

Semiconductor Physics and Computational Methods (21PYB102J)

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Module-IV

Concepts of Electrical measurements & Two point probe technique

Concepts of Electrical measurements



General Introduction:

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

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.,

$$V \propto I \text{ (or)}$$

$$V = I R$$

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

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.,

$$R \propto L / A \text{ (or)} \quad R = \rho L / A$$

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.

- A material's **conductivity, σ** , (or the inverse property, resistivity, $\rho = 1/\sigma$), relates to its ability to conduct electricity. In metals, conduction of electricity corresponds to conduction of electrons, which depends on charge density and on scattering of the electrons by the crystal lattice (phonons) or by lattice imperfections.
- In semiconductors, conductivity is determined by the number of available charge carriers (electrons or holes) and the carrier mobility. Because of the different mechanisms for conductivity, its dependence on temperature also differs. Conductivity increases with increasing temperature for semiconductors (more carriers are generated) and it decreases with increasing temperature for metals (more scattering by the lattice).
- Conductivity also depends on physical structure. In crystals, the crystal type and orientation affect conductivity because the electronic structure is intimately tied to the crystal structure. The size of the crystallites (grains) in polycrystalline materials is also important as it affects the scattering of carriers, and, at very small sizes may also affect electronic structure.

Table 1. General Characteristics for Conductivity Measurement Methods

Method	Favored material Type	Favored Material Form	Estimated Measurement Range
Two-point measurement	High-resistance metals	Solid bar	$10^2 - 10^9 \Omega$
Four-point measurement	Metals	Solid bar	$10^{-7} - 10^4 \Omega$
Four-point probe	Semiconductor surface, thin metallic films	Planar solid	$10^{-3} - 10^5 \Omega\text{-cm}$
Van der Pauw	Semiconductor surface, thin metallic films	Planar solid	$10^{-3} - 10^5 \Omega\text{-cm}$

Resistivity Measurement



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. The wafers resistivity is usually modified locally during device processing by diffusion and ion implantation.

Two general methods involved for measuring the resistance of the materials are:

- i. **Two point probe method**
- ii. **Four point probe method**
 - a. **Linear method**
 - b. **van der pauw method**

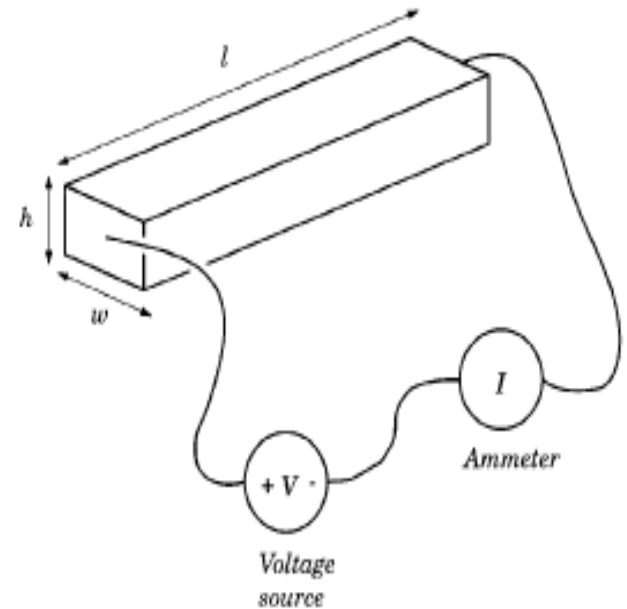
Two-probe method



Let us consider a rectangular bar of length 'l', height 'h' and width 'w' as shown in figure. copper wire is attached to both ends of the bar.

The resistivity of the bar can be measured by measuring voltage drop across the wire due to passage of known current supplied by the voltage source 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.,

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



In general, we use a multimeter for measuring the resistance of the materials. The typical range of resistance measured using the multimeter is $1\ \Omega$ to $2\ \text{M}\Omega$, but varies with the models and company.

While the two-probe method is a simple and advantageous method for measuring resistance above 1Ω directly, this method suffers from certain issues.

Two-probe method:

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

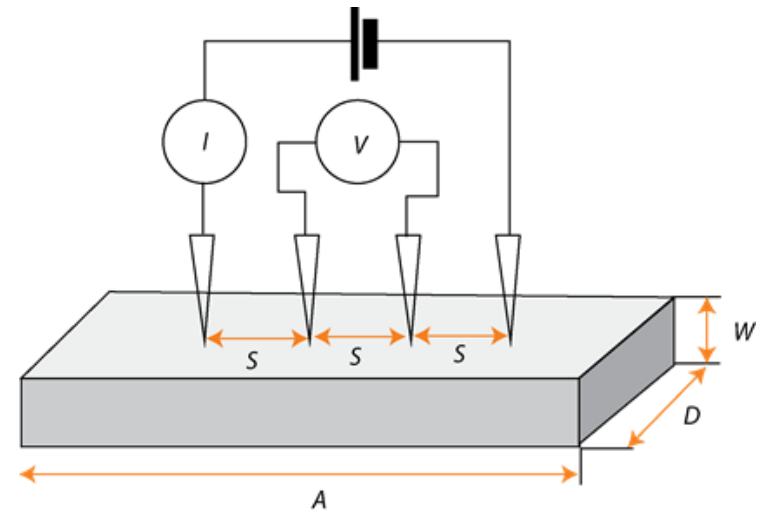
In order to overcome the above problems, four-probe method is widely used.

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Four-point probe technique-linear method & Van der Pauw method

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 used in two-probe method are replaced by pressure contacts to eliminate the last two problems summarized above.
- In this method, four probes are utilized to measure the resistance of the samples.
- 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.



Two common techniques used in four-probe method are

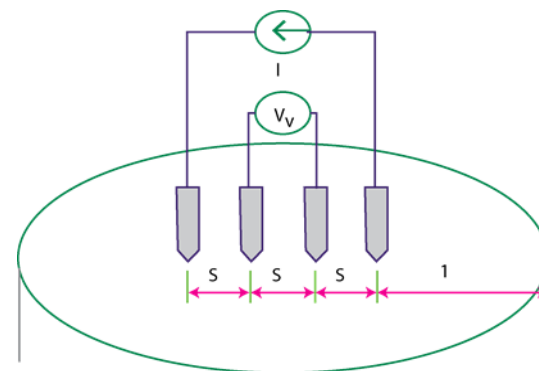
- (i) **Four-point collinear probe method**
- (ii) **van der Pauw method**

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

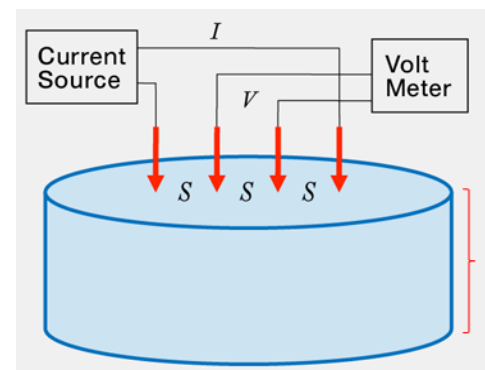
Four-point collinear probe method:

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.



Schematic of four-point collinear probe method.



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

Four-point collinear probe method: **For Bulk:**

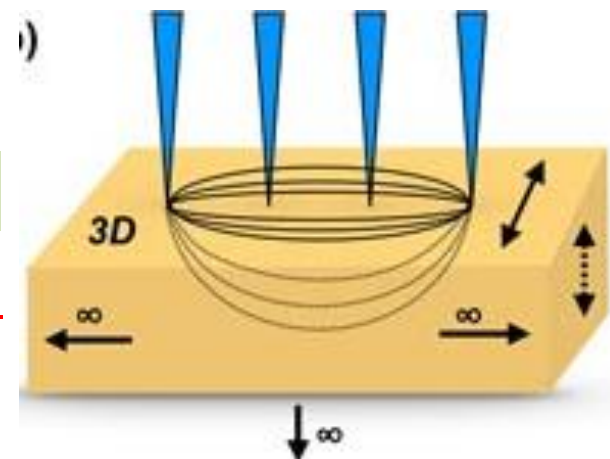
Consider a bulk material as shown in Figure , where the thickness (t) of the materials is much higher than the space between the probes (s), then the differential resistance due to spherical protrusion of current emanating from the outer probe tips is

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

Carrying out the integration between the inner probe tips,

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

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



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

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

Four-point collinear 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 $A = 2\pi xt$. Therefore, the derivation for resistance turns out to be:

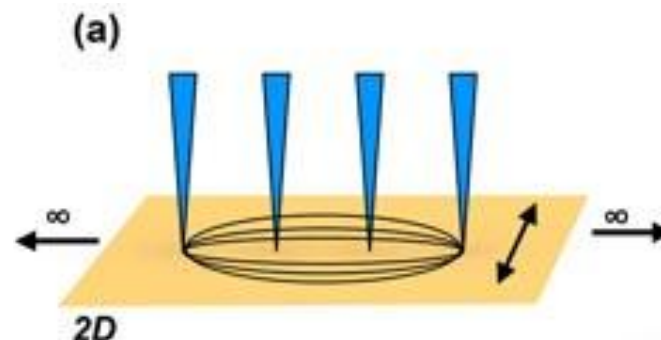
$$R = \int_{v1}^{v2} \rho \frac{dx}{2\pi xt} = \int_s^{2s} \frac{\rho}{2\pi t} \frac{dx}{x}$$

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

where probe spacing is uniform.

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

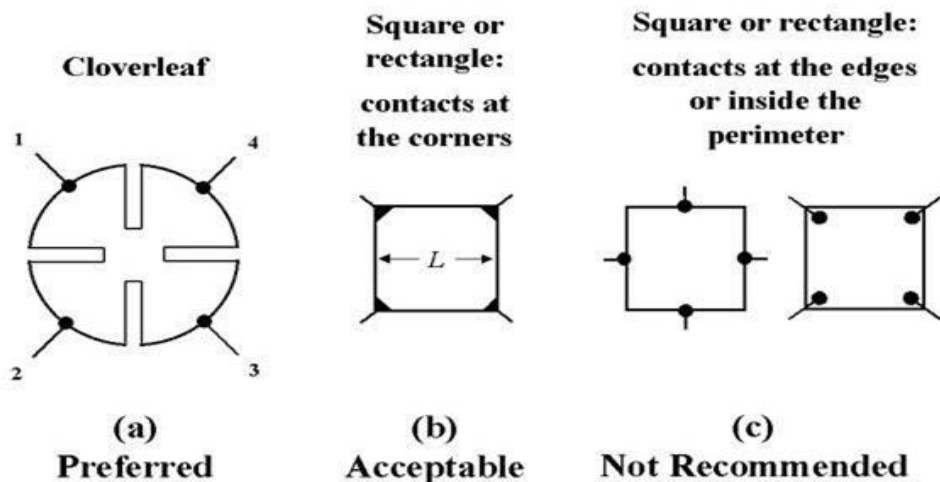
$$\rho = \frac{Vt\pi}{I \ln 2}$$



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

van der Pauw method

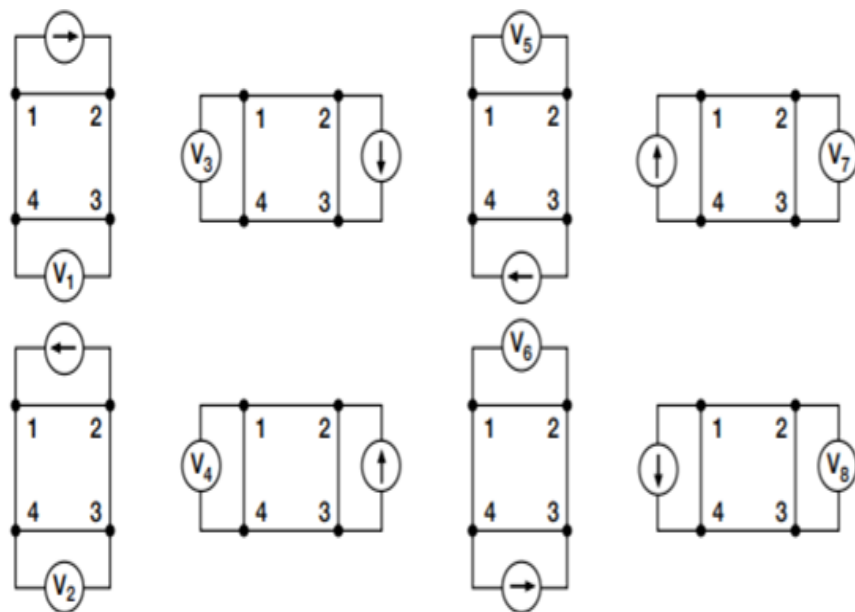
- ❑ The van der Pauw method is a technique commonly used to measure the resistivity and the Hall coefficient of a sample. There are some conditions that must be satisfied to use this technique:
- ❑ The sample must have a flat shape of uniform thickness.
- ❑ The sample thickness must be much less than the width and length of the sample.
- ❑ The sample must be homogeneous and isotropic.
- ❑ The sample must not have any isolated holes.
- ❑ 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.
- ❑ In order to reduce errors in the calculations, it is preferable that the sample be symmetrical.



Make four ohmic contact with the periphery.

The contacts are numbered from 1 to 4 in a counter-clockwise order, beginning at the top-left contact.

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



Once all the voltage measurements are taken, two values of resistivity, ρ_A and ρ_B , are derived as follows:

$$\rho_A = \frac{\pi}{\ln 2} f_A t_s \frac{(V_1 - V_2 + V_3 - V_4)}{4I}$$

$$\rho_B = \frac{\pi}{\ln 2} f_B t_s \frac{(V_5 - V_6 + V_7 - V_8)}{4I}$$

where: ρ_A and ρ_B are volume resistivity in ohm-cm; t_s is the sample thickness in cm; V_1 – V_8 represents the voltages measured by the voltmeter; I is the current through the sample in amperes; f_A and f_B are geometrical factors based on sample symmetry. ($f_A = f_B = 1$ for perfect symmetry).

Once ρ_A and ρ_B are known, the average resistivity (ρ_{AVG}) can be determined as follows:

$$\rho_{AVG} = (\rho_A + \rho_B)/2$$

Following properties of a material can be measured by this method:

1. Resistivity
2. Doping type (p- or n-type)
3. Density of majority carriers (majority carriers per unit area)
4. Charge density and doping level
4. Mobility of majority carriers

Advantage of four probe method over two probe method:

- ❖ Four point probe is preferred than two-point probe.
- ❖ 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.
- ❖ To measure very low resistance values, four probe method is used.
- ❖ The resistance of probe will not be added to that of sample being tested.

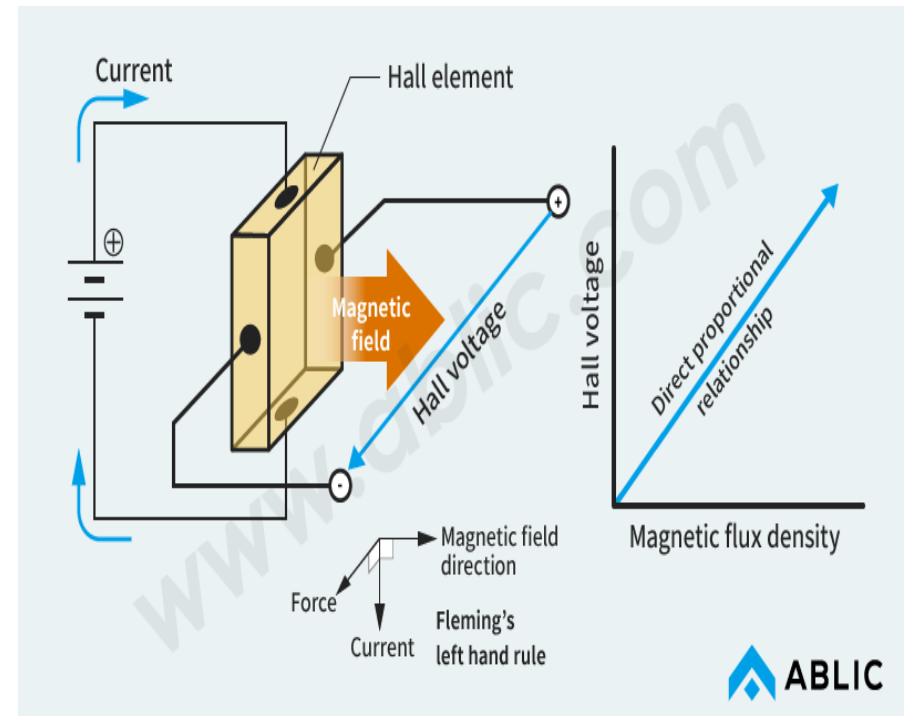
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18PYB103J –Semiconductor Physics

HALL EFFECT

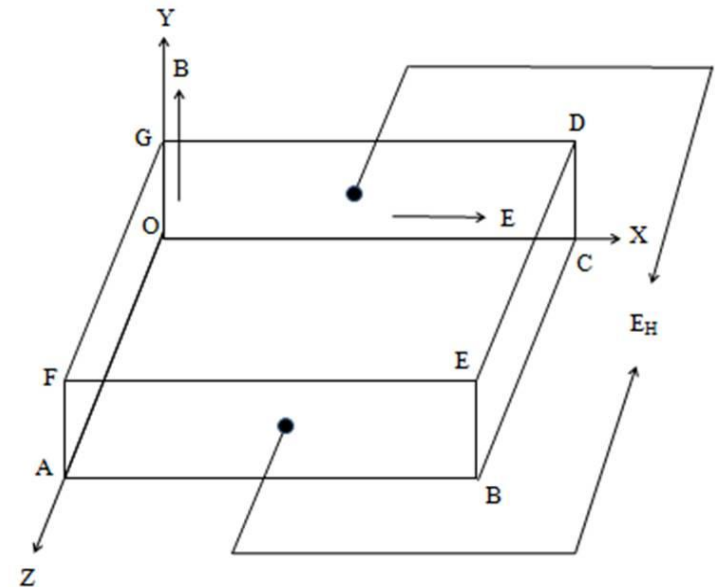
Definition:

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 majority 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).

At equilibrium , **$-eE_H = -Bev$** (or) **$E_H = Bv$** (1)

If J is the current density, then, **$J = -nev$** (2)

Where ‘n ‘ is the concentration of current carriers,

From equ. (2)

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

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

$$E_H = BJ / -ne$$ (4) .

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

$$\mathbf{E_H = R_H B J}$$

$$\text{(or) } \mathbf{R_H = E_H / B J} \quad (5)$$

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

$$\mathbf{R_H = - 1/ne} \quad (6)$$

- 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

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

We know that $R_H = E_H / BJ$ (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,

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

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

$$\mathbf{V_H = R_H w BJ / wt} \quad = \mathbf{R_H I B /t}$$

$$\text{(or) } \mathbf{R_H = V_H t / IB} \quad (12)$$

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

Experiment:

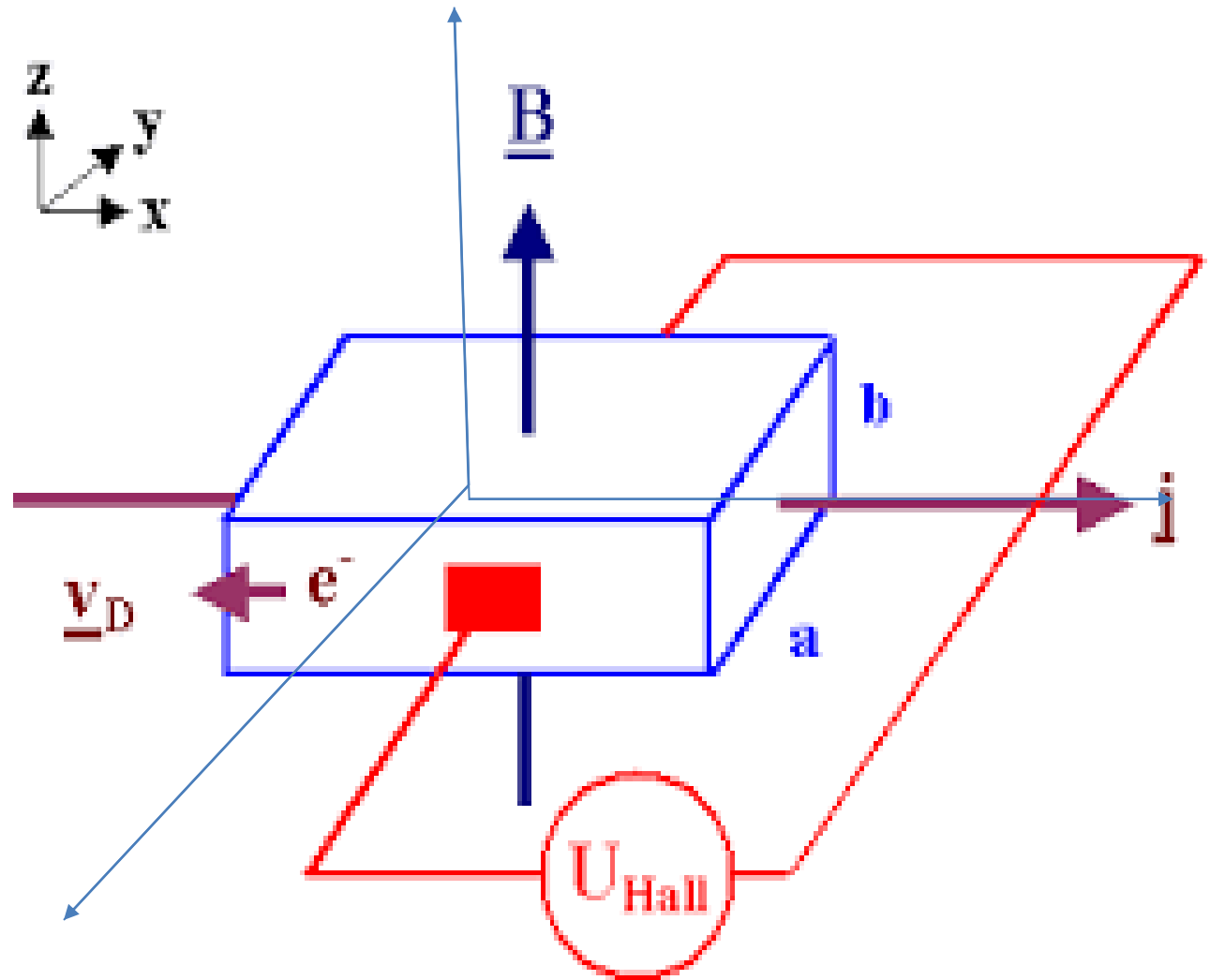
A rectangular slab of the given material having thickness 't' and width 'w' is taken . A current of 'I' amperes is passed through this sample by connecting it to a battery, 'Ba'. The sample is placed between two pole pieces of an electromagnet such that the field 'B' is perpendicular to I as shown in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

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

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 σ and R_H , μ 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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Module –IV ; LECTURE - 7

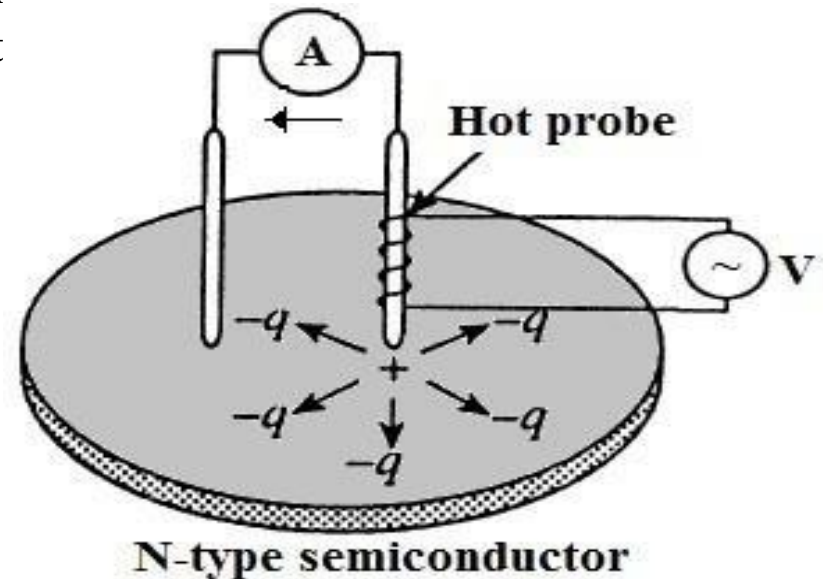
HOT PROBE METHOD FOR SEMICONDUCTOR THIN FILM

- 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
- These will define the possibility to apply material for various electronic devices
- The parameters of charge carriers are
 - (a) Type of semiconductor,
 - (b) Impurities concentration,
 - (c) Mobility of charged carriers,
 - (d) Diffusion coefficient.

HOT PROBE METHOD FOR SEMICONDUCTOR THIN FILM

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:

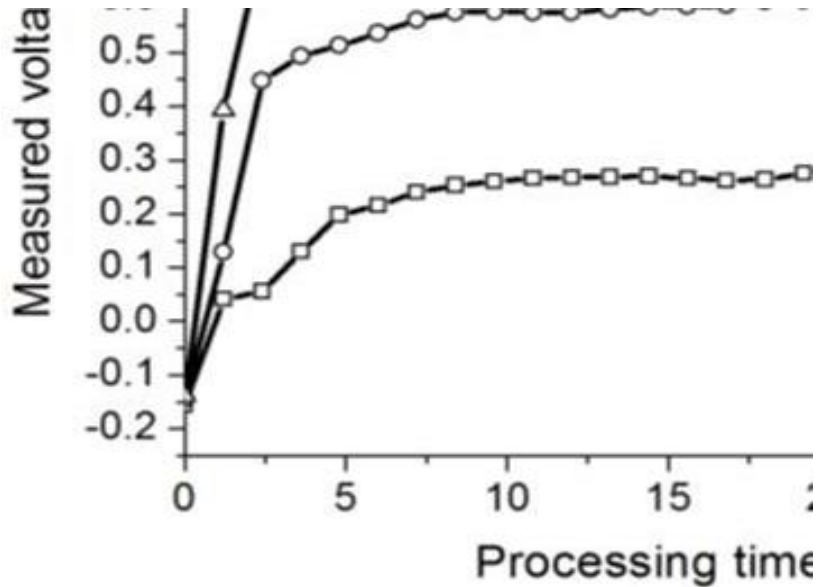
1. The heated probe excites additional free charged carriers of two types
2. The hot majority carriers begin to leave the heated part of the semiconductor surface by a diffusion mechanism. Simultaneously, a built-in electrical field is created between the electrodes and the second (cold) electrode is 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

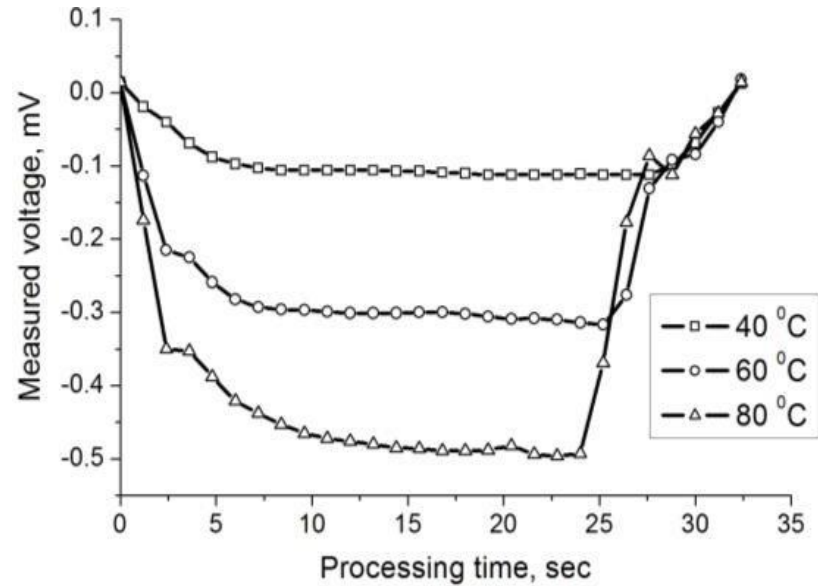
$$\nabla J + \frac{\partial Q}{\partial t} = 0$$

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

- Here Q is the uncompensated charge density excited by the heated electrode, J is the current density, ϵ_0 and ϵ_r are the absolute and relative permittivity, and E is the built-in electrical field.



(a) As deposited film of N-type



(b) Thermally treated film of P-type

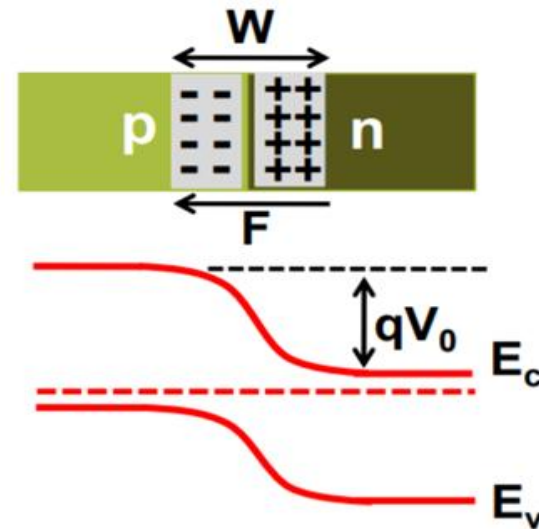
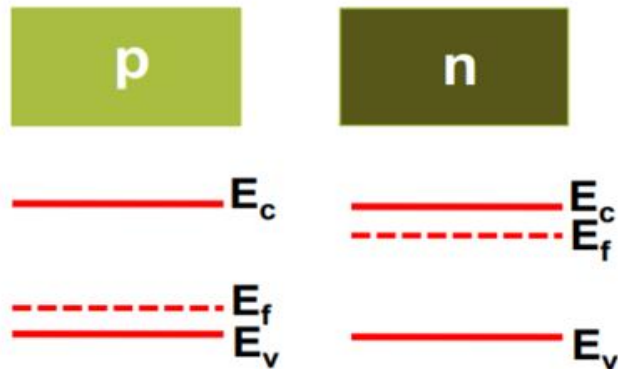
Hot-probe characteristics for vanadium oxide thin films deposited on the oxidized silicon surface by thermal evaporation.

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.**

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

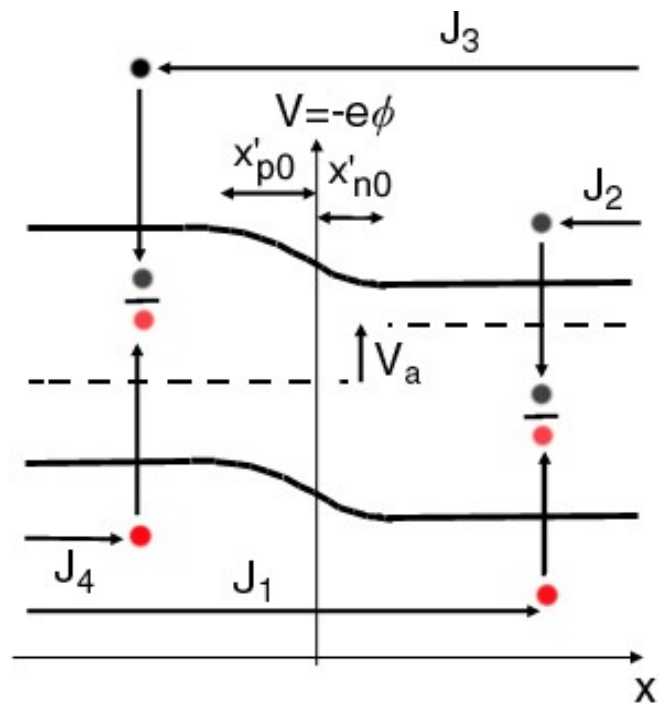
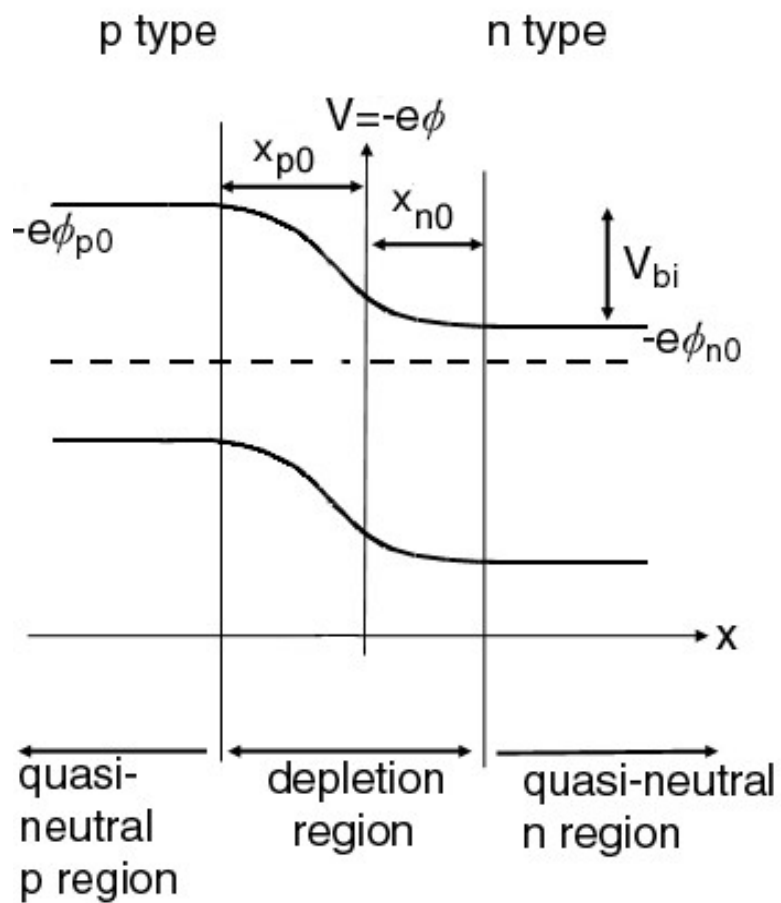
Principle:

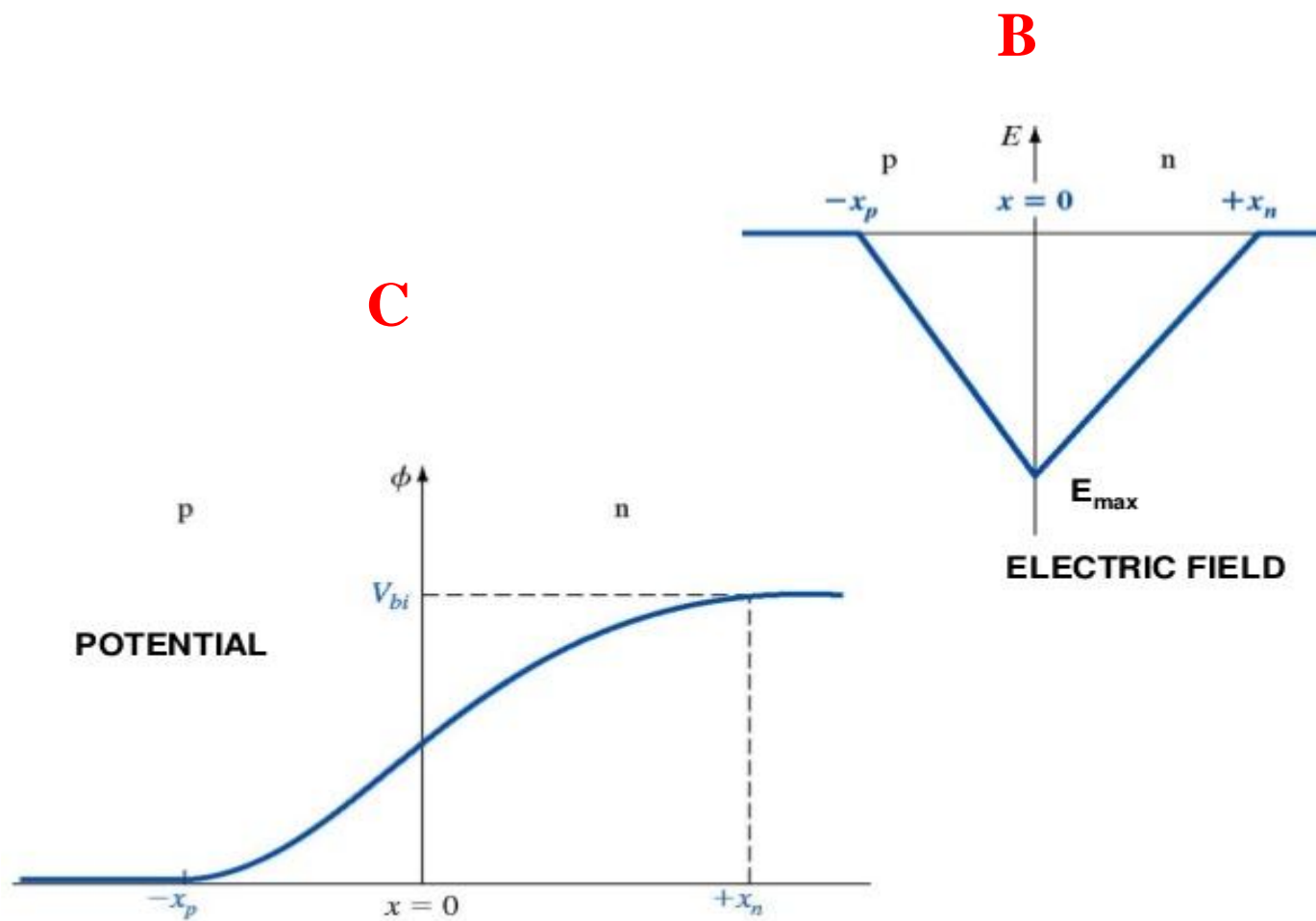
- The capacitance at an p-n or metal–semiconductor junctions depends on the properties of the charge-depletion layer formed at the junction
- The depletion regions is the vicinity of the PN junction and is “depleted” of free carriers due to the drift field required to maintain charge neutrality.

Experiment:

- As shown in figure (previous slide) an abrupt p-n 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 valance band energy E_v .
- The Fermi energy E_F defines the equilibrium condition for the charge neutrality.
- The difference in energy between the conduction bands as one crosses the PN junction is called the diffusion potential, V_{bi} (built-in-potential).

A





D

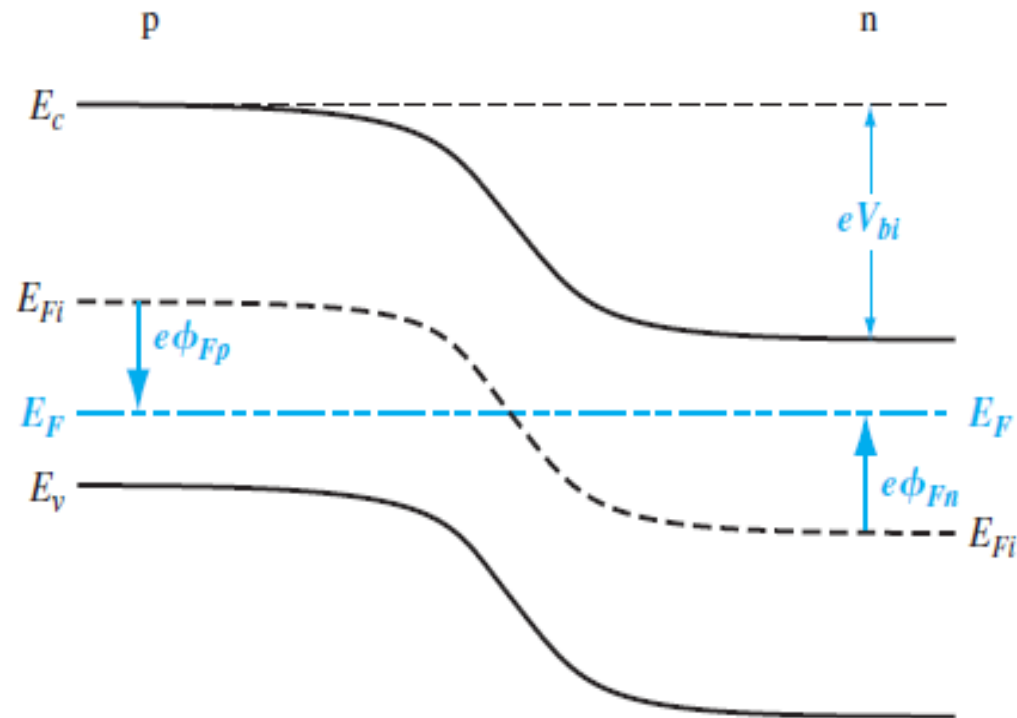


Figure 7.3 | Energy-band diagram of a pn junction in thermal equilibrium.

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 + and – indicates the junction region depleted of free carriers, leaving behind ionized donors and acceptors.
- In this region from Poisson's equations

$$\bullet \quad \frac{\partial^2 v}{\partial x^2} = \frac{\partial E}{\partial x} = \frac{\rho(x)}{\varepsilon} = \frac{e}{\varepsilon} [p(x) - n(x) + N_D^+(x) - N_A^-(x)]$$

For predominantly doped p-type

$$-\frac{\partial^2 v}{\partial x^2} \approx \frac{e}{\varepsilon} N_A^- \quad \text{for } -x_p \leq x < 0$$

And for n-type

$$-\frac{\partial^2 v}{\partial x^2} \approx \frac{e}{\varepsilon} N_D^+ \quad \text{for } 0 < x \leq x_n$$

- Where v - Voltage, ε – Electric field, e - charge, $p(x)$ and $n(x)$ –the hole and electron concentration(electric potential) comprising the mobile carriers.
- N_D^+ and N_A^- - the donor and acceptor doping concentrations
- $\varepsilon = K_s \varepsilon_0$ – The permittivity with dielectric coefficients
- *The* spatial dependence, x is measured relative to the physical location of the p-n junction. The solution of three equations is a form useful for C-V measurements is
- $V(x) = V_{bi} \left[2 \left(\frac{x}{w} \right) - \left(\frac{x}{w} \right)^2 \right]$
- *where* $V_{bi} = \frac{KT}{e} \ln \left(\frac{N_d N_a}{n_i^2} \right)$

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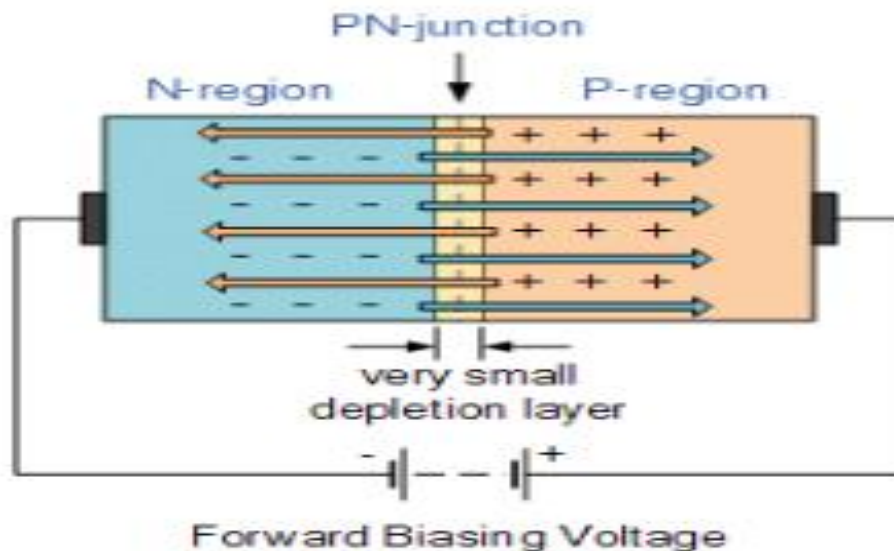
Extraction Parameters & I-V Characteristic of PN Junction Diode

PN Junction Diode

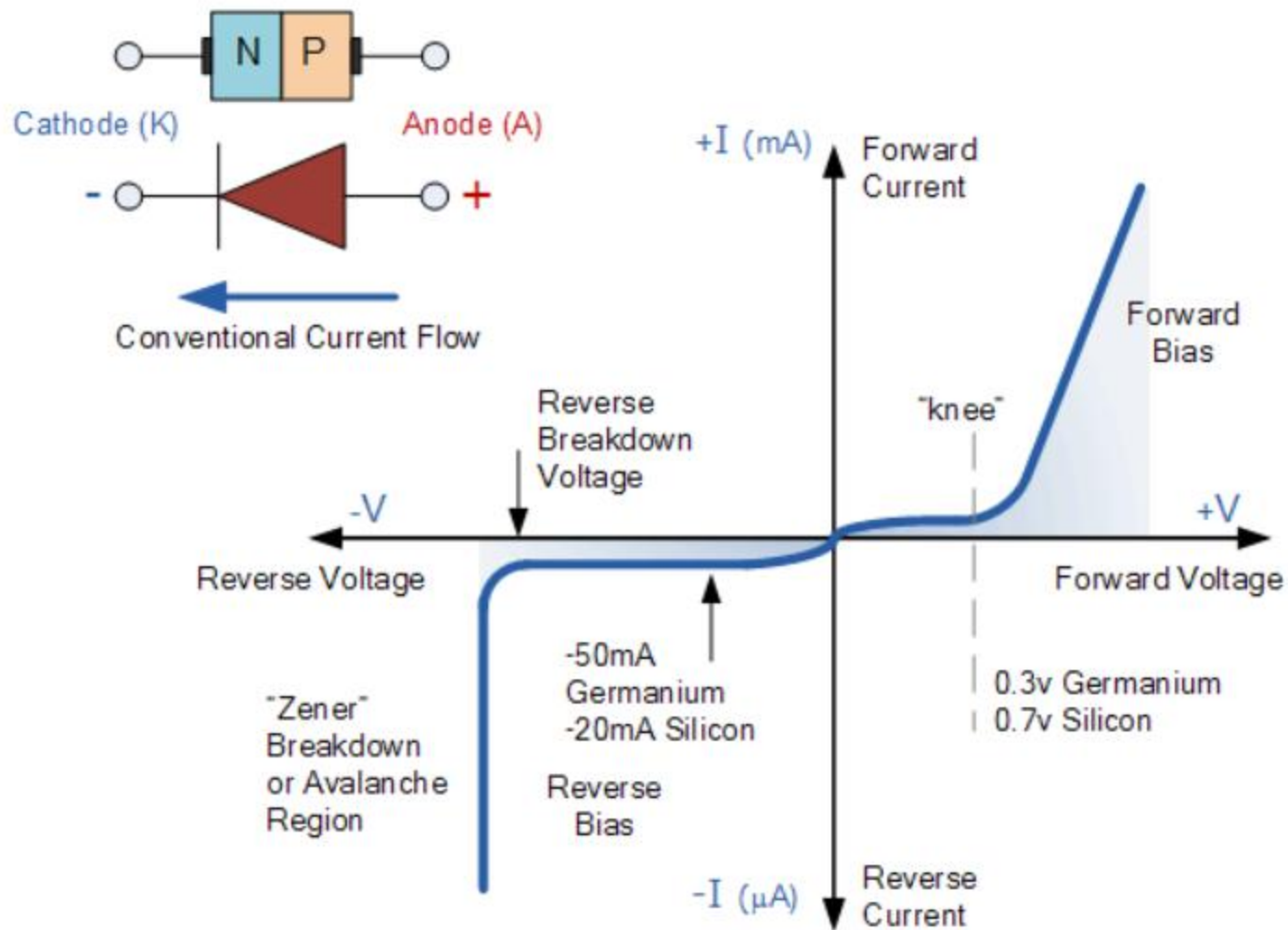
- if we join P-type and N-type semiconductor materials together they behave in a very different way and producing what is generally known as a “**PN Junction**”.
- The charge transfer of electrons and holes across the PN junction is known as **diffusion**. The width of these P and N layers depends on 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

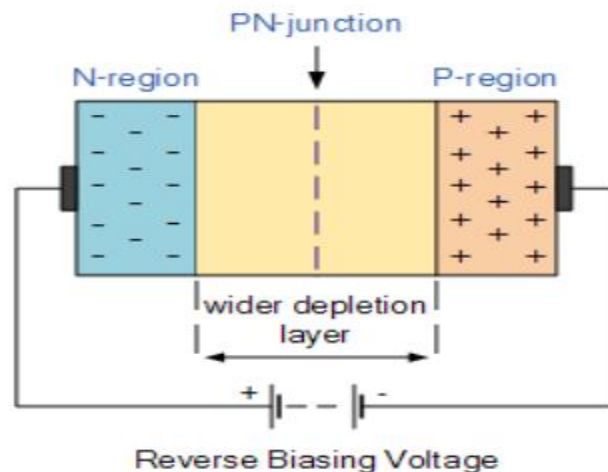
- A *PN Junction Diode* is one of the simplest semiconductor devices around, and which has the characteristic of passing current in only one direction only. However, unlike a resistor, a diode does not behave linearly with respect to the applied voltage as the diode has an exponential current-voltage (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, (μA).
- 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

21PYB102J –Semiconductor Physics

Boltzmann transport equation, Scattering
mechanism

What is Boltzmann transport equation?

- I. The Boltzmann Transport equation (BTE) has been originally developed by **Ludwig Boltzmann** to statistically describe transport of atoms and molecules (particles) of an idealized diluted gas
- I. It depicts how the probability distribution function of a system of particles changes as a result of external forces, collisions, and interactions.
- I. When charge carriers, such as electrons in semiconductors, are at equilibrium (i.e. in absence of external perturbations), their statistical distribution obeys the Fermi-Dirac distribution function given by

$$f_k^o = \frac{1}{e^{(E_k - E_F)/k_B T} + 1}$$

where E_F is the Fermi energy level and
 k_B is the Boltzmann constant.

The BTE describes the transport by two processes

1. **free streaming**
2. **scattering**

Second, to describe the scattering between electrons in the electron gas: we will use quantum mechanical perturbation theory (Fermi's Golden Rule).

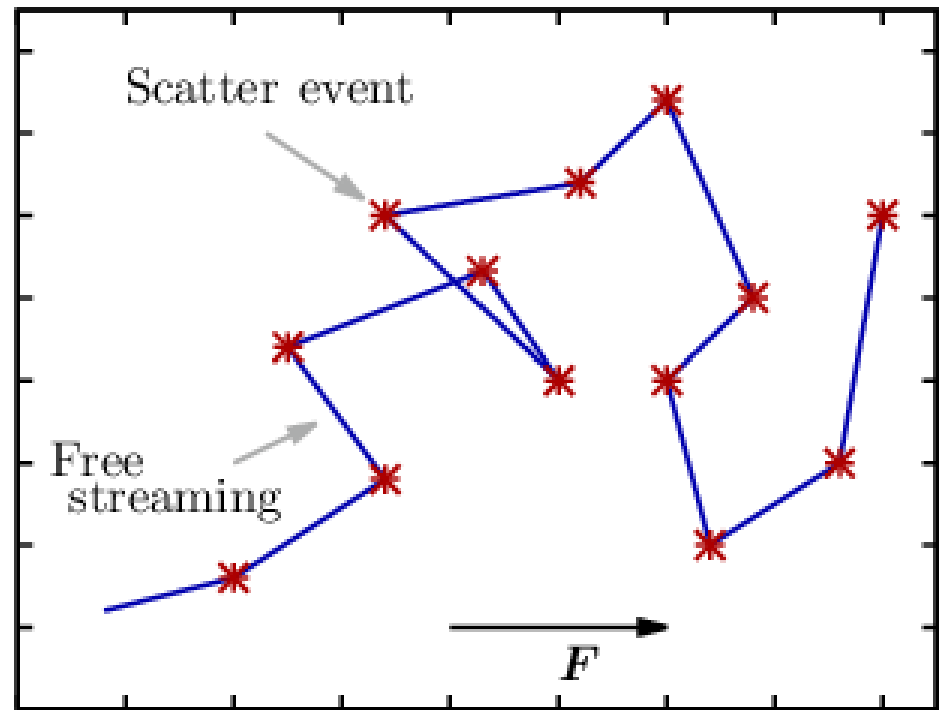


Illustration of the movement of an electron through a 2D semiconductor. The BTE treats the free streaming (blue lines) classically and the scattering events (red crosses) quantum-mechanically.

Electrons under perturbation: scattering

1. When electrons are subjected to an external perturbation such as **scattering**, their distribution function is **no longer described by the Fermi-Dirac function**, but by a function f_k that depends on time, space, and momentum.
2. We define a probability density function $f_k(\vec{r}, \vec{k}, t)$ that describes the probability of finding an electron at position \vec{r} with a wave vector \vec{k} at time t .

$$N = \int d^3r \int d^3k f(\vec{r}, \vec{k}, t).$$

Electron under scattering or collision

- Since the number of electrons is conserved, the integral remains constant even if forces are applied.
- The integral will remain constant if the time derivative of function 'f' is zero.

$$\frac{d}{dt} f(\vec{r}, \vec{k}, t) = 0.$$

- Writing total derivative:

$$\frac{d}{dt} f(\vec{r}, \vec{k}, t) = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt} + \frac{\partial f}{\partial z} \frac{dz}{dt} + \frac{\partial f}{\partial k_x} \frac{dk_x}{dt} + \frac{\partial f}{\partial k_y} \frac{dk_y}{dt} + \frac{\partial f}{\partial k_z} \frac{dk_z}{dt} + \frac{\partial f}{\partial t} = 0.$$

$$\frac{d}{dt}f(\vec{r}, \vec{k}, t) = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt} + \frac{\partial f}{\partial z} \frac{dz}{dt} + \frac{\partial f}{\partial k_x} \frac{dk_x}{dt} + \frac{\partial f}{\partial k_y} \frac{dk_y}{dt} + \frac{\partial f}{\partial k_z} \frac{dk_z}{dt} + \frac{\partial f}{\partial t} = 0.$$

This can be written more compactly as

$$\frac{d}{dt}f(\vec{r}, \vec{k}, t) = \frac{d\vec{r}}{dt} \cdot \nabla_{\vec{r}} f + \frac{d\vec{k}}{dt} \cdot \nabla_{\vec{k}} f + \frac{\partial f}{\partial t} = 0$$

We know the expression for crystal momentum $\vec{F}_{\text{ext}} = \hbar \frac{d\vec{k}}{dt}$

And velocity $\vec{v} = \frac{d\vec{r}}{dt}$

$$\frac{\partial f}{\partial t} = -\frac{1}{\hbar} \vec{F}_{\text{ext}} \cdot \nabla_{\vec{k}} f - \vec{v} \cdot \nabla_{\vec{r}} f.$$

These collisions do not alter the number of electrons but their momenta change suddenly. Collisions are included with a collision term.

$$\frac{\partial f}{\partial t} = -\frac{1}{\hbar} \vec{F}_{\text{ext}} \cdot \nabla_{\vec{k}} f - \vec{v} \cdot \nabla_{\vec{r}} f + \left. \frac{\partial f}{\partial t} \right|_{\text{collisions}}.$$

This equation is called the [Boltzmann equation](#).

DEPARTMENT OF PHYSICS AND NANOTECHNOLOGY SRM INSTITUTE OF SCIENCE AND TECHNOLOGY

21PYB102J –Semiconductor Physics

Introduction of TCAD in basic level



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Technology Computer-Aided Design (TCAD)



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- I. TCAD is a computer simulation technique that is widely used in the semiconductor industry to **design, optimize, and analyze semiconductor** devices and processes. It is a numerical modeling method for semiconductor devices.
- I. TCAD is a branch of Electronic Design Automation (EDA) that models semiconductor fabrication and semiconductor device operation. TCAD software solutions are key to developing new semiconductor processes and devices, dramatically reducing costs and time to market.
- I. **Objectives:**
 - ❖ Understand quantitatively how fundamental material parameters vary in semiconductor, e.g. band gap, electron affinity, dielectric constant.
 - ❖ **Understand relationships between various potentials and energies important for understanding device operation.**
 - ❖ **Understand how biasing affects various potentials and energies at device terminals / ohmic contacts.**

TCAD types :

The modeling of the fabrication is termed *Process TCAD*, while the modeling of the device operation is termed *Device TCAD*.

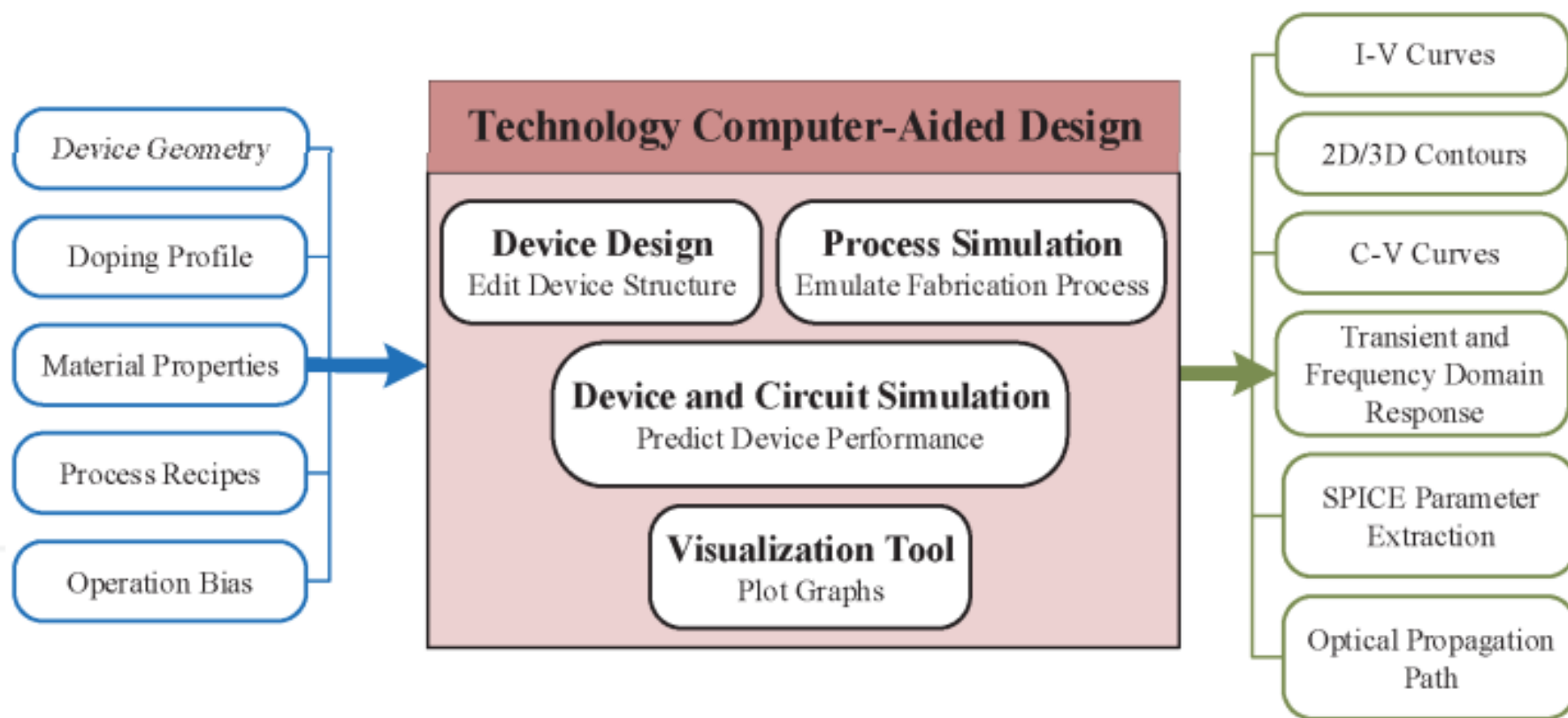
- Process TCAD

- Modeling of semiconductor-chip process-manufacturing steps like lithography, deposition, etching, ion implantation, diffusion, oxidation, silicidation, mechanical stress, etc.
- Requires detailed modeling of the *physical principles of manufacturing*, **Calibration of models needs** expensive experiments (ad-hoc wafer fabrication)

- Device TCAD

- Modeling of electrical, thermal, optical and mechanical behavior of semiconductor devices (e.g., diode, BJT, MOSFET, solar cell,...).
- Focuses on the physical principles at the basis of **carrier transport and of optical generation in semiconductor devices**. Models are more easily generalized than for process physics

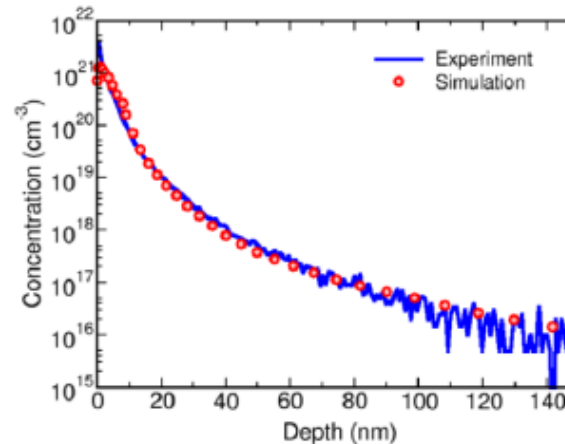
Principle tools inside TCAD device simulation suites with input and output files.



What is TCAD? – Examples

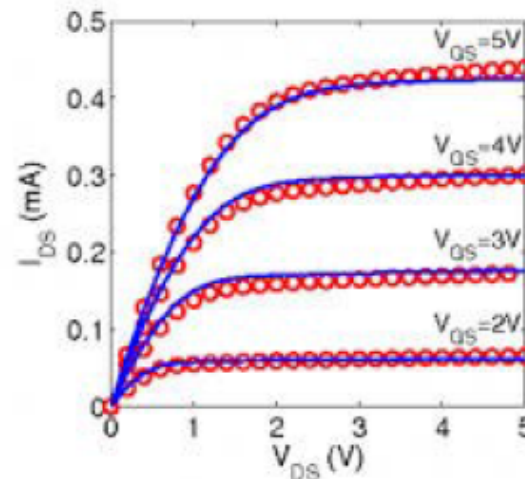
- Process simulations

Simulate doping profiles obtained by specific processing techniques, calibrate the model with experimental data and then optimize the process to obtain the desired profile.



- Device simulations

Simulate the output characteristics of a MOSFET device and calibrate the device architecture to fine-tune the device performance.



Advantages of TCAD

- 1) The device features can be optimized if hands-on calculations are too complicated or impose unacceptable assumptions.
- 2) It helps to make predictions (scaling, new device concepts) when hands-on calculations are not viable (e.g., complex devices, modeling of distributed statistical effects or process yield).
- 3) To get insights. No real experiment will probably be ever able to measure some of the physical quantities calculated by TCAD tools (e.g., local distribution of carriers, local electric field, etc.).
- 4) Reduce Development Costs, Reduce the time and manufacturing cycles spent to develop semiconductor technologies.
- 5) To quickly screen technological options and drive the industrial strategy .