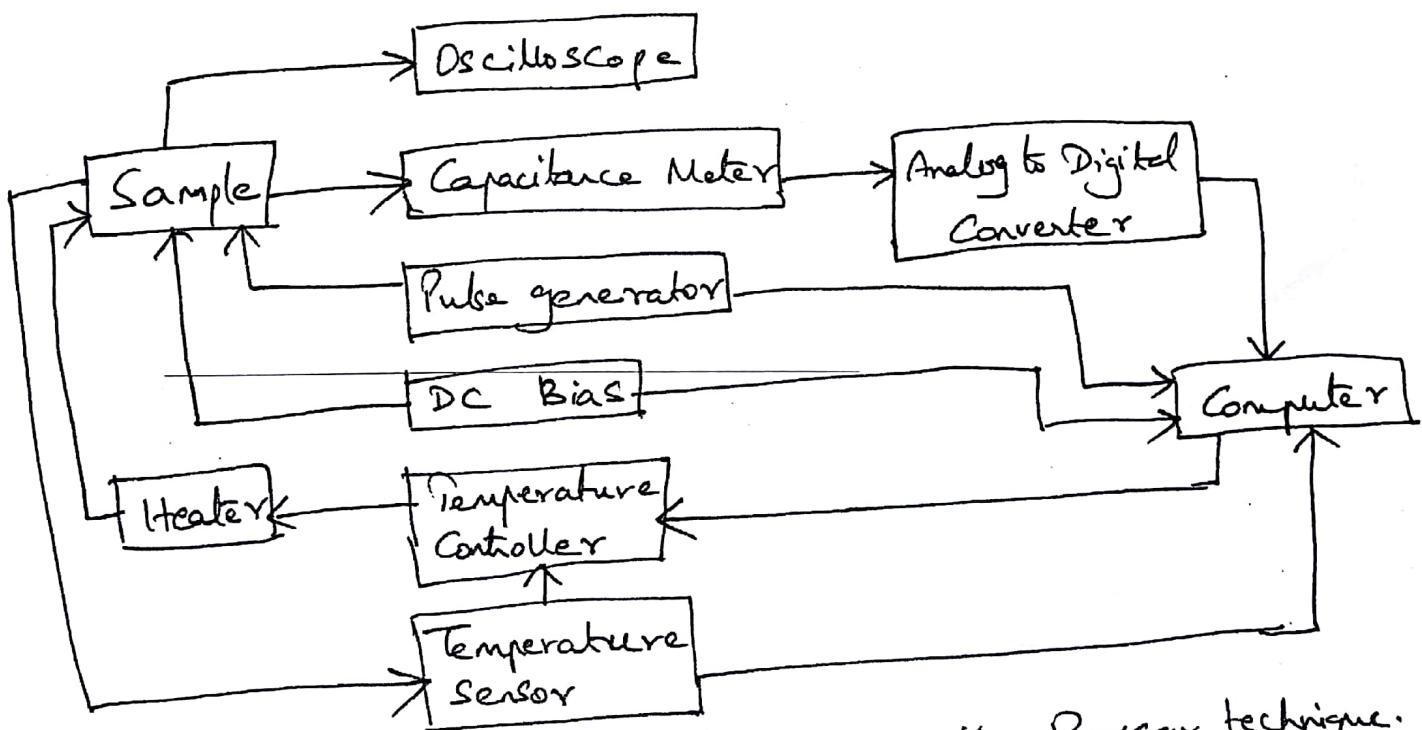
But  $\tau_n = \frac{1}{e_n}$

then,  $C(t) = C(0) e^{-e_n t}$

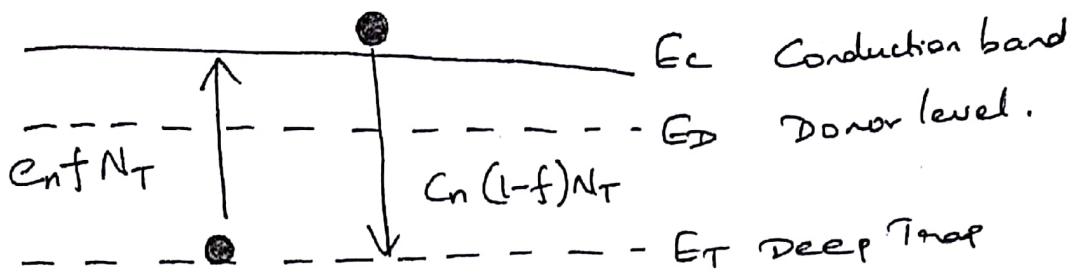
- If the decaying capacitance transient is measured at two different time delays  $t_1$  and  $t_2$  from the termination of the bias pulse, then the difference in the capacitances will be given by

$$S = \Delta C = C(t_1) - C(t_2) = C(0)(e^{-e_n t_1} - e^{-e_n t_2})$$

- The capacitance difference  $S$  is the DLTS signal.



A DLTS Spectrometer using the Boxcar technique.



$E_v$  Valence Band.

Electron transitions between the trapping level and the conduction band.

→ The rate of electron Capture

$$\frac{dc_n}{dt} = n v_{th} \sigma_n (1-f) N_T$$

where,  $c_n$  → Capture probability.

$\sigma_n$  → electron Capture Cross-Section

$v_{th}$  → Thermal Velocity

$n$  → electron Concentration

$(1-f)$  → probability that a trap is vacant.

$f$  → fermi-Déroc probability factor (a fraction of total Concentration of traps  $N_T$  is filled)

→ The electron detrapping rate

$$\frac{de_n}{dt} = e_n \bar{N}_T = e_n f N_T$$

where,  $e_n$  → electron emission rate

$\bar{N}_T$  → Concentration of occupied traps  $N_T$

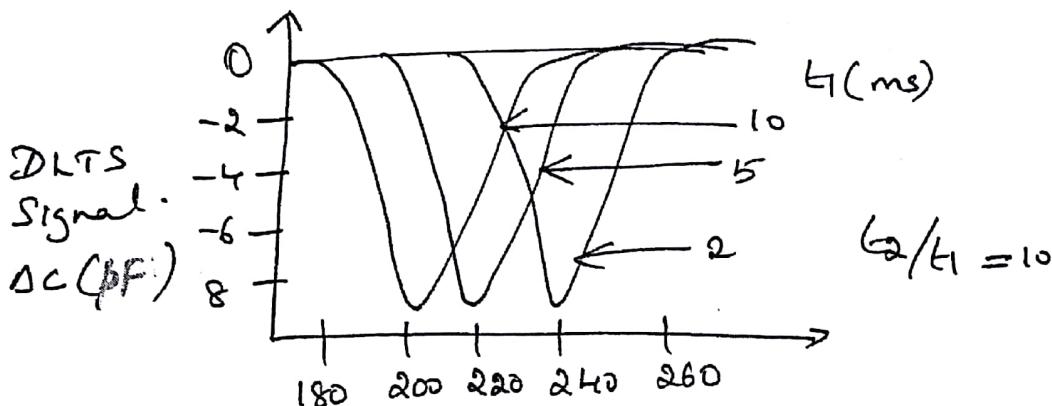
By monitoring the DLTS Signal  $s$ , as a function of temperature, it is observed that at low temperatures ( $T \ll T_m$ ) and at high temperatures ( $T \gg T_m$ ), the signal is very small.

- However, at an intermediate temperature  $T_m$ , the signal will go through a maximum value. At this temperature,

$$\frac{ds}{dT} = \frac{ds}{den} \times \frac{den}{dT} = 0$$

Therefore,  $\frac{ds}{den} = -t_1 e^{-ent_1} + t_2 e^{-ent_2} = 0$

which gives,  $en = \frac{\ln(t_2/t_1)}{t_2 - t_1}$



- By varying  $t_2$  and  $t_1$ , but keeping the ratio  $t_2/t_1$  constant (thus changing the value of  $en$ ) and repeating the temperature scan, a different curve will be obtained, with signal  $S$  peaking at different temperatures  $T_m$ .

$N_D(x) \leftarrow N_A(x) \rightarrow$  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,  $V_{bi} = \frac{kT}{q} \ln \left( \frac{N_A N_D}{n_e n_h} \right)$

## Photoluminescence

- When a Crystalline Solid absorbs energy (usually in the form of radiation) and re-emits it in the Visible (or nearly visible) region of the Spectrum, this phenomenon is called as luminescence.
- It is a two step process:
  - (i) excitation of electrons from a lower energy state to a higher energy state as a result of absorption of energy.
  - (ii) emission of light radiation when the electrons fall back to a lower energy state
- When the luminescence is produced by the bombardment of photons of an electromagnetic radiation lying in the range from infrared to X-rays, it is called photoluminescence.
- The time during which the luminescence is observed, depends on the time interval between the acts of excitation and emission.
- If the emission takes place within  $10^{-8}$  seconds of excitation or if the emission takes place as long as the excitation is maintained, the phenomenon is called ~~the~~ fluorescence.
- If the luminescent emission continues for some time even after the excitation has been removed, it is known as phosphorescence or afterglow.