Lecture-01

Basic Electronics-Introduction

Topics to be covered:

✓What is electricity

✓Voltage, Current, Resistance

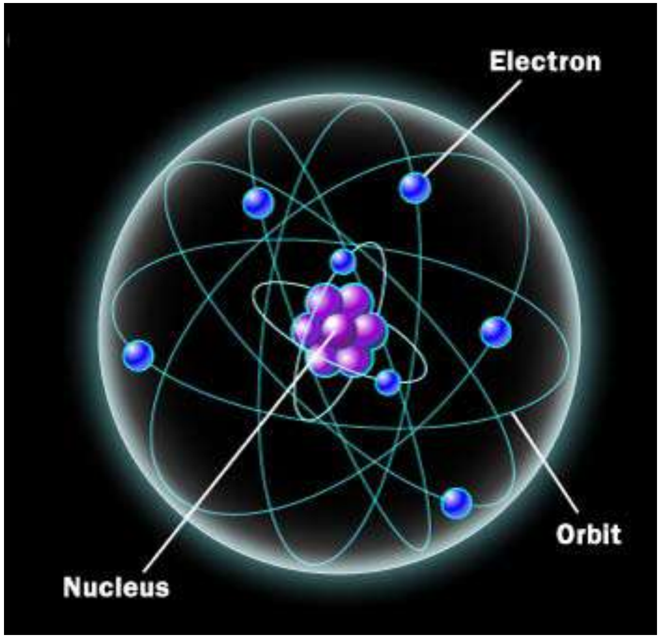
✓Ohm’s Law

✓Capacitors, Inductors

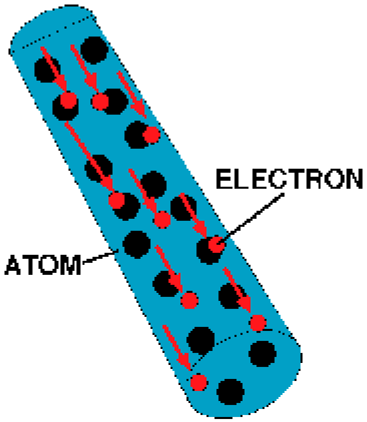
✓Semiconductors

What is Electricity?

- Everything is made of atoms
- There are 118 elements, an atom is a single part of an element
- Atom consists of electrons, protons, and neutrons



- Electrons (- charge) are attracted to protons (+ charge), this holds the atom together
- Some materials have strong attraction and refuse to loss electrons, these are called insulators (air, glass, rubber, most plastics)
- Some materials have weak attractions and allow electrons to be lost, these are called conductors (copper, silver, gold, aluminum)
- Electrons can be made to move from one atom to another, this is called a current or electricity.



Voltage:

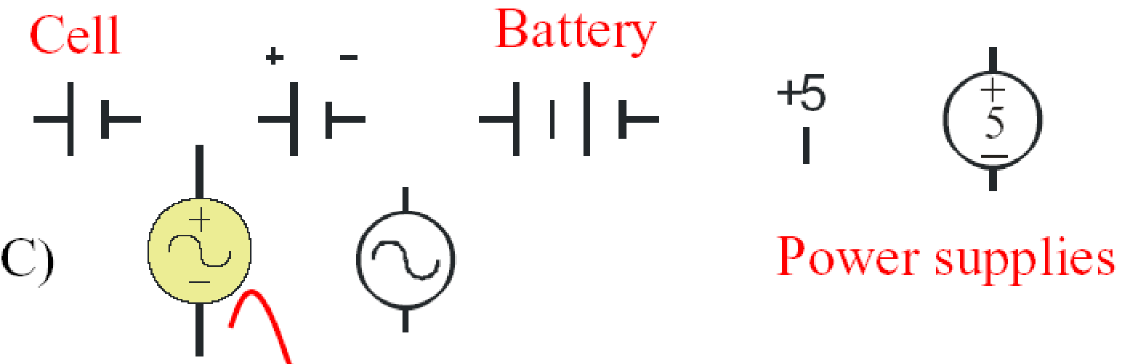
- A battery has positive terminal (+) and a negative terminal (-). The difference in charge between each terminal is the potential energy the battery can provide. This is labeled in units of volts.
- Voltage is like differential pressure always measure between two points.
- Measure voltage between two points or across a component in a circuit.
- When measuring DC voltage make sure polarity of meter is correct, positive (+) red, negative (-) black.

Voltage sources:

Symbols

UniPolar

BiPolar (AC)



Properties

Constant Voltage, independent of the amount of current

Usually ideal

Examples

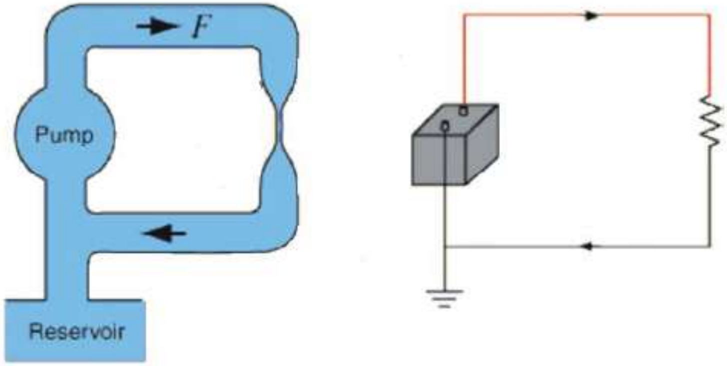
Batteries

Power Supplies

Signal Generators

Ground

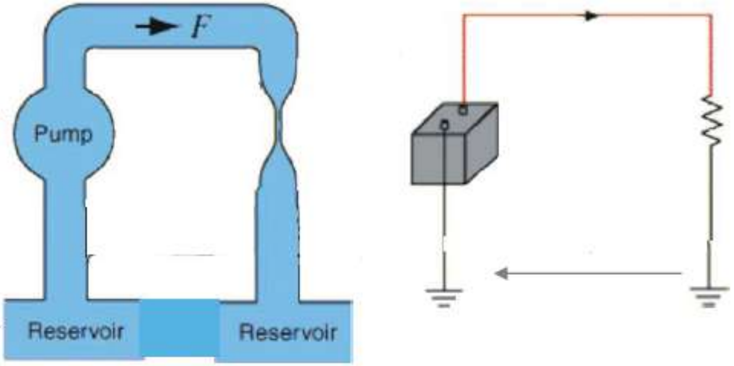
Provides a reference point



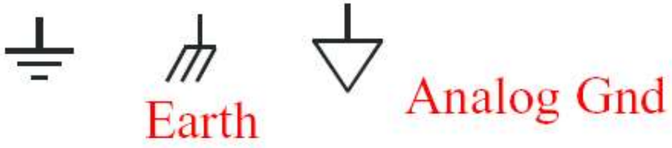
Purely a reference point

Does not participate in current flow

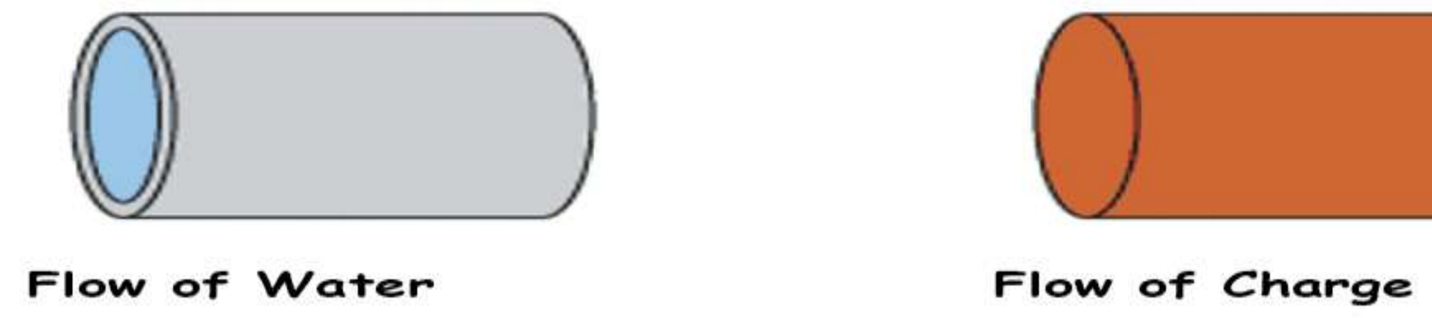
An integral path in the current flow



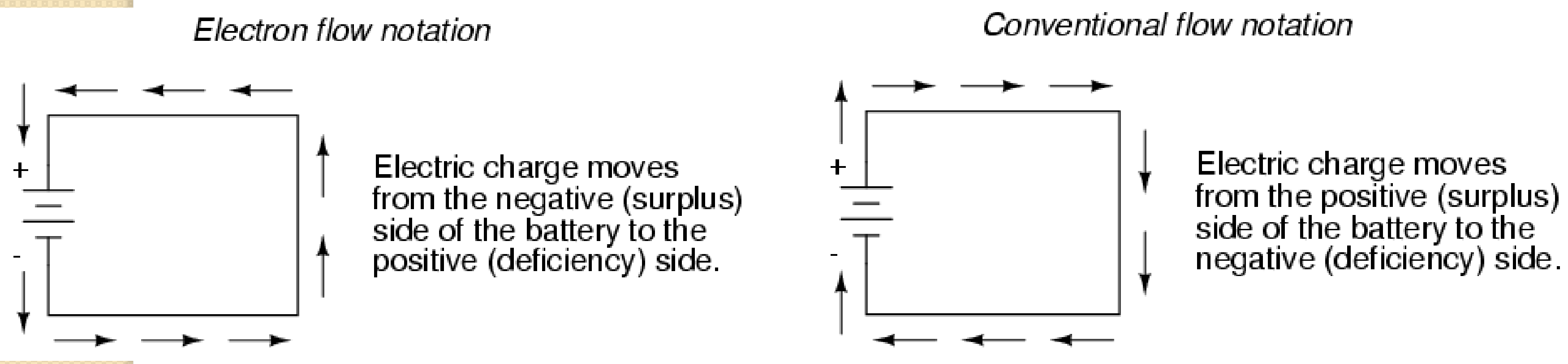
Symbols



Current



- **Uniform flow of electrons thru a circuit is called *current.***



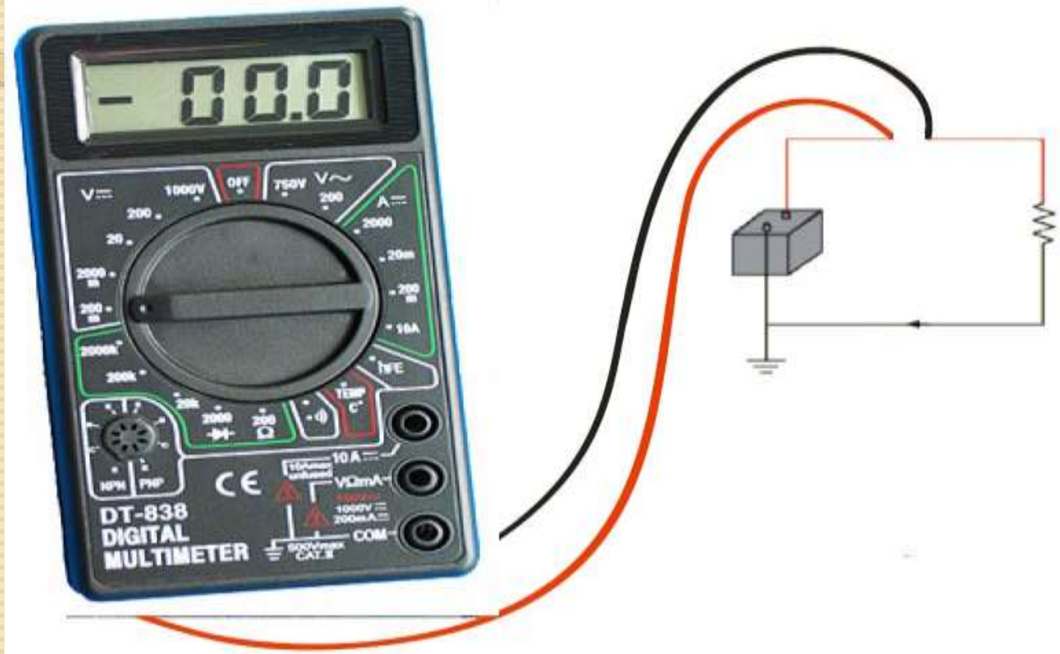
Electron flow notation

Electric charge moves from the negative (surplus) side of the battery to the positive (deficiency) side.

Conventional flow notation

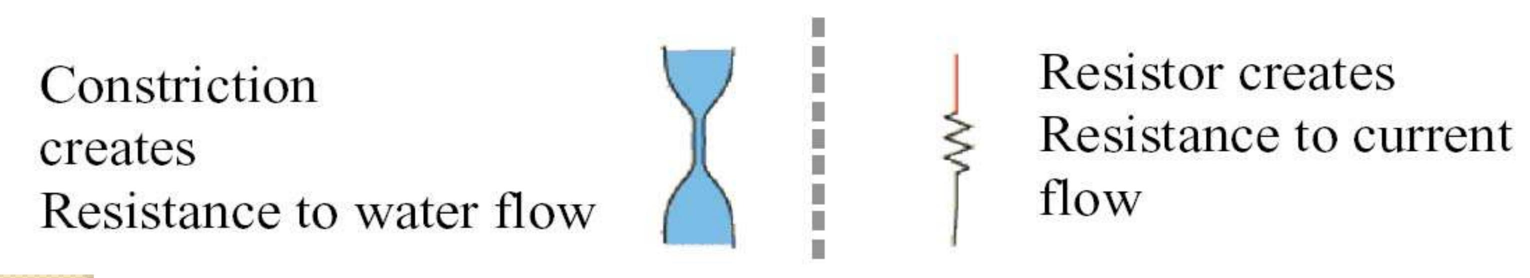
Electric charge moves from the positive (surplus) side of the battery to the negative (deficiency) side.

Measuring current:



- To measure current, must break circuit and install meter in line.
- Measurement is imperfect because of voltage drop created by meter.

Resistance

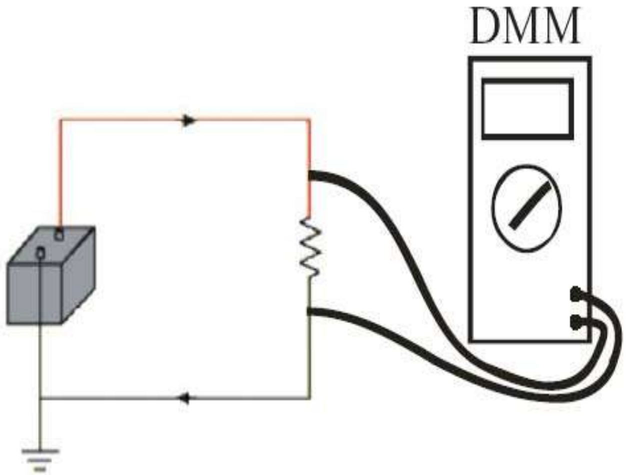

Constriction creates Resistance to water flow

Resistor creates Resistance to current flow

- ➢**All materials have a resistance that is dependent on cross-sectional area, material type and temperature.**

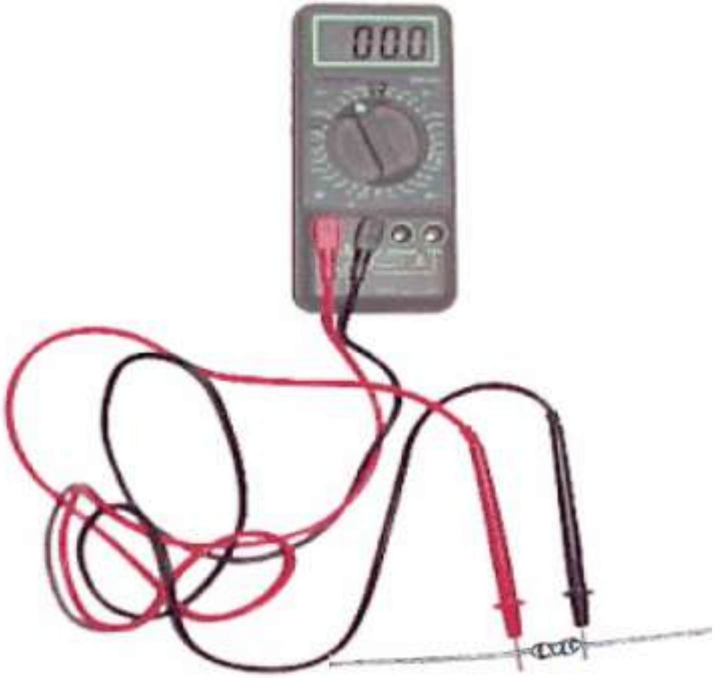
- ➢**A resistor dissipates power in the form of heat.**

Measuring a resistance



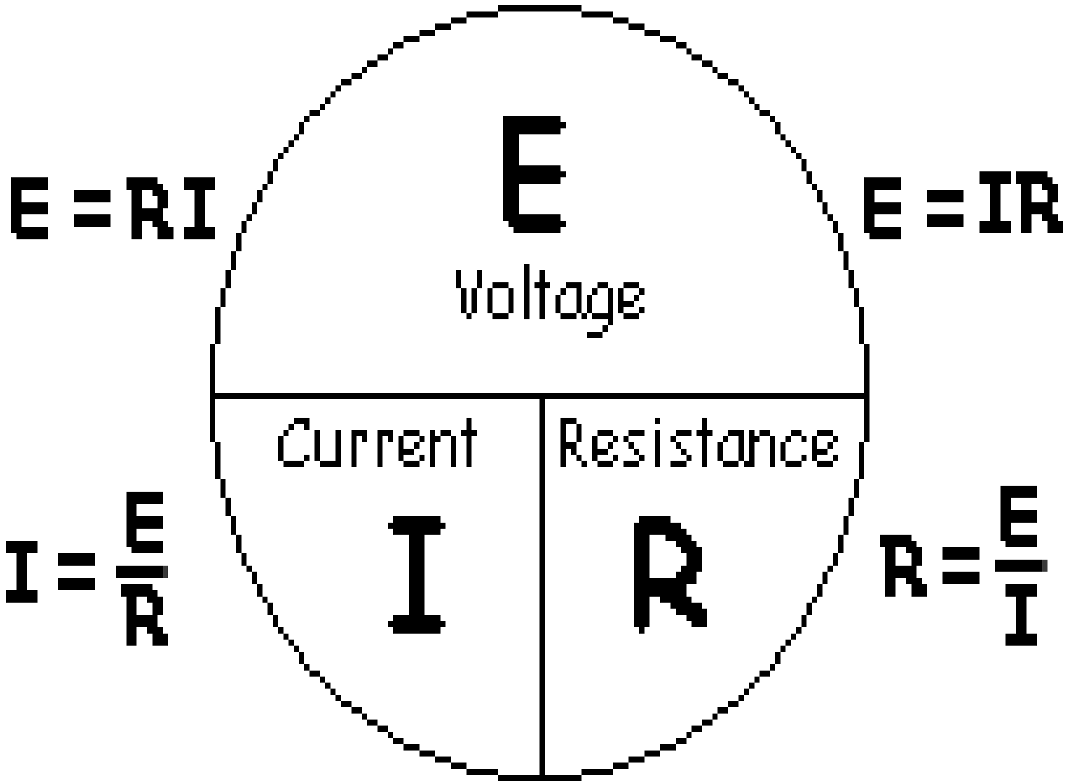
Will this work like we expect it to?

NO! don't do this!



When measuring resistance, remove component from the circuit.

Ohm’s Law



Electric Circuit Components

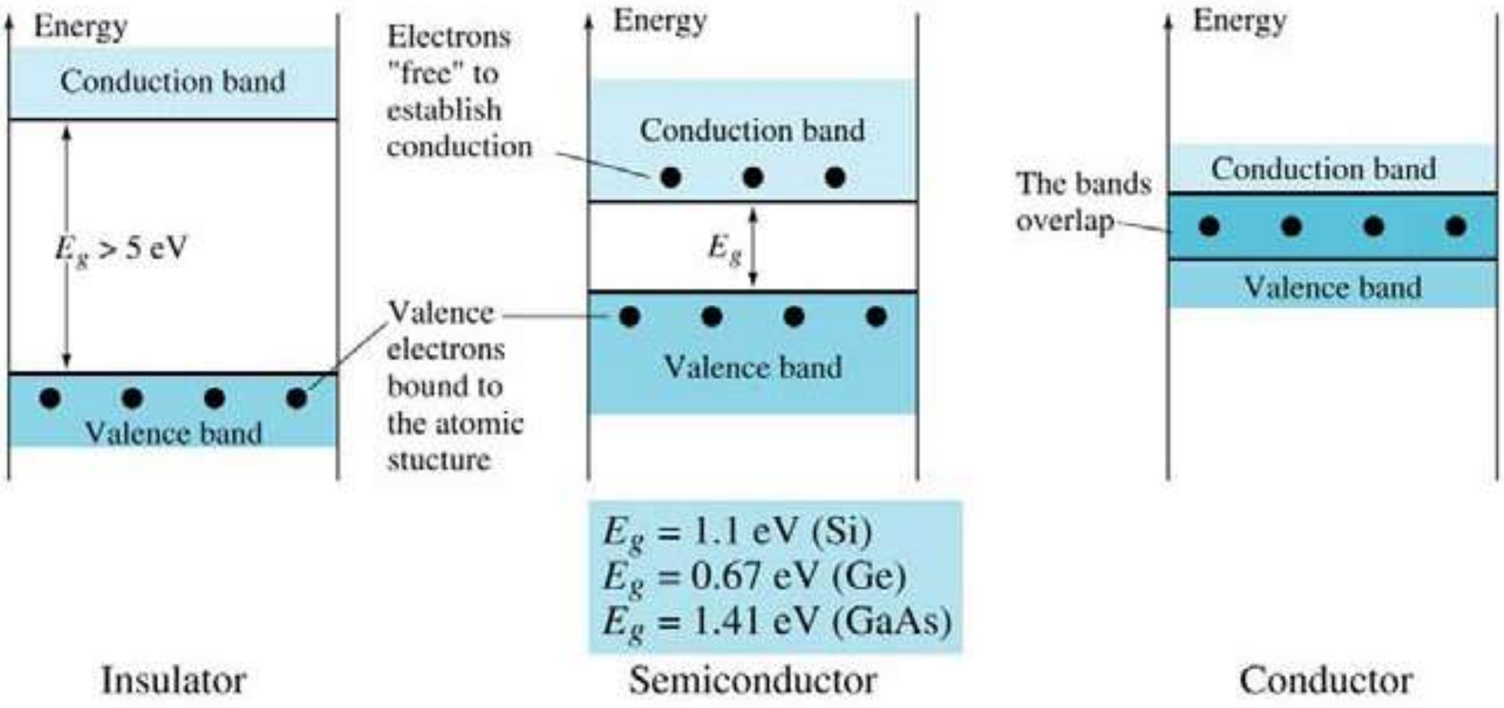
Passive:

- **Resistors**
- **Capacitors**
- **Inductors**

Active:

- **Voltage Sources**
- **Current Sources**
- **Amplifiers**

Insulators,metals & semiconductors



$E_g = 1.1$ eV (Si)
$E_g = 0.67$ eV (Ge)
$E_g = 1.41$ eV (GaAs)

Properties:

- Insulators have larger values of Eg so that it takes more energy to excite e- into the conduction band.
- Semiconductors are partially conducting under typical.

  conditions since the energy required to lift electrons is not so much larger than thermal energies at room temperatures.
- Their conductivity is a strong function of T.
- Freeze-out at low T.
- Conduction at high T.
- Metals has higher conductivity than insulators & semiconductors as the conduction band & valence band are overlapped.

Expected questions:

1. Define semiconductors, metals & insulators. Explain with the help of energy band diagrams.

Lecture-02
Basic Electronics:Unit-01

Topics to be covered:

- ✓Commonly used semiconductors.
- ✓Electronic configuration of Ge & Si.
- ✓The energy band theory of crystals.
- ✓The eV unit of energy.

Commonly used semiconductors:

The two most commonly used semiconductors are:

- Germanium.
- Silicon.

Why?

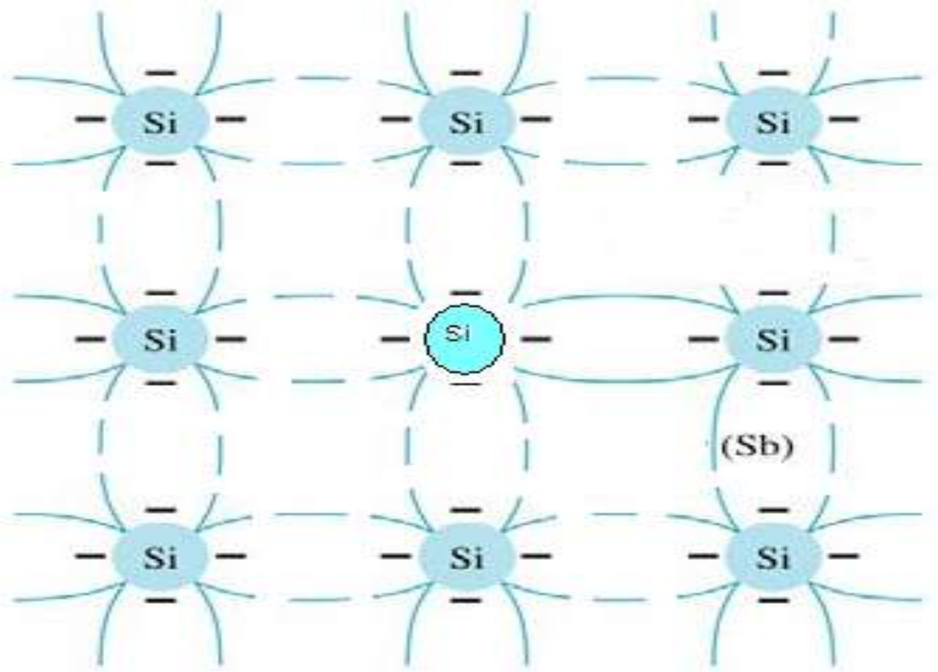
Electronic configuration of Ge & Si:

- The atomic number if Si is 14 & Ge is 32, thus has 4 valence electrons, so that atom is tetravalent.
- Si = $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$.
- Ge = $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$.

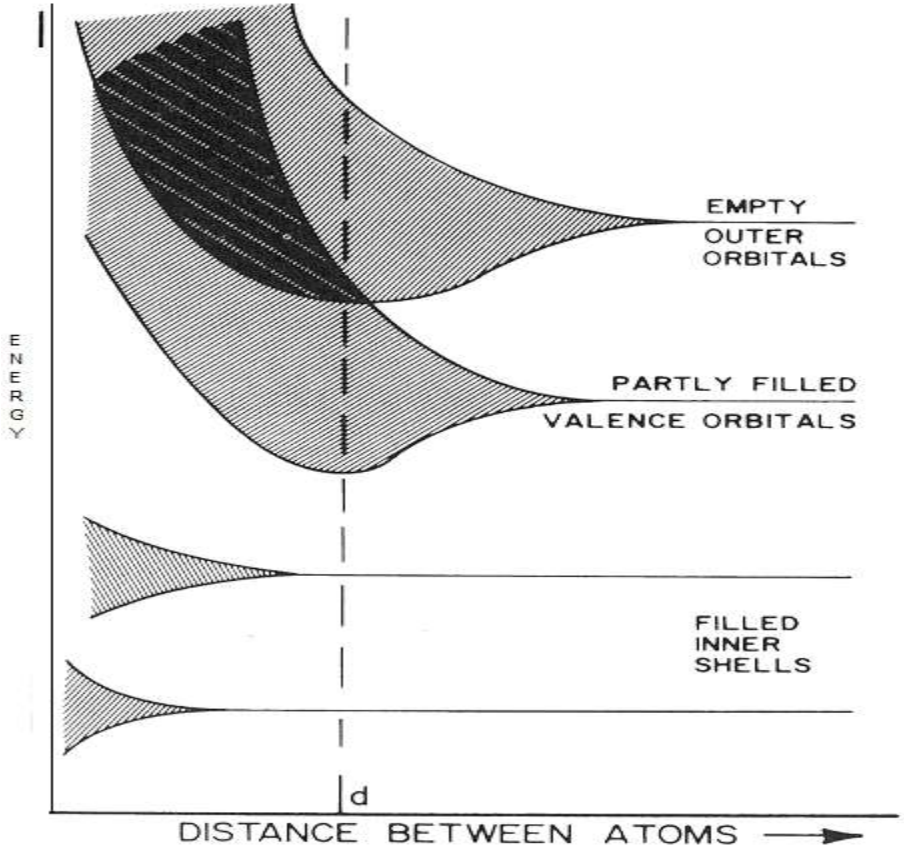
Refer to the crystal structure of silicon in next slide:

- Each valence electron of germanium/silicon is shared by one of its four nearest neighbours.
- A covalent bond is represented by dashed lines.
- Each valence electron is thus tightly bounded to nucleus & hence inspite of availability of four valence electrons the crystal has low conductivity.

Crystal structure of silicon:



Energy band theory of crystals:



The eV unit of energy:

- The unit of work or energy, called electron volt (eV) is defined as follows

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules.}$$

- The name electron volt arises from the fact that if an electrons falls through a potential of one volt, its K.E will increase by decrease in P.E or by

$$qV = (1.6 \times 10^{-19} \text{C})(1\text{V}) = 1.6 \times 10^{-19} \text{J} = 1\text{eV}$$

Expected questions:

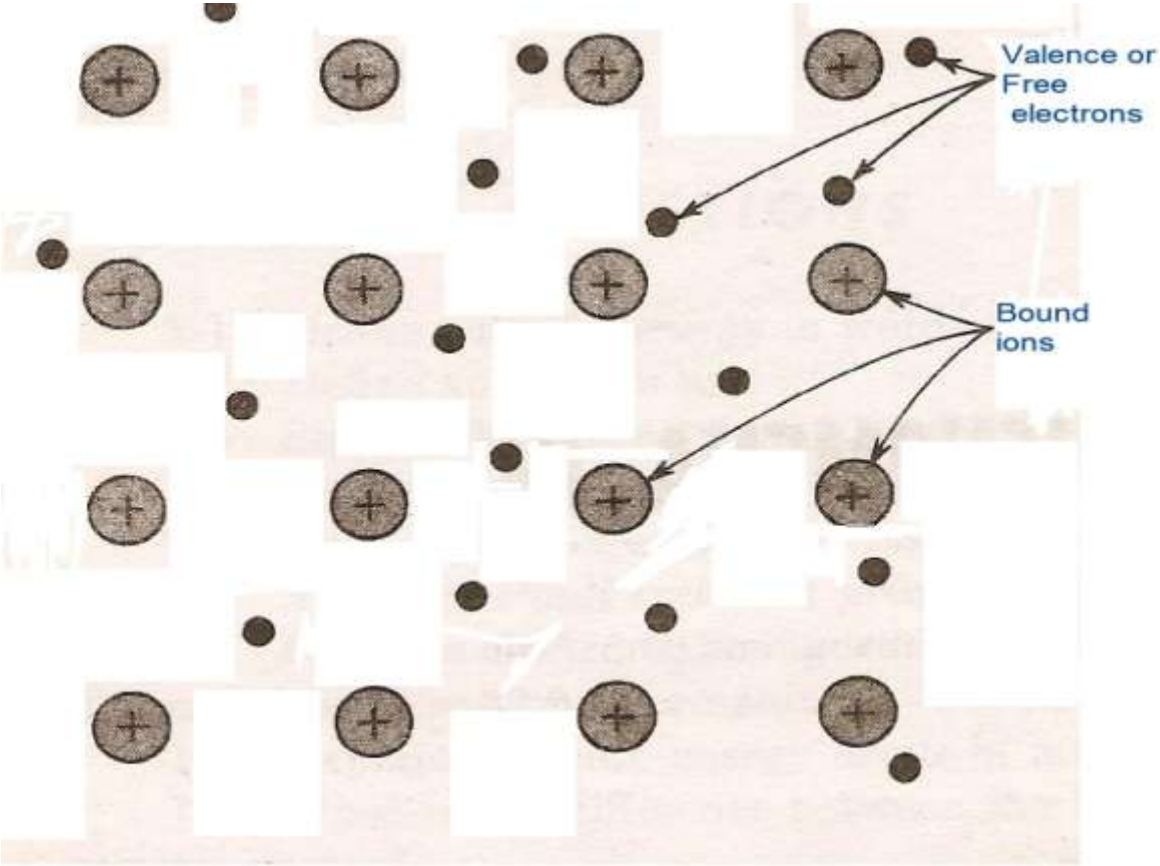
1. Why si & ge are most widely used semiconductors ?
2. Explain why a semiconductors behave like insulators at 0 degree kelvin ?
3. Define an electron volt.
4. Explain the effect of temperature on conductivity of insulator, s/c & metal.

Lecture-03
Basic Electronics:Unit-01

Topics to be covered:

- ✓Electron gas description of metal.
- ✓Mean free path.
- ✓Drift velocity.
- ✓Mobility.
- ✓Current density.
- ✓Conductivity.

Electron gas description of metal:



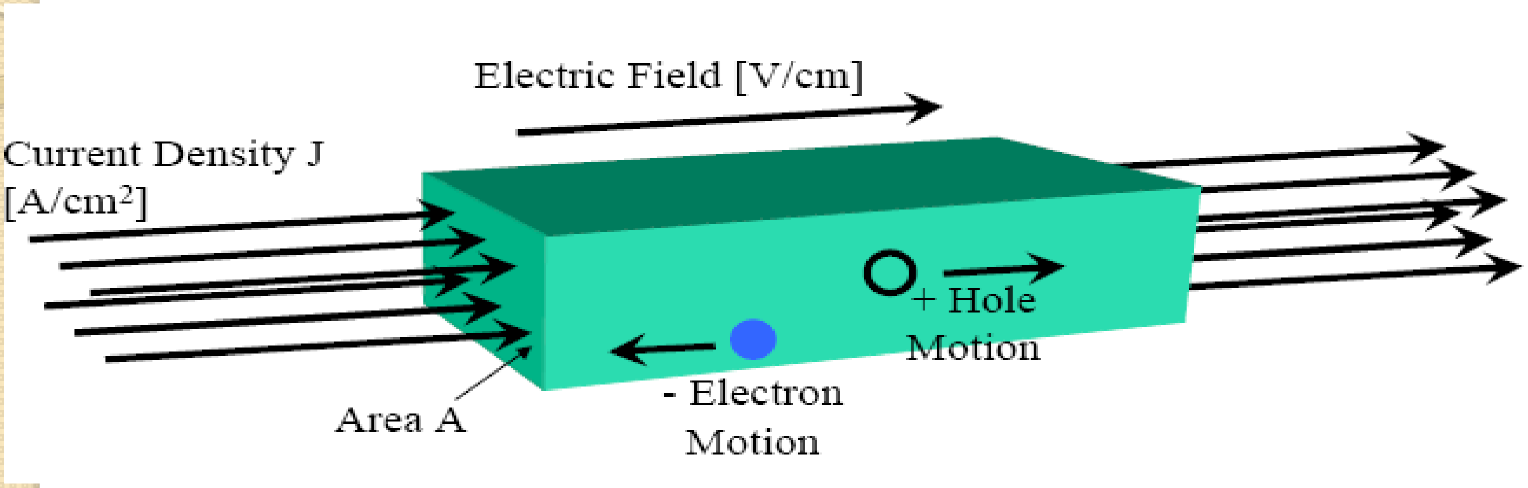
Mean free path:

Refer the fig in last slide:

- Ions are almost stationary.
- Electrons are in continuous motion.
- Thus electrons collide with this ions & their direction changes on each collision.

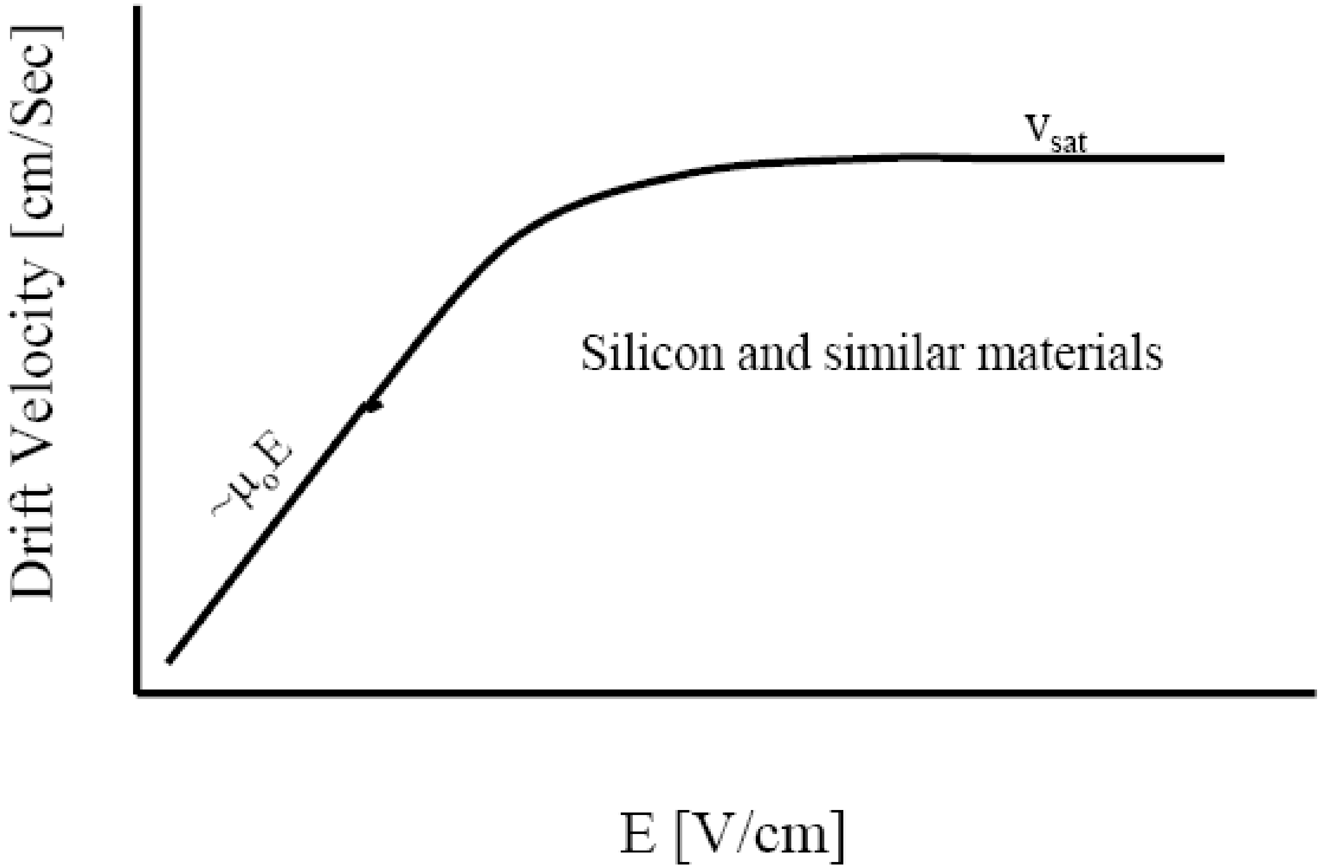
  The average distance between each collision is called mean free path.

Drift velocity:



- Holes move in the direction of the electric field (from + to -).
- Electrons move in the opposite direction of the electric field (from - to +).
- Average net motion is described by the drift velocity, v_d with units cm/second.
- Net motion of charged particles gives rise to a current called as drift current
- Thus V_d proportional to applied E.

Drift velocity versus E:



Mobility:

In physics, **electron mobility** (or simply, **mobility**), is a quantity relating the drift velocity of electrons(V_d) to the applied electric field(E) across a material, according to the formula:

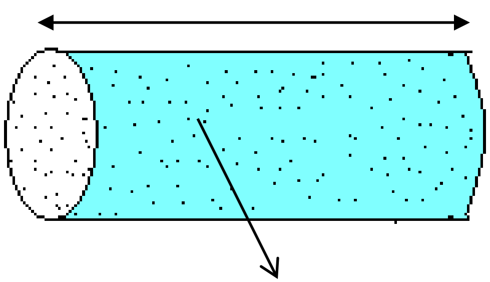
$$V_d = \mu E$$

Here μ is the [illegible]he semiconductor and measures the ease with which carriers can move through the crystal. [μ]= cm^2/V-Second.

Current density:

J is current per unit area:

J=I/A ------ (1)



Let the time taken by electrons to travel distance L m is T sec.

Thus I = Total charge/sec A=area

= N q / T = N q v/L.

v = drift speed in m/s.

Finally from (1):

J=N q v/LA ------ (2)

Also the electron concentration n is defined as

n = electrons per volume i.e (e^{-s}/m^3)

= N/LA

Thus from (2) $\boxed{J = n\ q\ v = \rho v}$

Here ρ = n q is called charge density in Coulombs/m^3.

Conductivity:

- Conductivity is defined as ability of a conductor to conduct.
- Current density

$$J = n\,q\,v = n\,q\mu E = \sigma E \qquad \text{-----(1)}$$

- Where

$$\sigma = n\,q\mu \qquad \text{-----(2)}$$

is called co the metal in (ohm-meter)$^{-1}$.

- From eq^{n} (1) it is clear that conduction current is proportional to applied voltage as stated by Ohm's Law.

Expected questions:

- In a certain wire charge moves past a point in 0.5 second. Find the current in amperes. (Answer: 8 amp).
- Give the electron gas description of metal.
- Define mobility & conductivity & give their dimensions.
- Define mean free path.

Lecture-04

Basic Electronics:Unit-01 Problems:

Lecture-05 Basic Electronics:Unit-01

Topics to be covered:

✓Electrons & holes (Review).
✓Contribution of hole in conductivity.
✓Intrinsic semiconductors.
✓Extrinsic semiconductors.
✓Doping & dopants (Impurities).
✓Donors (pentavalent impurities).
✓Acceptors (Trivalent impurities).
✓Mass action law.

Electrons & holes in pure s/c:

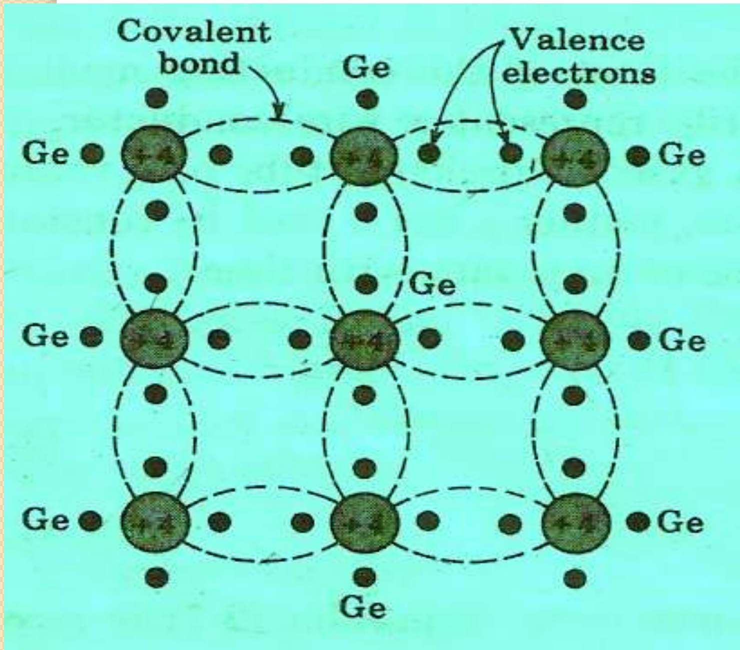


Fig:Crystal structure of Ge

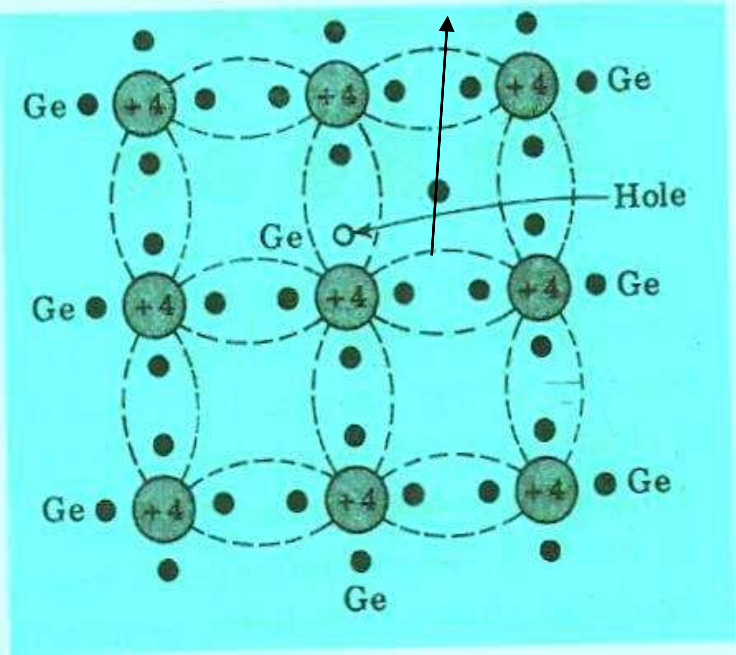
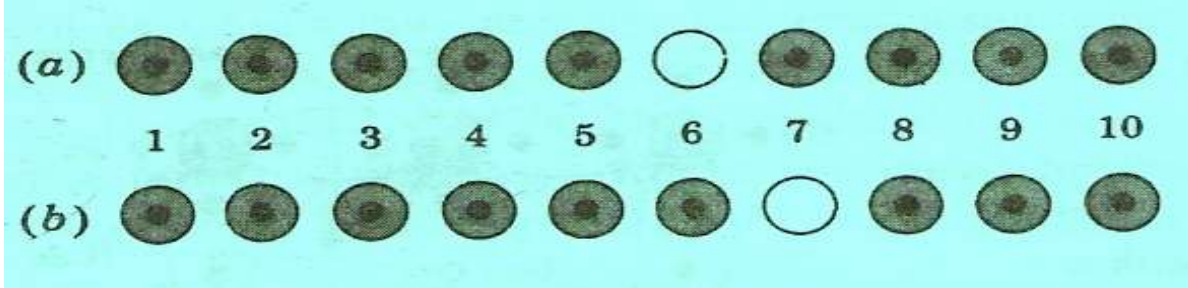

Free electron

Fig: Crystal structure of Ge with broken covalent bond

Contribution of hole to conductivity:



- Any broken bond (hole) makes easier for a valence electron to leave its covalent bond & fill this hole.
- The vacant hole can be further occupied by some other electron.
- Thus the hole moves in a direction opposite to that of electron.

Intrinsic & Extrinsic semiconductors:

- Intrinsic or pure semiconductor:

$$\boxed{n=p=n_i}$$

n_i = intrinsic concentration.

- Extrinsic semiconductors:

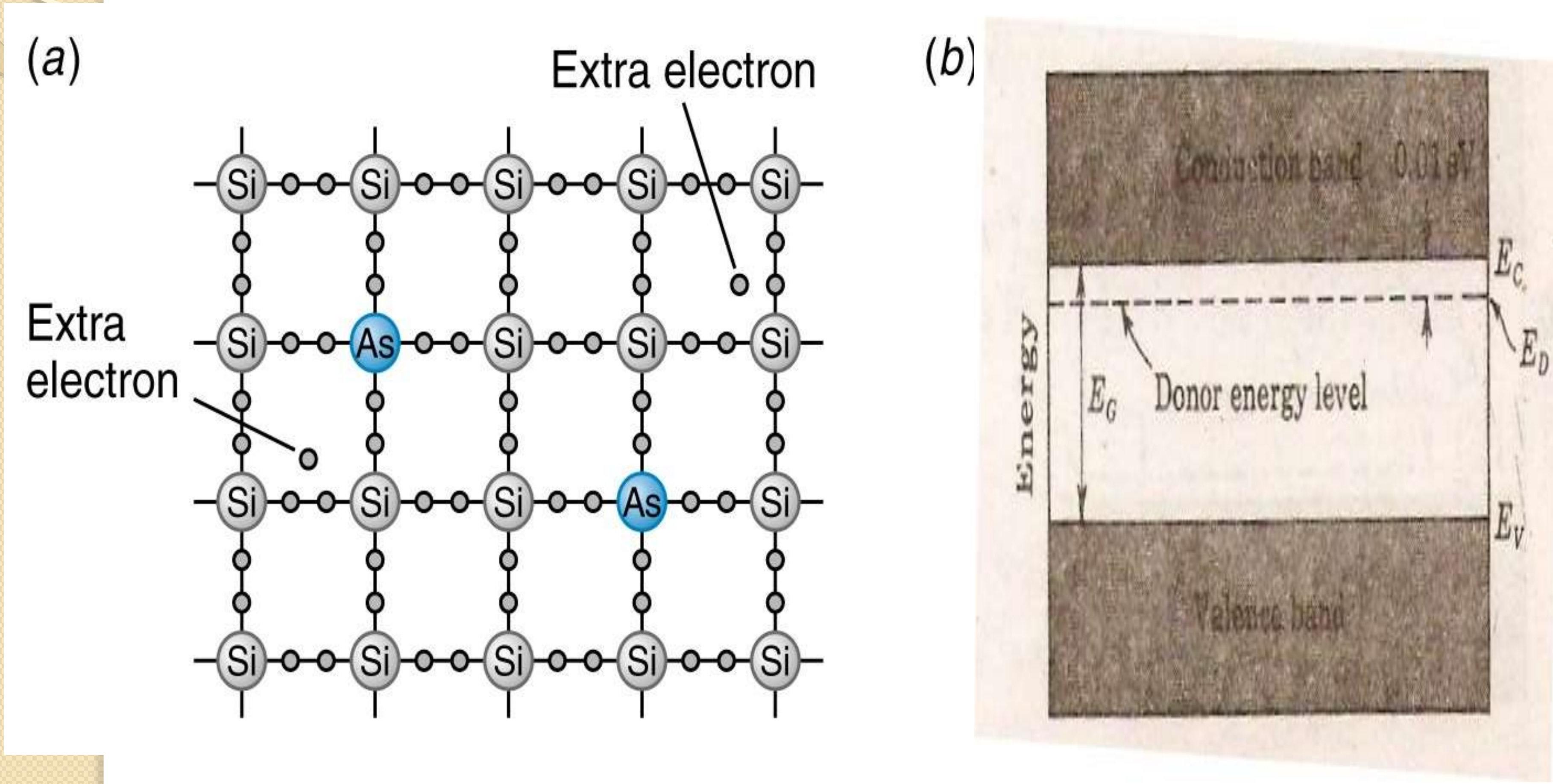
$$\boxed{n \neq p}$$

- Extrinsic s/c are further classified as n-type & p-type semiconductor (depending upon doping).

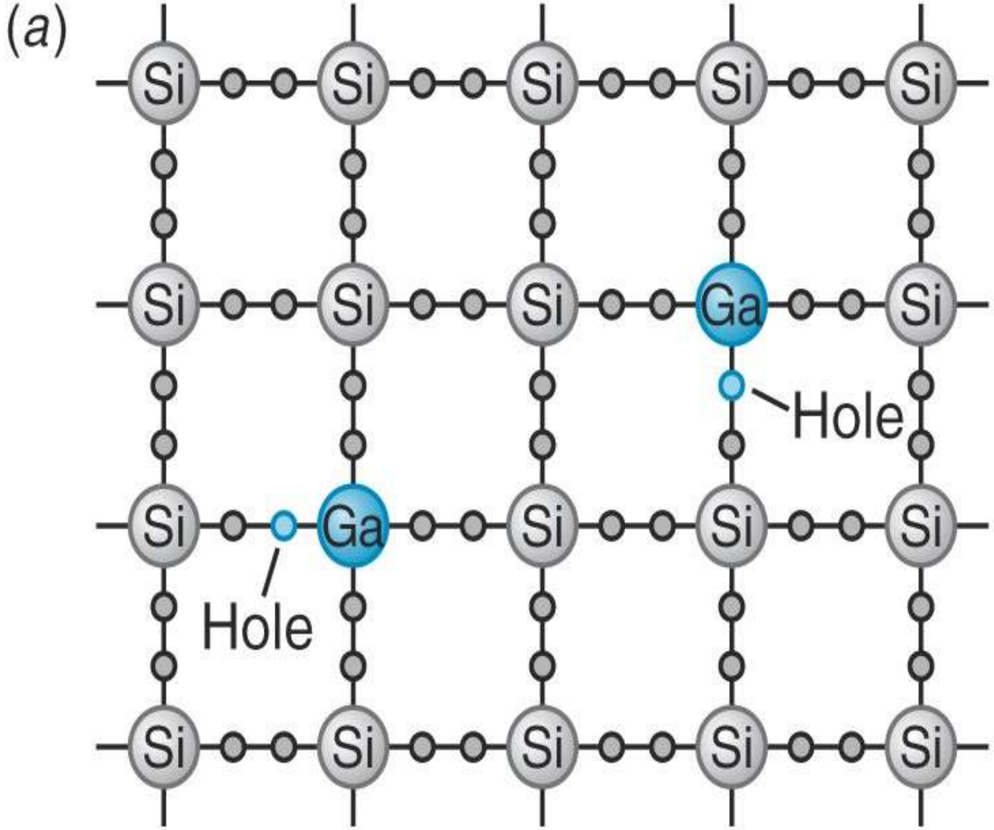
Doping:

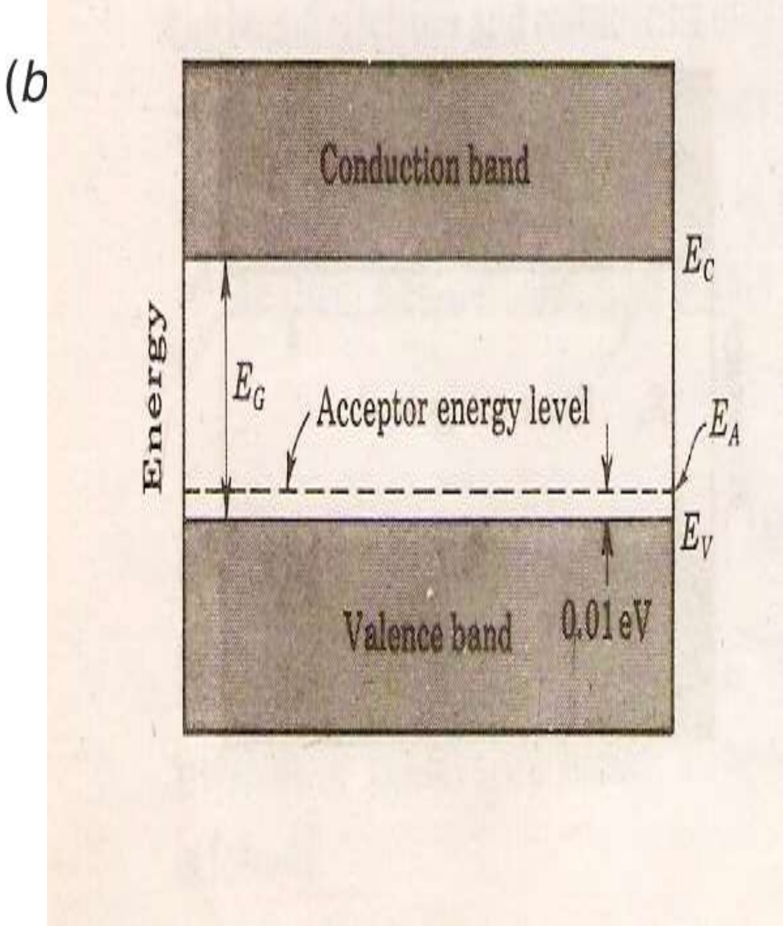
- The doping is the process of adding impurity atoms to intrinsic silicon or germanium to improve the conductivity of the semiconductor.
- Increase the conductivity of a semiconductor by adding a small amount of another material called a dopant (instead of heating it!)
- By substituting a semiconductor atom with a special impurity atom (Column V or Column III element), a conduction electron or hole is created.
- Column V – Pentavalent impurity - as they have five valence electrons they create a conduction electron & are called Donors or Donor impurities (antimony, phosphorous & arsenic).
- Column III – Trivalent impurity as - they have three valence electrons they create a conduction hole & are called Acceptors or Acceptor impurities (boron, gallium & indium).

Donor impurities (Pentavalent atoms):



Acceptor impurities (Trivalent atoms):





P-type & n-type semiconductors:

- **p-type semiconductor is created by adding trivalent atoms to an intrinsic semiconductor.**

  Majority carriers: Holes.

  Minority Carriers: Electrons.

- **n-type semiconductor is created by adding pentavalent atoms to an intrinsic semiconductor.**

  Majority carriers: Holes.

  Minority Carriers: Electrons.

- **Commonly used trivalent impurities:**

  Aluminum (Al)
  Boron (B)
  Gallium (Ga)
  Indium (In)

- **Commonly used pentavalent impurities:**

  Phosphorus (P)
  Antimony (Sb)
  Arsenic (As)
  Bismuth (Bi)

Mass action law:

Statement: Under thermal equilibrium, the product of free –ve & +ve concentrations is constant independent of amount of donor & acceptor impurity doping i.e

$$\boxed{n.P = n_i^2}$$

n_i= intrinsic concentration.

Expected questions:

1. Define a electron & hole in a semiconductors.
2. Explain how holes contributes to the process of conductivity ?
3. Define intrinsic concentration of holes. What is the relationship between this density of & intrinsic concentration of electrons ? What do these equal at 0 degree kelvin.
4. Write shortnotes on donor & accptor impurities.
5. State mass action law.

Lecture-06
Basic Electronics:Unit-01

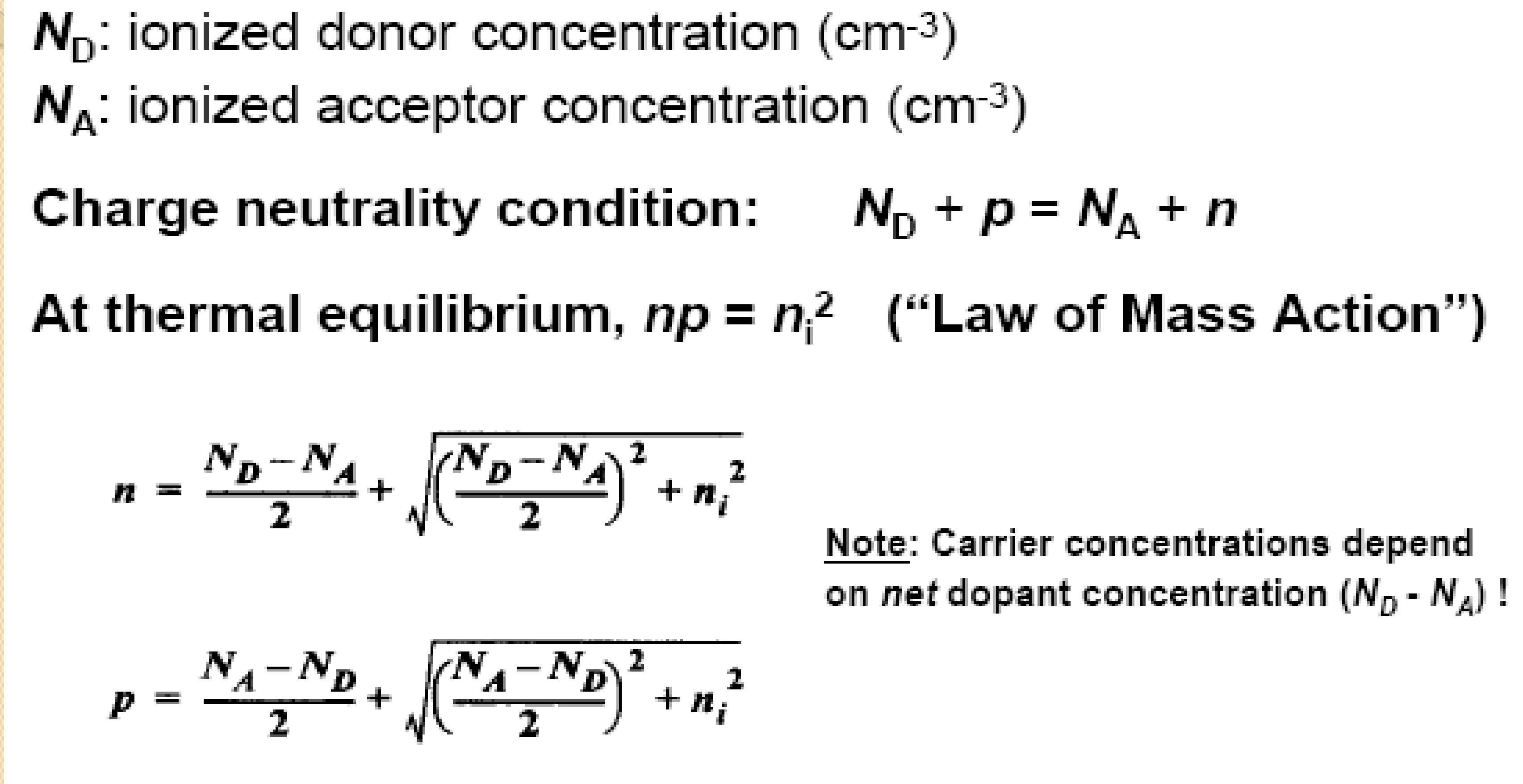
Topics to be covered:

✓Charge densities in s/c

✓Electrical properties of Ge & Si:

1. Conductivity .
2. Intrinsic concentration.
3. The energy gap.
4. Mobility.

Charge density in semiconductor:



N_D: ionized donor concentration (cm^{-3})
N_A: ionized acceptor concentration (cm^{-3})

Charge neutrality condition: $N_D + p = N_A + n$

At thermal equilibrium, $np = n_i^2$ ("Law of Mass Action")

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Note: Carrier concentrations depend on *net* dopant concentration (N_D - N_A) !

N-type material:

- In an n-type material the free electron concentration is approximately equal to the density of donor atoms i.e

$$\boxed{n_n = N_D.}$$

- Thus c of holes in n-type s/c using mass action law is:

$$\boxed{p_n = n_i^2 / N_D.}$$

P-type material:

- In an p-type material the free hole concentration is approximately equal to the density of acceptor atoms i.e

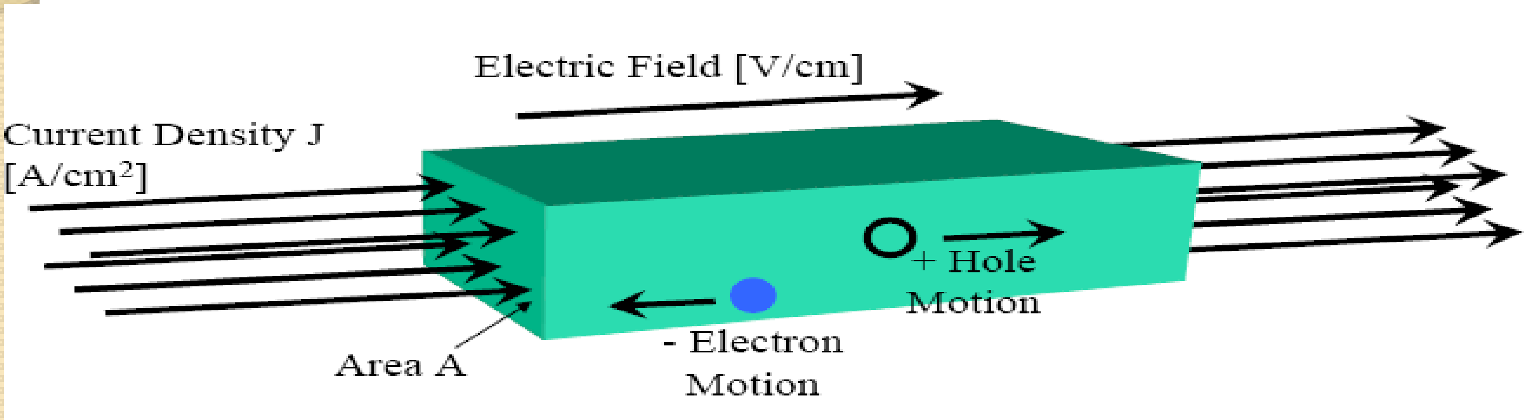
$$\boxed{p_p = N_A}$$

- Thus conce electrons in p-type s/c using mass action law:

$$\boxed{n_p = n_i^2/N_A}$$

Electrical properties of si & ge:

1. Conductivity:



On application of electric field E the electrons & holes move in opposite directions but since they are of opposite sign the net current is in same direction.

Hence J is given by:

$$J = (n\mu_n + p\mu_p)\, qE$$
$$= \sigma E.$$

where $\sigma = (n\mu_n + p\mu_p)\, q$ is the conductivity.

Electrical properties of si & ge:

2. Intrinsic concentration: With increase in temperature the density of hole-electron pair increases & thus conductivity increases. It has been found that n_i varies with temperature T as

$$n_i^2 = A_o T^3 e^{(-EGo / kT)}$$

Where

- E_{Go} is the energy gap at 0 degree kelvin.
- K is Boltzman constant in eV/K & A_0 is constant.

Electrical properties of si & ge:

3. The Energy Gap: The forbidden energy gap depends on temperature. Experimentally it is found that

- $E_G = 1.21 – 3.60 \times 10^{-4} T$ for silicon.

At room temperature $E_G = 1.1$ eV.

- $E_G = 0.785 – 2.23 \times 10^{-4} T$ for germanium.

At room temperature $E_G = 0.72$ eV.

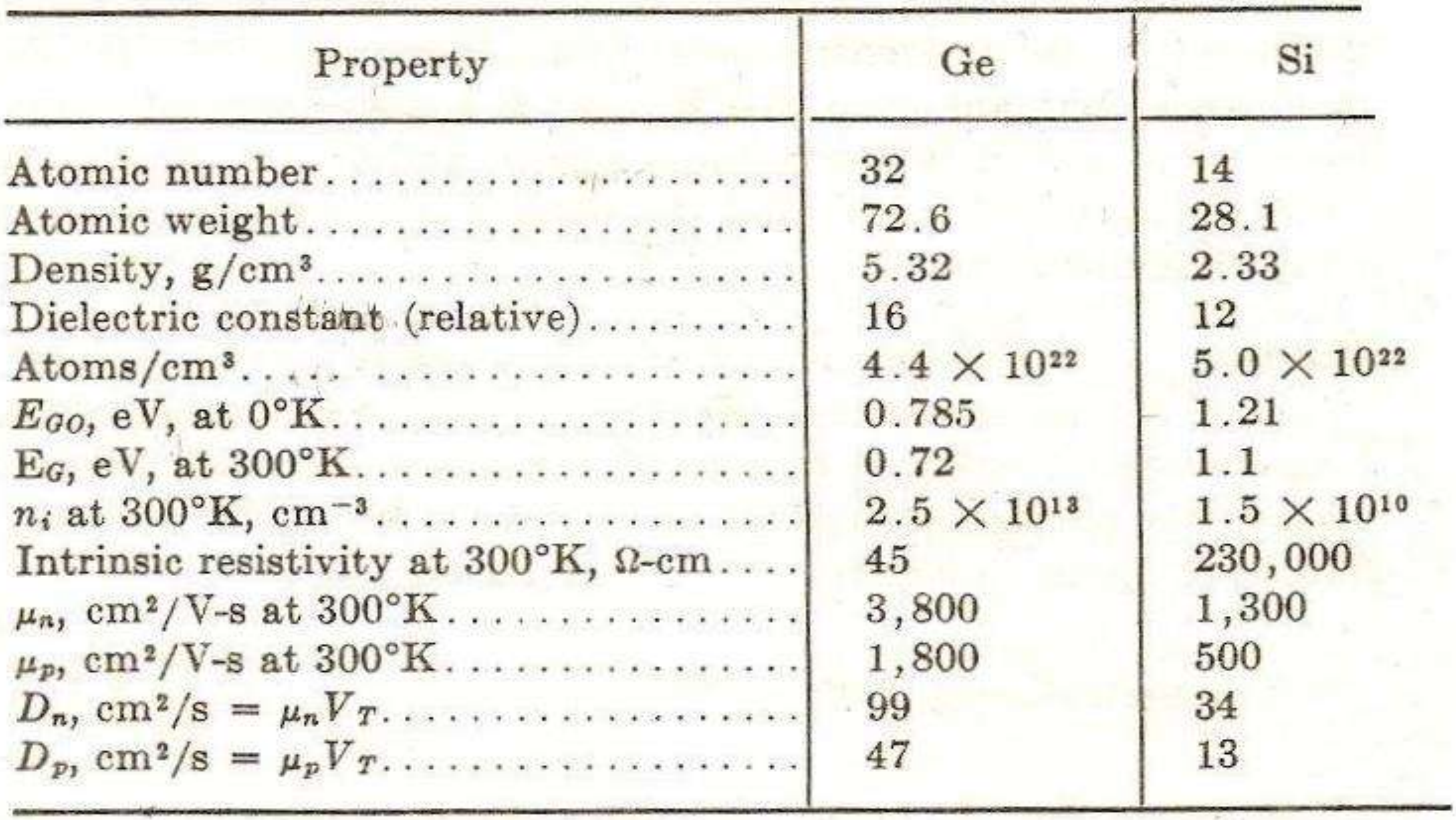
Electrical properties of si & ge:

4. Mobility: For temperature range 100 t0 400 degree K:

$$\mu \propto T^{-m}$$

- For silicon m = 2.5 (2.7) for electrons (holes).
- For germanium m= 1.66 (2.33) for electrons (holes).

properties of silicon & germanium.



Property	Ge	Si
Atomic number	32	14
Atomic weight	72.6	28.1
Density, g/cm^3	5.32	2.33
Dielectric constant (relative)	16	12
$Atoms/cm^3$	4.4×10^{22}	5.0×10^{22}
E_{GO}, eV, at 0°K	0.785	1.21
E_G, eV, at 300°K	0.72	1.1
n_i at 300°K, cm^{-3}	2.5×10^{13}	1.5×10^{10}
Intrinsic resistivity at 300°K, Ω-cm	45	230,000
μ_n, $cm^2/V\text{-}s$ at 300°K	3,800	1,300
μ_p, $cm^2/V\text{-}s$ at 300°K	1,800	500
D_n, $cm^2/s = \mu_n V_T$	99	34
D_p, $cm^2/s = \mu_p V_T$	47	13

Expected questions:

1. A semiconductor is doped with donor & acceptor concentration N_D & N_A respectively. Write the equations to determine n & p.
2. Explain the electrical properties of silicon & germanium.

Lecture-07
Basic Electronics:Unit-01

Topics to be covered:

- ✓Factors on which conductivity depends.
- ✓Conductivity modulation.
    - Thermistors.
    - Photoconductors.
- ✓Generation of charge carriers.
- ✓Recombination of charge carriers.

Conductivity depends on:

- Conductivity is given by the equation:

$$\sigma = (n\mu_n + p\mu_p)\, q$$

- Conductivity of a s/c is proportional to the concentration of free carriers ‘n’ & ‘p’.

- Conductivity can thus be increased by varying ‘n’ or ‘p’ (conductivity modulation).

Conductivity modulation:

1. Thermistors:

- The conductivity of a ge(si) increases approximately 6(8) percent per degree rise in temperature.

- This feature can be limitation or advantage depending upon application.

- Due to this property of s/c , it is also called (or used) as thermistors.

Conductivity modulation:

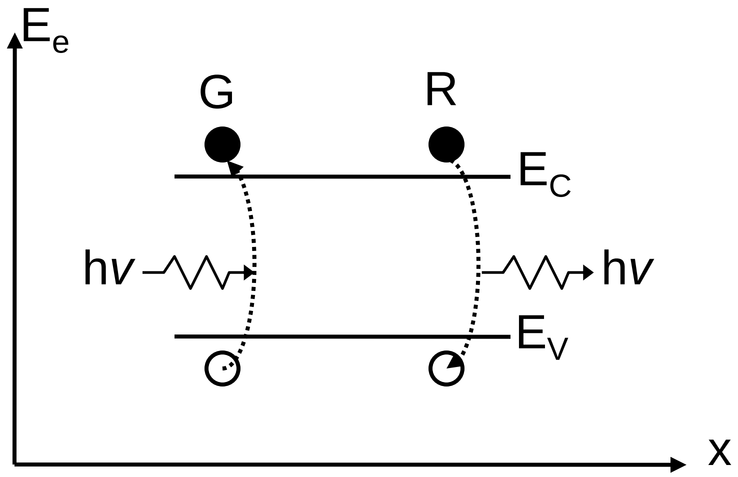
2. Photoconductors:

- ✓ Illuminating the s/c supplies radiant energy to the s/c & thus few covalent bonds are broken resulting in generation of new electron hole pairs.
- ✓ Conductivity increases or the resistance decreases.
- ✓ Are called photoresistors or photoconductors.

Generation & recombination:

- Generation (G):
  How e^- and h^+ are produced or created.

- Recombination (R): How e^- and h^+ are destroyed or removed



Mean life time of charge carrier:

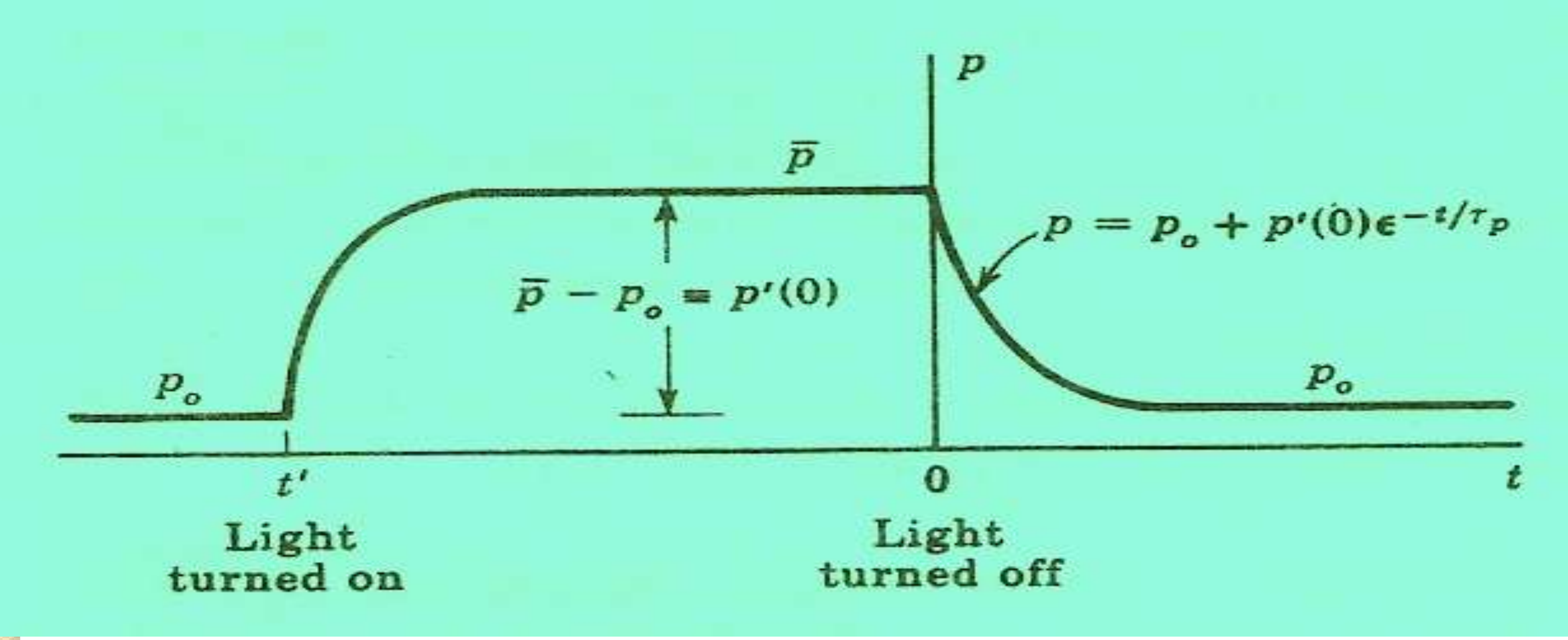
- In pure s/c concentration of electrons is equal to concentration of holes. Due to increase in temperature some new electron-hole pairs are generated. This process is called generation of charge carriers.

- Recombination is a process in where a electron moves from conduction band to valence band & get combined with holes.

- On an average a e^- or a hole exists for T_p or T_n seconds. This time is called mean life time of carrier.

Related derivation:

Consider a bar of n-type silicon containing thermal equilibrium concentration p_o & n_o. The process is illustrated below:



Derivation contd…….

1. At t = t’ the specimen is illuminated & new e^{-} - hole pairs are generated.
2. Since electron-hole pairs are generated thus excess concentration of charge carriers is same.
3. Percentage increase in majority carrier concentration is very less & hence only minority carrier concentration is considered.
4. At t=0, the radiation is removed. It can be shown that hole (minority) concentration decreases exponentially to zero for t > 0 i.e

$$p = p_o + p'(0)\epsilon^{-t/\tau_p}$$

Expected questions:

- Define conductivity modulation.
- Given a intrinsic semiconductor specimen, state two physical process to increase the conductivity.
- Define mean life time of carrier.
- Explain physically the meaning of the following statement: An electron & hole recombine & disappear.
- Radiation falls on a s/c specimen which is uniformily illuminated & a steady state is reached. At t=0, the light is turned off:

  a) Sketch the minority carrier concentration as a function of time for $t \geq 0$.

  b) Define all symbols in the equation describing your sketch.

Lecture-08
Basic Electronics:Unit-01

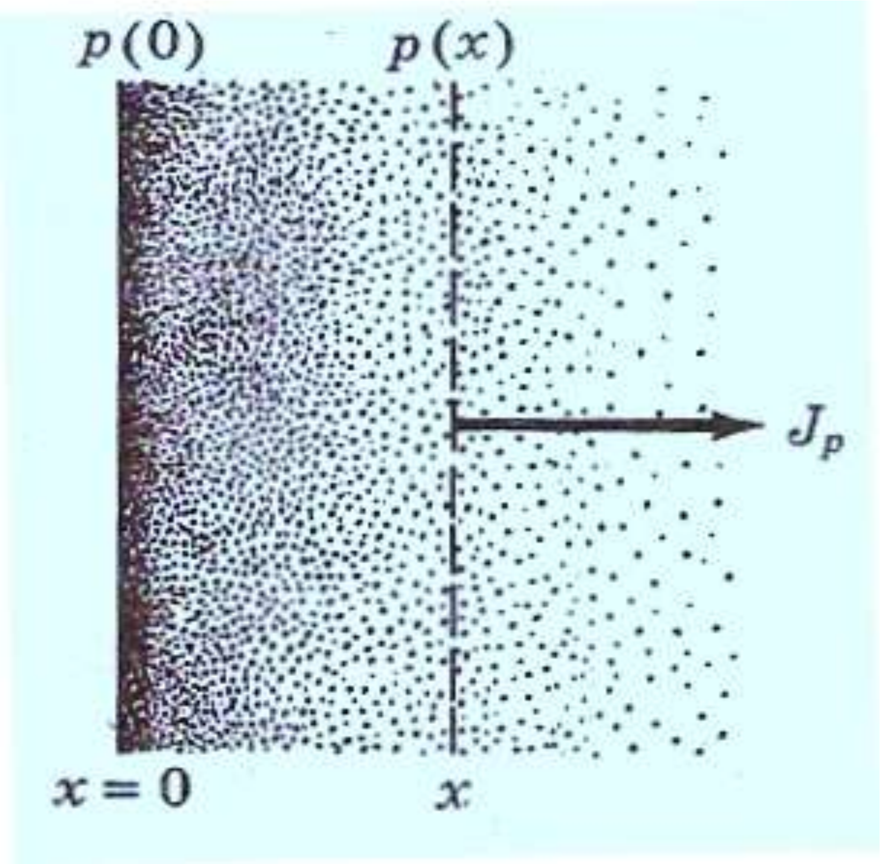
Topics to be covered:

- ✓Diffusion.
- ✓Diffusion current.
- ✓Einstein relationship.
- ✓Equations of total current.

Diffusion:

Current Flow:

- Drift: charged particle motion in response to an electric field.
- Diffusion:Particles tend to spread out or redistribute from areas of high concentration to areas of lower concentration.



Diffusion current:

- In semiconductors, “flow of carriers” from one region of higher concentration to lower concentration results in a “diffusion current”.

- Thus diffusion hole current density

$$J_p \quad -dp/dx$$

$$\propto \; J_p = -qD_p \, dp/dx \text{ amp/m}^2$$

Where D_p(m^2/sec) is the diffusion constant for holes.Negative sign shows that p decreases with increasing x as shown in figure(slide 2).

- The diffusion electron current density

$$J_n = qD_n \, dn/dx \text{ amp/m}^2$$

Einstein relationship

- According to the Einstein's relation for a s/c, the ratio of diffusion constant (D_P,D_n)to the mobility (μ_p, μ_n) of the charge carriers is constant and equal to volt equivalent of the temperature (V_T).

- $$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

where,

D_p = Diffusion constant for holes in m^2/sec,

D_n = Diffusion constant for electrons in m^2/sec,

μ_p = Holes mobility in m^2/sec,

μ_n = Electrons mobility in m^2/sec,

V_T = Volt equivent of temperature.

Equations of total current

- The total current is the sum of drift current and diffusion current. Thus, for a P- type s/c the total current per unit area,

$$Jp = q.\,\mu_p.\,p.\,E + (-q\,.Dp.dp/dx)$$

$$= q.\,\mu_p.\,p.\,E - q\,.Dp.\,dp/dx$$

- Similarly, for an N-type s/c

$$Jn = q.\,\mu_n.\,n.\,E-(\,-q\,.Dn.dn/dx)$$

$$= q.\,\mu_n.\,n.\,E + q\,.Dn.\,dn\,/\,dx$$

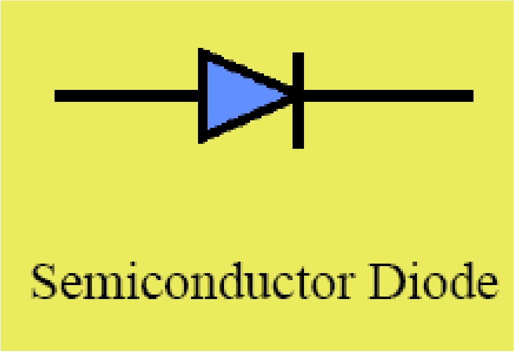
Lecture-09

Basic Electronics:Unit-01

Problems:

Lecture-10

Basic Electronics:Unit-0



Topics to be covered:

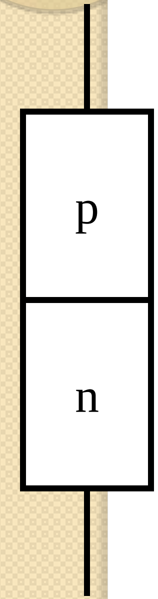
Diode -introduction.

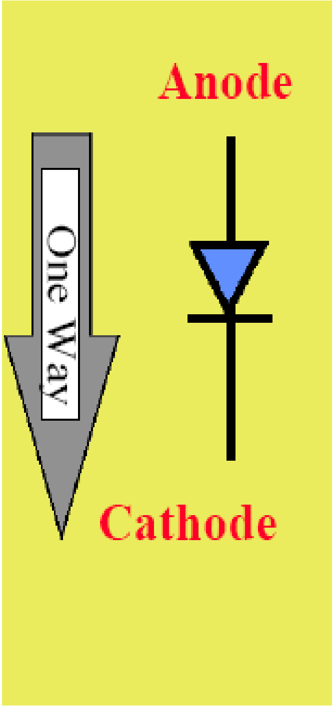
Open circuited p-n junction.

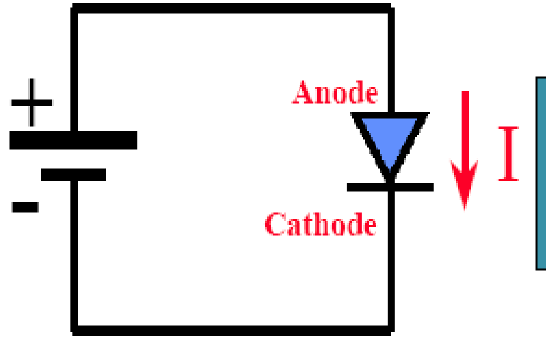
Why diodes?

- R, C, L are linear circuit elements.
- Many signal processing functions need nonlinear elements.
- Diode is the most fundamental nonlinear circuit element.
- Basic function: to allow current to flow only in one direction
- Diode → Di + Electrode

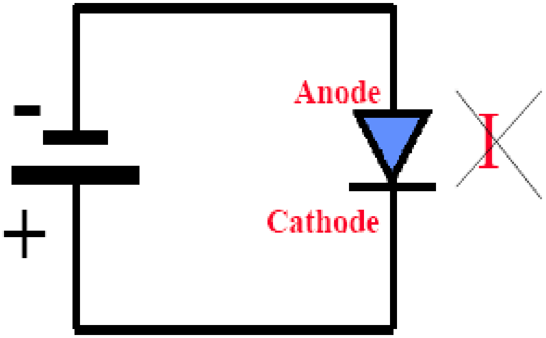
Diode symbol & operation:





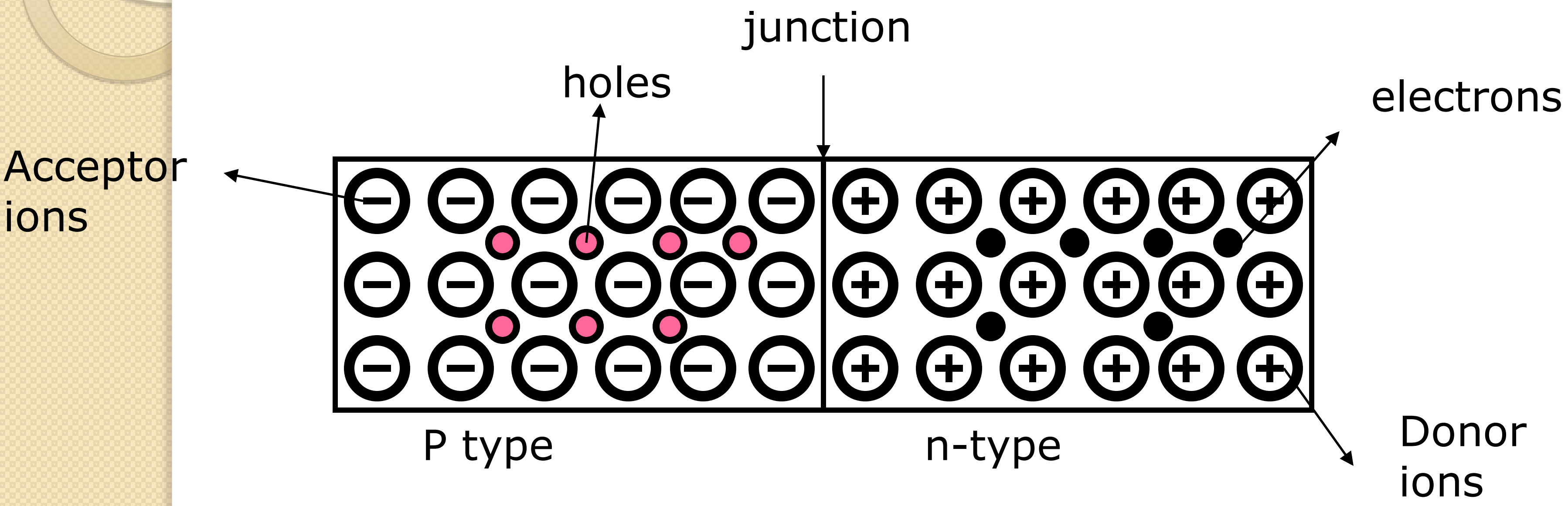


FORWARD BIASED



REVERSE BIASED

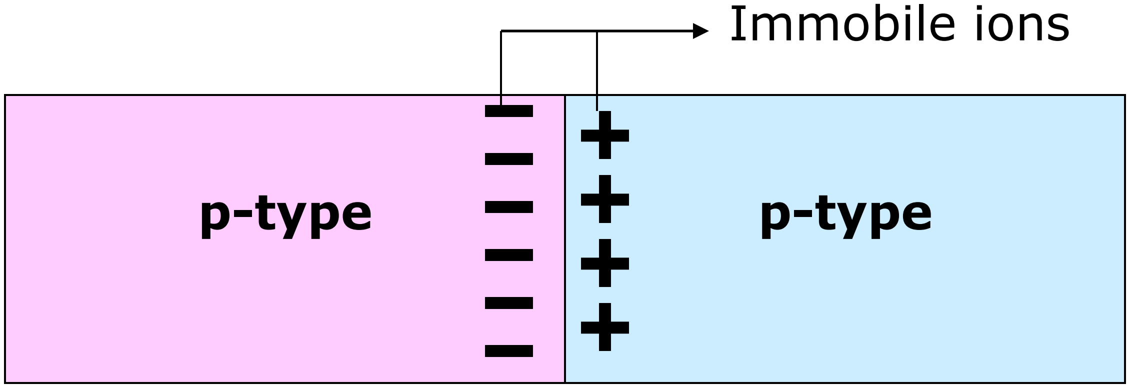
Open circuited p-n junction (formation of depletion region):



- Being free particles, **electrons** start diffusing from n-type material into p-material.
- Being free particles, **holes,** too, start diffusing from p-type material into n-material.
- However, every electrons transfers a negative charge (-q) onto the p-side and also leaves an uncompensated (+q) charge of the donor on the n-side. Every hole creates one positive charge (q) on the n-side and (-q) on the p-side.

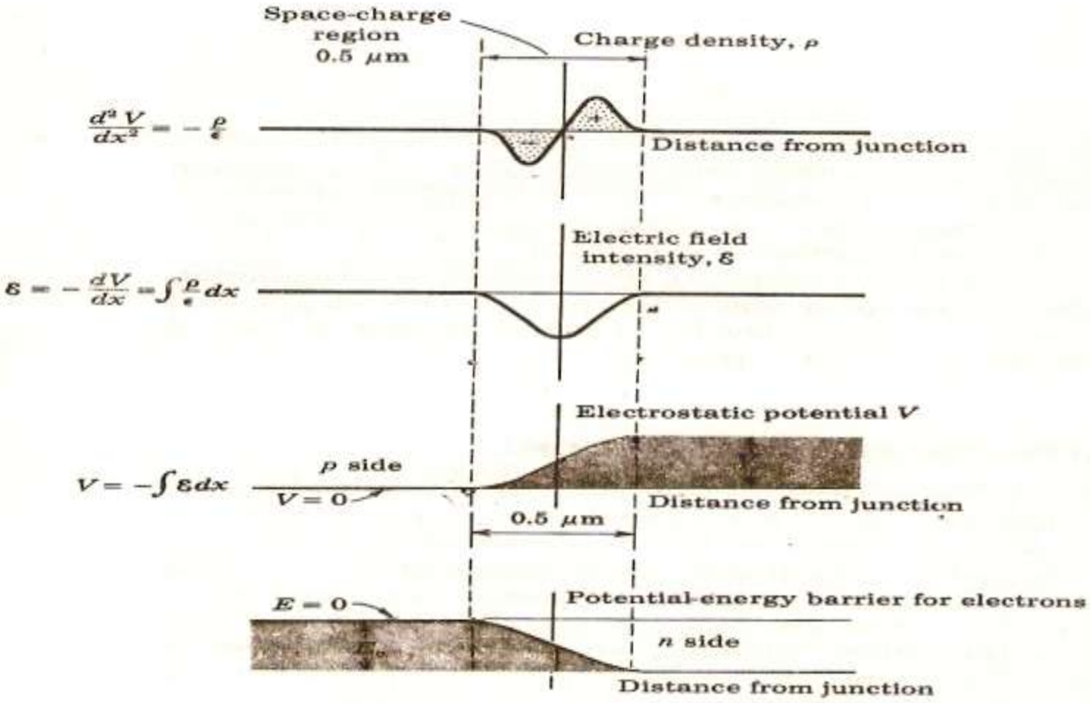
Formation of depletion region:

- Negative charge stops electrons from further diffusion.
- Positive charge stops holes from further diffusion.
- The diffusion forms a dipole charge layer at the p-n junction interface.
- **There is a "built-in" VOLTAGE at the p-n junction interface that prevents penetration of electrons into the p-side and holes into the n-side.**



Defining depletion region:

Thus at eqilibrium there exists a layer of –ve charges in p region & layer of +ve charges in n region near the junction which do not contain any free electron or hole & consist only of immobile ions . This region is called depletion region or space charge region. Its width is generally 0.5 to 1 micron.



Plots of charge density, electric field intensity & potential energy barriers at the junction

Diode applications:

- Rectifiers.
- Clippers.
- Clampers.

………… To be studied later.

Expected questions:

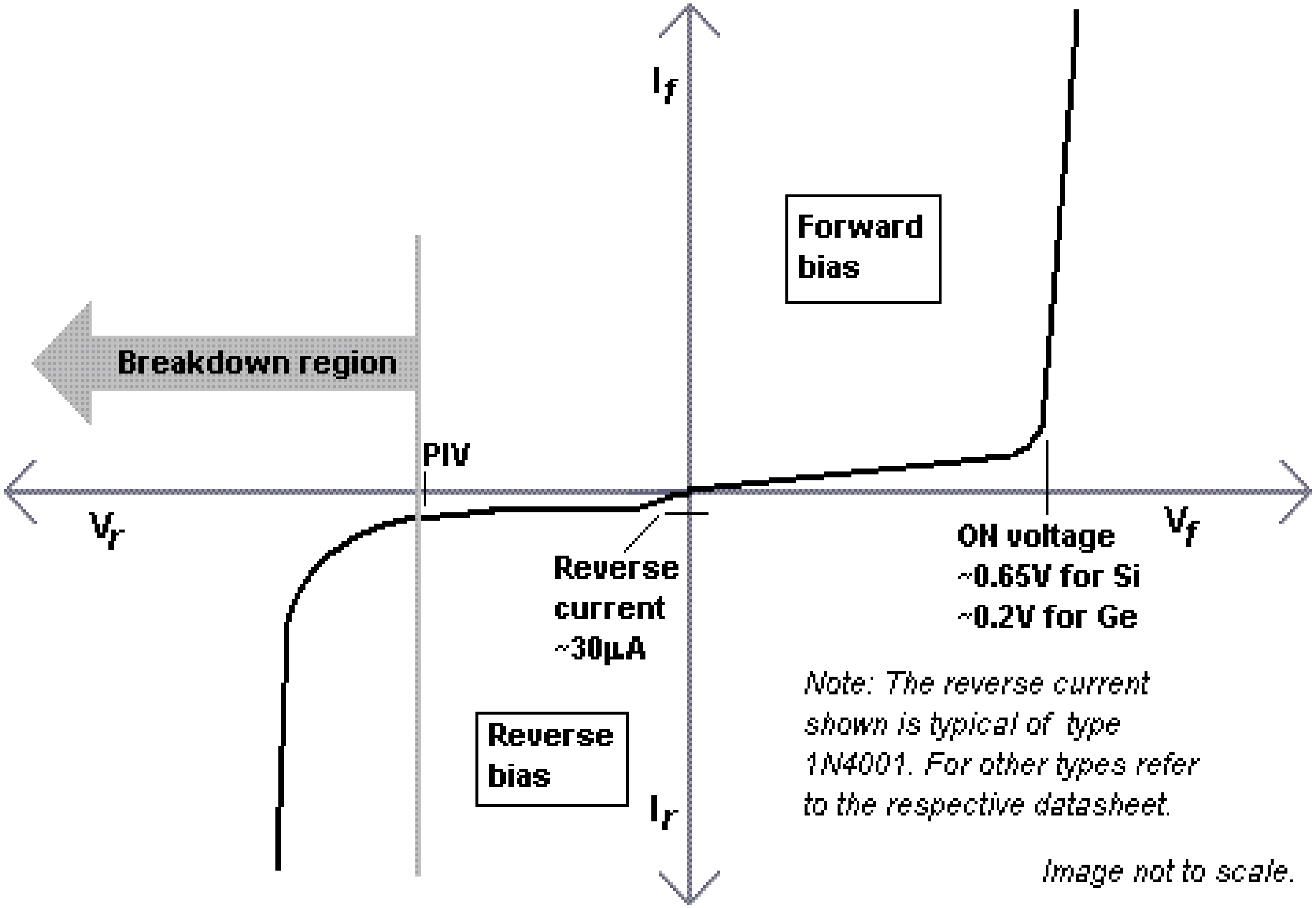
1) Define diode. Draw its symbol & explain its operation.
2) Define depletion region. Explain how it is formed.
3) Draw & explain the waveforms of charge density, Electric field intensity & potential energy barriers of n & p side.

LECTURE 12 :

- TOPIC TO BE COVERED :

➢ **Voltage-current characteristics:**

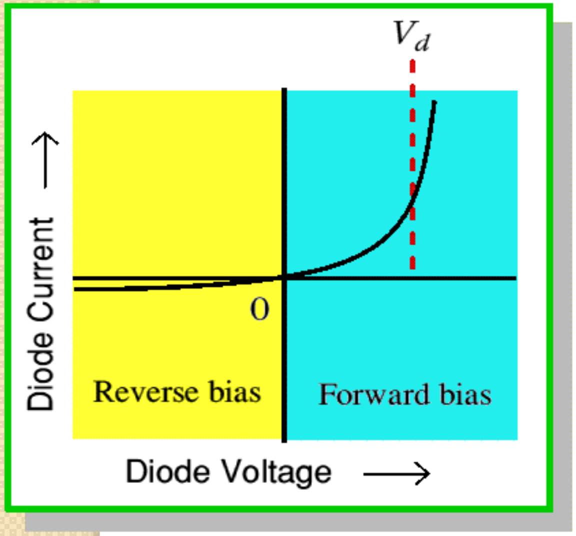
Voltage-current characteristics:



Note: The reverse current shown is typical of type 1N4001. For other types refer to the respective datasheet.

Image not to scale.

I-V characteristics of P-N diode



Observation :-

* Cut-in voltage for Si & Ge diodes are 0.6 and 0.2v respectevely.

* Breakdown voltage of silicon diode is higher that that of the Ge diode. So SI. Diodes can withstand to a higher reverse voltage.

*The reverse saturation current Io for a Ge diode is few µA at room tempreture.

Temperature dependency of reverse saturation current.

- The *Shockley ideal diode equation* or the *diode law* (named after transistor co-inventor William Bradford Shockley, not to be confused with tetrode inventor Walter H. Schottky) is the I–V characteristic of an ideal diode in either forward or reverse bias (or no bias). The equation is:
- Where
- *I* is tl$I = I_S \left(e^{V_D/(nV_T)} - 1 \right),$

- For even rather small *forward bias* voltages the exponential is very large because the thermal voltage is very small, so the subtracted '1' in the diode equation is negligible and the forward diode current is often approximated as

$$I = I_S e^{V_D/(nV_T)}$$

Lecture 13:

- Topic to be covered :
- **Diode Resistance**
- **The piecewise Linear VI characteristic of a pn diode.**

Diode Resistance

Using the Shockley equation, the small-signal diode resistance *rD* of the diode can be derived about some operating point (Q-point) where the DC bias current is *IQ* and the Q-point applied voltage is *VQ*. To begin, the diode **small-signal conductance** is found, *gD*, that is, the change in current in the diode caused by a small change in voltage across the diode, divided by this voltage change, namely:

$$g_D = \left.\frac{dI}{dV}\right|_Q = \frac{I_0}{V_T} e^{V_Q/V_T} \approx \frac{I_Q}{V_T}$$

- The latter approximation assumes that the bias current IQ is large enough so that the factor of 1 in the parentheses of the Shockley diode equation can be ignored. This approximation is accurate even at rather small voltages, because the thermal voltage $VT \approx 26$ mV at 300K, so VQ/VT tends to be large, meaning that the exponential is very large

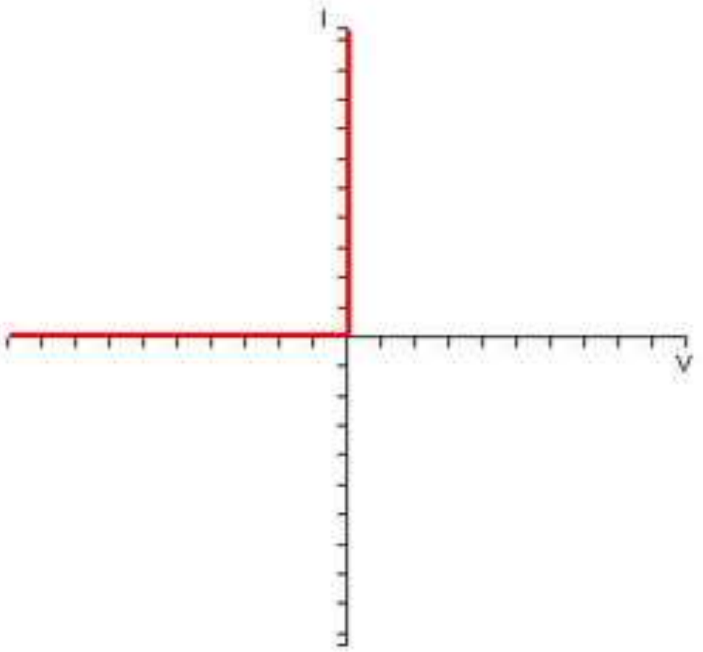
- Noting that the small-signal resistance *rD* is the reciprocal of the small-signal conductance just found, the diode resistance is independent of the ac current, but depends on the dc current, and is given as:

$$r_D = \frac{V_T}{I_Q}$$

The piecewise Linear VI characteristic of a pn diode.

- Firstly, let us consider a mathematically idealized diode. In such an ideal diode, if the diode is reverse biased, the current flowing through it zero. This ideal diode starts conducting at 0 V and for any positive voltage an infinite current flows and the diode acts like a short circuit. The I-V characteristics of an ideal diode are shown below:

The piecewise Linear VI characteristic of a pn diode.



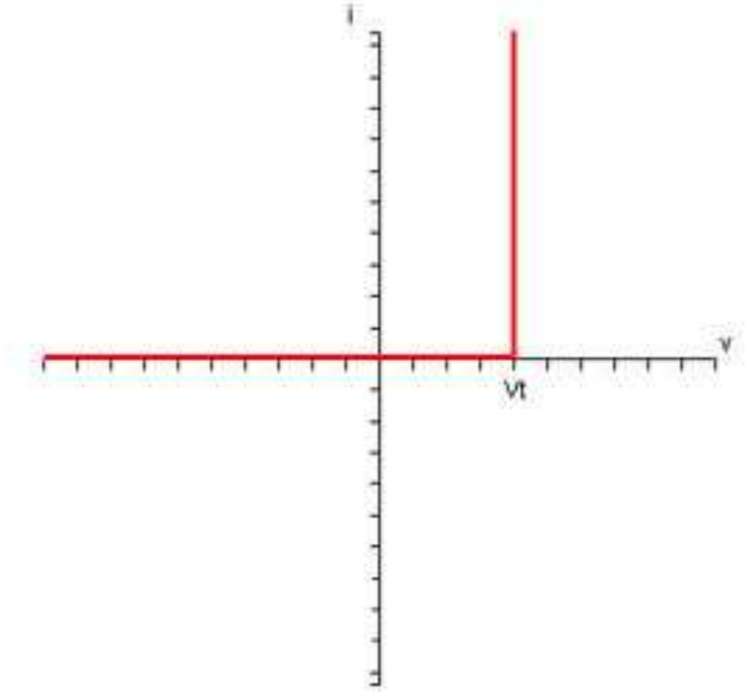
I-V characteristic of an ideal diode.

- **Ideal diode in series with voltage source**

  Now let us consider the case when we add a voltage source in series with the diode in the form shown below:

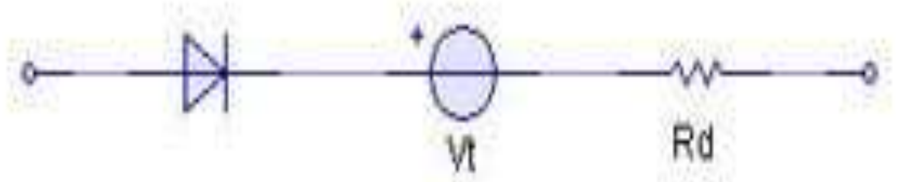
Ideal diode with a series voltage source.

- . In order to get the diode to conduct, the voltage at the anode will need to be taken to *Vt*. This circuit approximates the cut-in voltage present in real diodes. The combined I-V characteristic of this circuit is shown below:



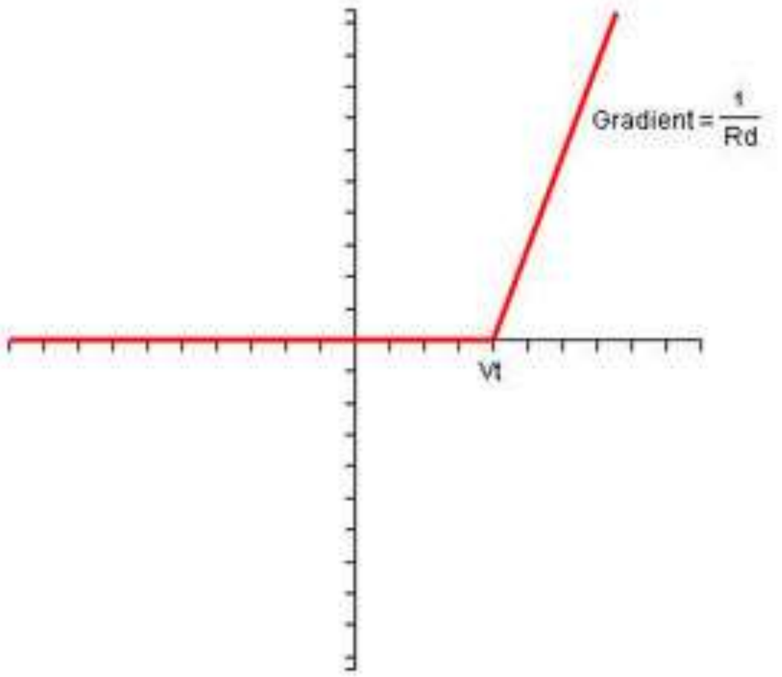
I-V characteristic of and ideal diode with a series voltage source.

- **Diode with voltage source and current-limiting resistor**
- The last thing needed is a resistor to limit the current, as shown below:



Ideal diode with a series voltage source and resistor.

The *I-V* characteristic of the final circuit looks like this:



I-V characteristic of and ideal diode with a series voltage source and resistor.

Lecture 15

- Topic to be covered :

➢ **Diffusion capacitance**

Capacitance

- The charge in the diode carrying current I_Q is known to be

$$Q = I_Q \tau_F + Q_J$$

- where τ_F is the forward transit time of charge carriers:[2] The first term in the charge is the charge in transit across the diode when the current I_Q flows. The second term is the charge stored in the junction itself when it is viewed as a simple capacitor; that is, as a pair of electrodes with opposite charges on them. It is the charge stored on the diode by virtue of simply having a voltage across it, regardless of any current it conducts.
- In a similar fashion as before, the diode capacitance is the change in diode charge with diode voltage:

$$C_D = \frac{dQ}{dV_Q} = \frac{dI_Q}{dV_Q}\tau_F + \frac{dQ_J}{dV_Q} \approx \frac{I_Q}{V_T}\tau_F + C_J$$

where

$$C_J = \frac{dQ_J}{dV_Q}$$

is the junction capacitance and the first term is called the diffusion capacitance, because it is related to the current diffusing through the junction.

Diffusion capacitance

- **Diffusion capacitance** is the capacitance due to transport of charge carriers between two terminals of a device, for example, the diffusion of carriers from anode to cathode in forward bias mode of a diode or from emitter to base (forward biased junction in active region) for a transistor. In a semiconductor device with a current flowing through it (for example, an ongoing transport of charge by diffusion) at a particular moment there is necessarily some charge in the process of transit through the device. If the applied voltage changes to a different value and the current changes to a different value, a different amount of charge will be in transit in the new circumstances.

- The change in the amount of transiting charge divided by the change in the voltage causing it is the diffusion capacitance. The adjective "diffusion" is used because the original use of this term was for junction diodes, where the charge transport was via the diffusion mechanism.

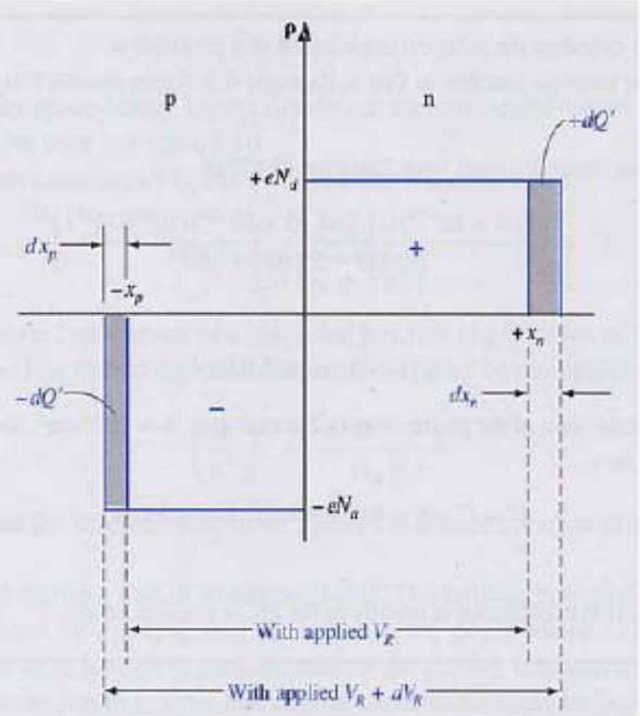
the amount of charge in transit through the device at this particular moment, denoted *Q*, is given by

$Q = I(V)\tau F$.

Consequently, the corresponding diffusion apacitance:*Cdiff*.is

$$C_{diff} = \frac{dQ}{dV} = \frac{dI(V)}{dV}\tau_F$$

Depletion Capacitance



D.A. Neaman, *Semiconductor Physics & Devices*, 2nd Ed., Irwin

Per unit area

$$C_j = \frac{dQ}{dV} = \frac{qN_D dx_n}{dV} = \frac{qN_A dx_p}{dV} = qN_D \frac{dx_n}{dV}$$

$$x_n = \left[\frac{2\varepsilon_s (V_{bi} - V)}{q}\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

$$C_j = \left[\frac{q\varepsilon_s N_A N_D}{2(V_{bi} - V)(N_A + N_D)}\right]^{1/2} = \frac{\varepsilon_s}{W}$$

Similar to a parallel-plate capacitor

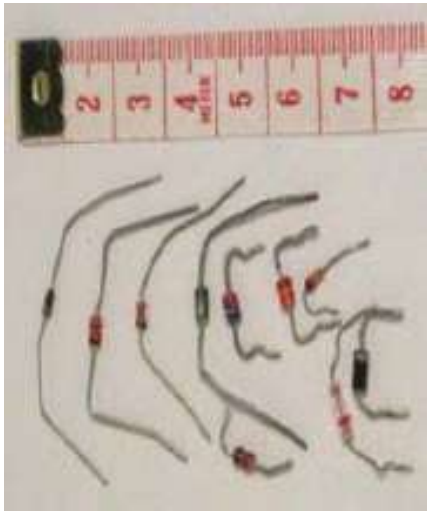
Reverse bias $V = -V_R$

$$C_j = \left[\frac{q\varepsilon_s N_A N_D}{2(V_{bi} + V_R)(N_A + N_D)}\right]^{1/2}$$

PN-junction diodes: Applications

- Diode applications:
  - Rectifiers
  - Switching diodes
  - Zener diodes
  - Varactor diodes

- Photodiodes
  - pn junction photodiodes
  - p-i-n and avalanche photodiodes



- Solar Cells
- Light Emitting Diodes
- Lasers

PN-junction diodes: Applications

- Solid state lighting, photovoltaic,
- photo detection, radio demodulation
- over-voltage protection, Logic gates
- temperature measurement, etc.

Lecture 16

- Topic to be covered:

➢ Avalanche & Zener Breakdown

Avalanche & Zener Breakdown :

Avalanche breakdown can occur within insulating or semiconducting solids, liquids, or gases when the electric field in the material is great enough to accelerate free electrons to the point that, when they strike atoms in the material, they can knock other electrons free: the number of free electrons is thus increased rapidly as newly generated particles become part of the process.

- This phenomenon is usefully employed in special purpose semiconductor devices such as the avalanche diode, the avalanche photodiode and the avalanche transistor, as well as in some gas filled tubes

The avalanche process

- Avalanche breakdown is a current multiplication process that occurs only in strong electric fields, which can be caused either by the presence of very high voltages, such as in electrical transmission systems, or by more moderate voltages which occur over very short distances, such as within semiconductor devices.

- As avalanche breakdown begins, free electrons are accelerated by the electric field to very high speeds. As these high-speed electrons move through the material they inevitably strike atoms. If their velocity is not sufficient for avalanche breakdown (because the electric field is not strong enough) they are absorbed by the atoms and the process halts. However, if their velocity *is* high enough, when they strike an atom, they knock an electron free from it, ionizing it

Applications

- In avalanche transistors and avalanche photodiodes, this effect is used to multiply normally tiny currents, thus increasing the gain of the devices: in avalanche photodiodes, current gains of over a million can be achieved
- Also, the phenomenon is very fast, meaning that avalanche current quickly follows avalanche voltage variations or starting charge (number of free electrons available to start the process) variations, and this gives to avalanche transistors and avalanche photodiodes the capability of working in the microwave frequency range and in pulse circuits .

PROBLEMS:

PROBLEMS :

UNIT -2

RECTIFIER AND FILTER

LECTURE 1:

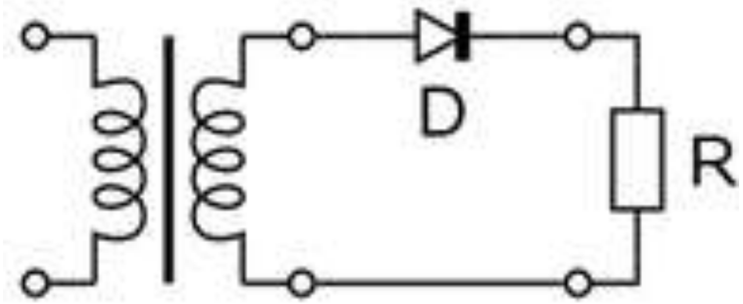
- TOPIC TO BE COVERED :

➢ LOAD LINE ANALYSIS

➢ HALF WAVE RECTIFIER

Load line Analysis :

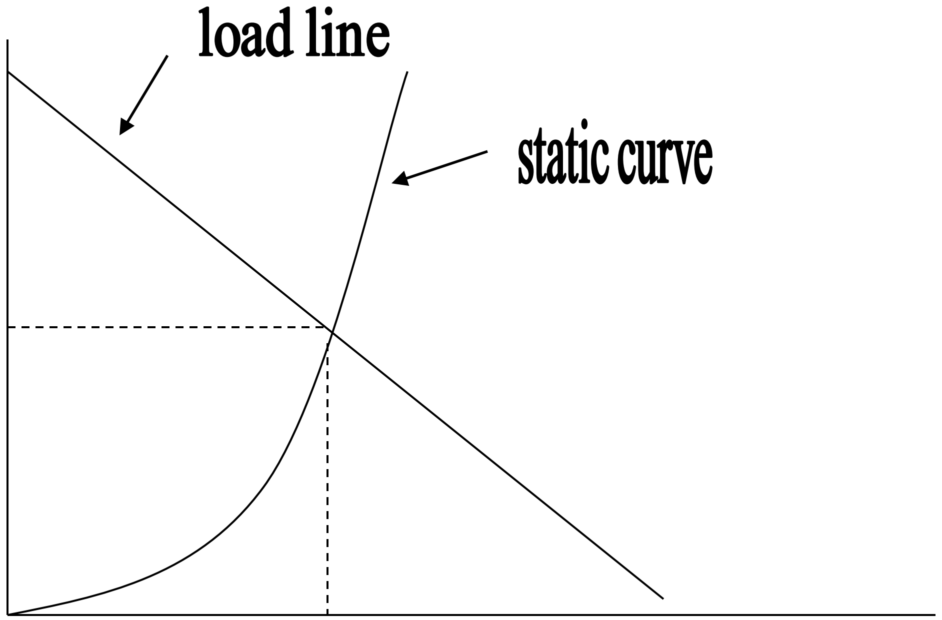
- Consider basic diode ckt



From KVL

$$V = V_i - I R_L$$

In order to determine the v & I is not sufficient. The other relation between v & I is given by the static characteristics of diode ,given as below :



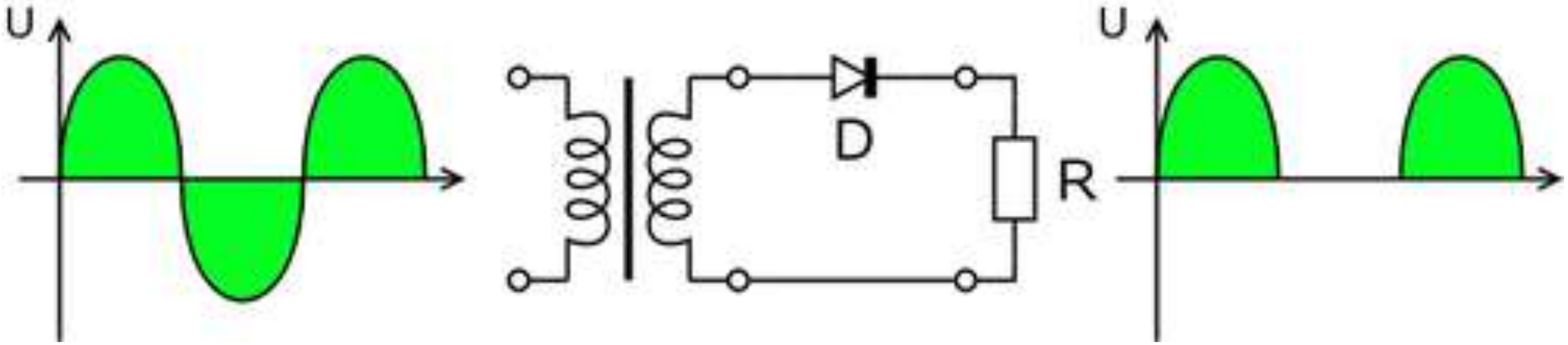
Rectifier :

- A **rectifier** is an electrical device that converts alternating current (AC) to direct current (DC), a process known as **rectification**. Rectifiers have many uses including as components of power supplies and as detectors of radio signals. Rectifiers may be made of solid state diodes, vacuum tube diodes, mercury arc valves, and other components.

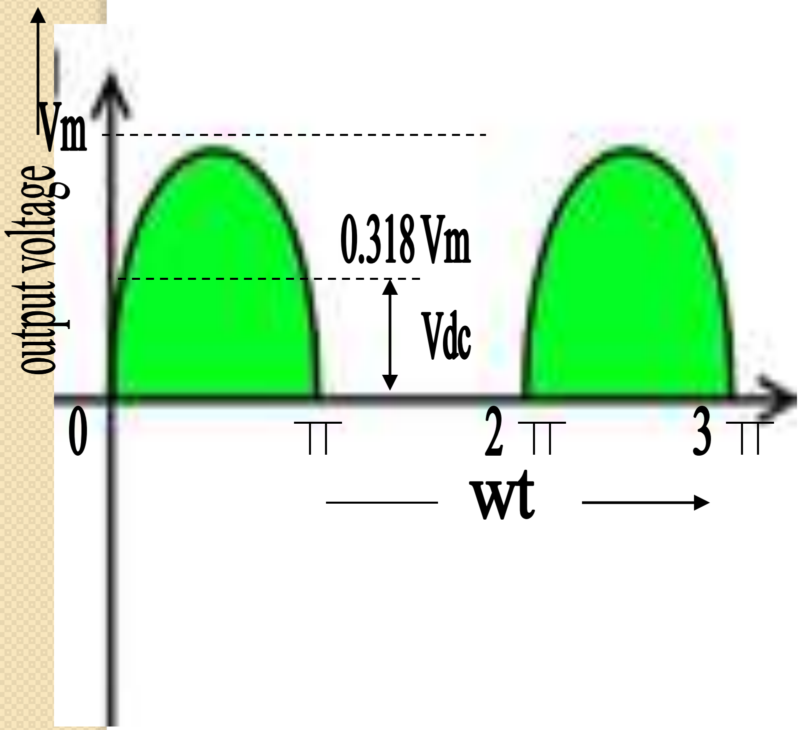
Half-wave rectification

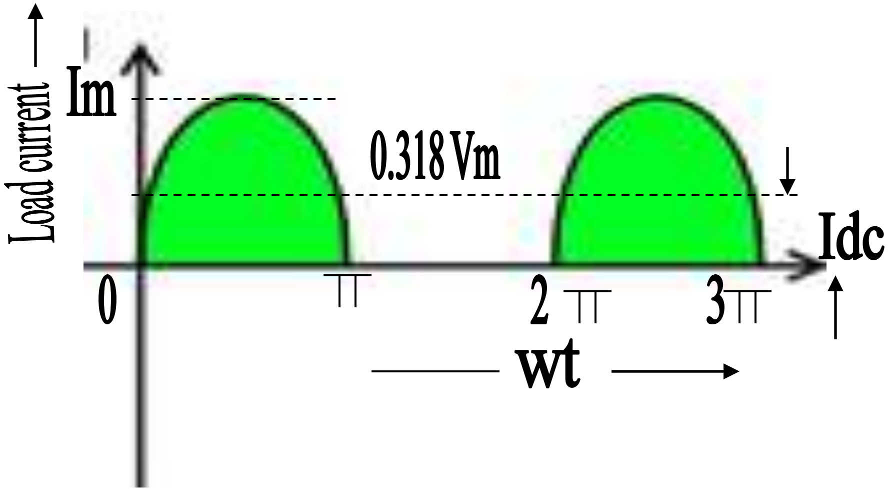
- In half wave rectification, either the positive or negative half of the AC wave is passed, while the other half is blocked. Because only one half of the input waveform reaches the output, it is very inefficient if used for power transfer. Half-wave rectification can be achieved with a single diode in a one phase supply, or with three diodes in a three-phase supply.

Half-wave rectifire :



Average values of output voltage and current in HWR





$$V_{dc} = \frac{\text{Area under the curve over full cycle}}{\text{Base}}$$

$$= \frac{V_m}{\pi}$$

$$= 0.318 V_m$$

- $I_{dc} = \frac{V_{dc}}{R_L}$

$$= \frac{V_m}{\pi R_L}$$

$$= \frac{I_m}{\pi}$$

$$= 0.318\, I_m$$

Rectifier characteristics

1. Voltage regulation-

$$\% R = \frac{V_{noload} - V_{load}}{V_{load}} * 100$$

2. Efficiency :

$$\eta = \frac{P_{dc}}{P_{ac}}$$

3.Peak inverse voltage : (PIV)

The maximum voltage which can be subjected to the diode in reverse bias in rectifier circuit is called Peak inverse voltage.

4. Ripple factor :

$$\gamma = \frac{\text{RMS value of ac component}}{\text{Avg or dc component}}$$

$$\gamma = \frac{I_{ac}}{I_{dc}}$$

5. Transformer utilization factor (TUF):

$$\text{TUF} = \frac{\text{DC power delivered to load}}{\text{AC power delivered of xformer}}$$

$$= \frac{I^2_{dc} R_L}{I_{rms} V_{rms}}$$

- $= I^2_m / \; ^2 R_L$

  π

  $\overline{\qquad I_m /2 V_{rms}}$

  $= I_m * 2 * R_L * 2$

  $\overline{\qquad\qquad ^2 * V_m \qquad\qquad}$

  π

  $= 4 \qquad = 0.287$

  $\overline{\qquad}$ $\quad ^2$

  π

Disadvantages

1. Ripple factor is 1.21,thus output contains lots of varying components.
2. The max theoritical efficiency is 40.6 % but practically the value will be less.
3. The rectification is done only for half cycle.
4. Load X-former utilization factor is 0.287.

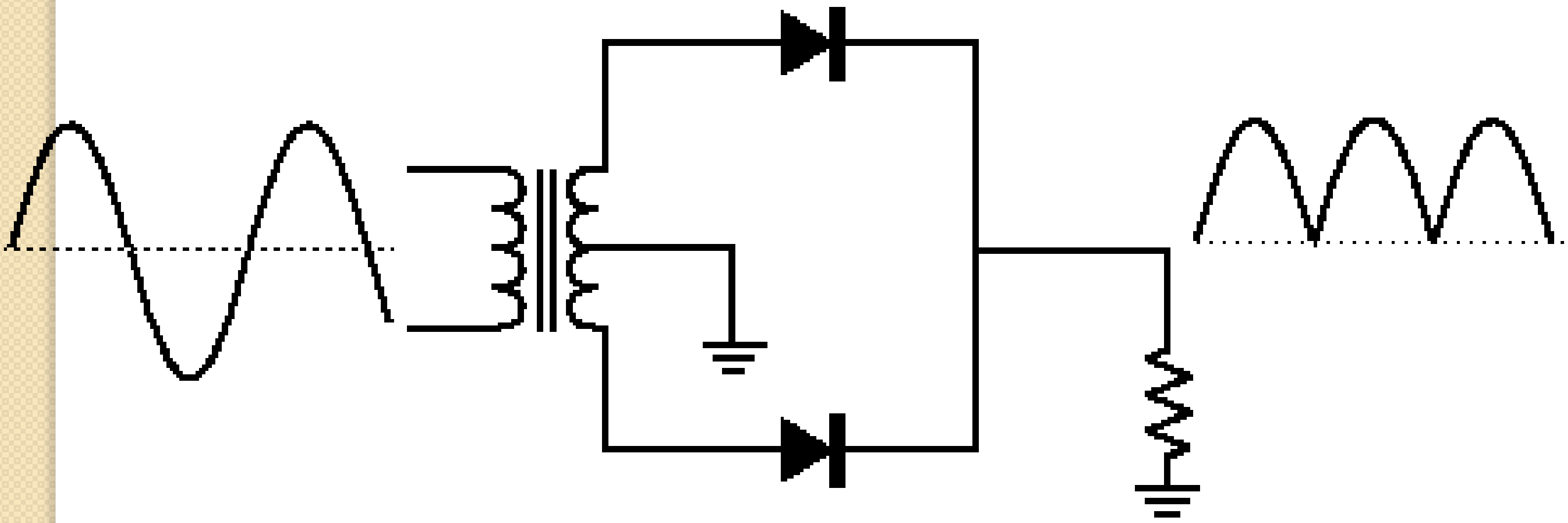
LECTURE 2:

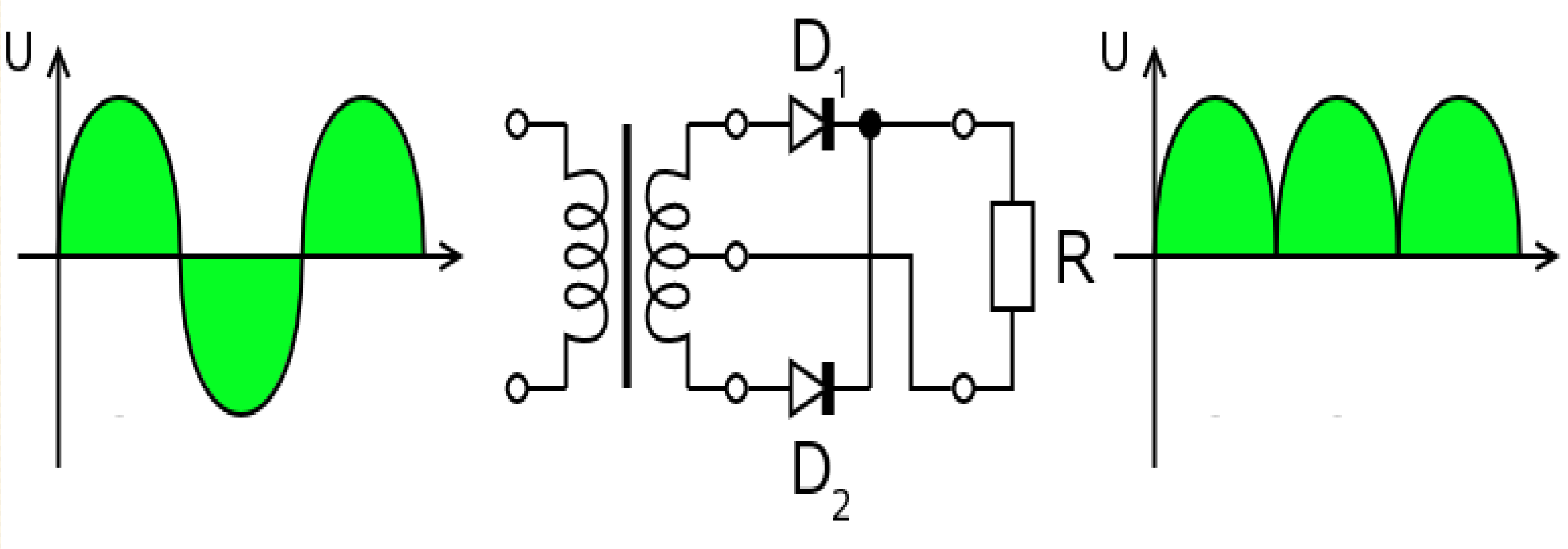
- TOPIC TO BE COVERED :
- FULL WAVE RECTIFIER

Full-wave rectification

- Full-wave rectification converts both polarities of the input waveform to DC(direct current), and is more efficient. However, in a circuit with a non-center tapped transformer, four diodes are required instead of the one needed for half-wave rectification. This is due to each output polarity requiring two rectifiers each, for example, one for when AC terminal 'X' is positive and one for when AC terminal 'Y' is positive. The other DC output requires exactly the same, resulting in four individual junctions (See semiconductors, diode). Four rectifiers arranged this way are called a diode bridge or bridge rectifier:

Full-wave rectifier :




U
D1
D2
R
U

Charateristics :

- ***Ripple Factor***

  The ripple factor for a Full Wave Rectifier is given by

$$\gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

- RMS value of the voltage at the load resistance is

$$V_{rms} = \left[\frac{1}{\pi}\int_0^{\pi} V_m^{\,2}\sin^2\omega t\, d(\omega t)\right]^{1/2} = \frac{V_m}{\sqrt{2}}$$

$$\therefore \gamma = \sqrt{\left(\frac{V_m/2}{2V_m/\pi}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{8}\right)^2 - 1} = 0.482$$

Efficiency

- Efficiency, h is the ratio of the dc output power to ac input power

$$\eta = \frac{dc\ output\ power}{ac\ input\ power} = \frac{P_{dc}}{P_{ac}}$$

$$\frac{V_{dc}^{2}/R_{L}}{V_{rms}^{2}/R_{L}} = \frac{\left[2V_{m}/\pi\right]^{2}}{\left[V_{m}/\sqrt{2}\right]^{2}} = 8/\pi^{2} = 0.812 = \underline{\underline{81.2\%}}$$

Transformer Utilization Factor

Transformer Utilization Factor, TUF can be used to determine the rating of a transformer secondary. It is determined by considering the primary and the secondary winding separately and it gives a value of 0.693.

Form Factor

Form factor is defined as the ratio of the rms value of the output voltage to the average value of the output voltage.

$$Form\ factor = \frac{rms\ value\ of\ output\ voltage}{average\ value\ of\ the\ output\ voltage}$$

$$= \frac{\left(\frac{V_m}{\sqrt{2}} \right)}{\left(\frac{2V_m}{\pi} \right)} = \frac{\pi}{2\sqrt{2}} = \underline{\underline{1.11}}$$

Average values of output voltage and current in FWR :

- the average voltage or the dc voltage available across the load resistance is

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{2V_m}{\pi R_L} = \frac{2I_m}{\pi} \quad and \quad I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$V_{dc} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t)$$

Applications :

- The primary application of rectifiers is to derive DC power from an AC supply.
- Rectifiers also find a use in detection of amplitude modulated radio signals.
- Rectifiers are also used to supply polarised voltage for welding.

LECTURE 3:

- TOPIC TO BE COVERED :

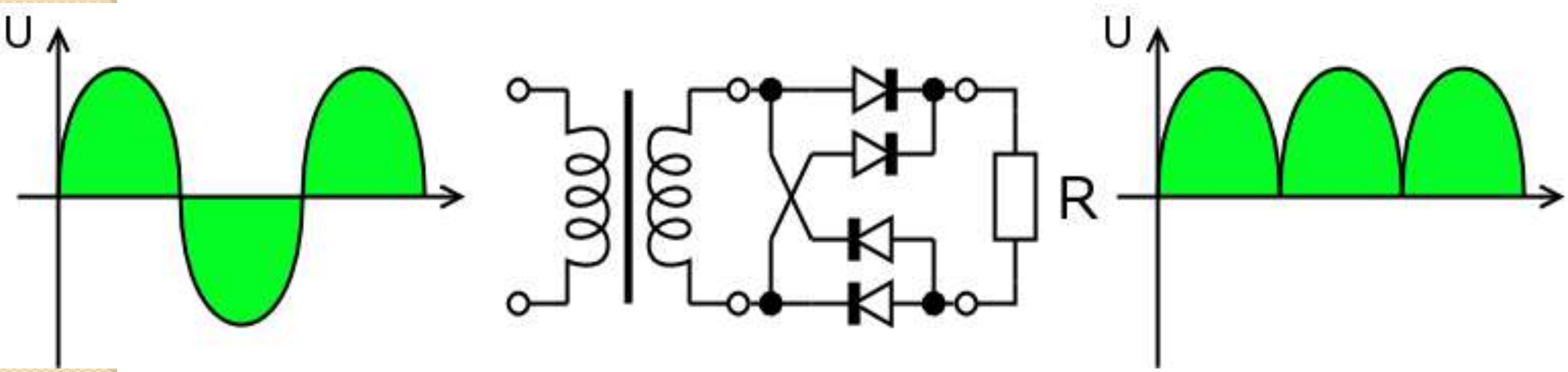
➢ BRIDGE RECTIFIER & PROBLEM

Bridge rectifier

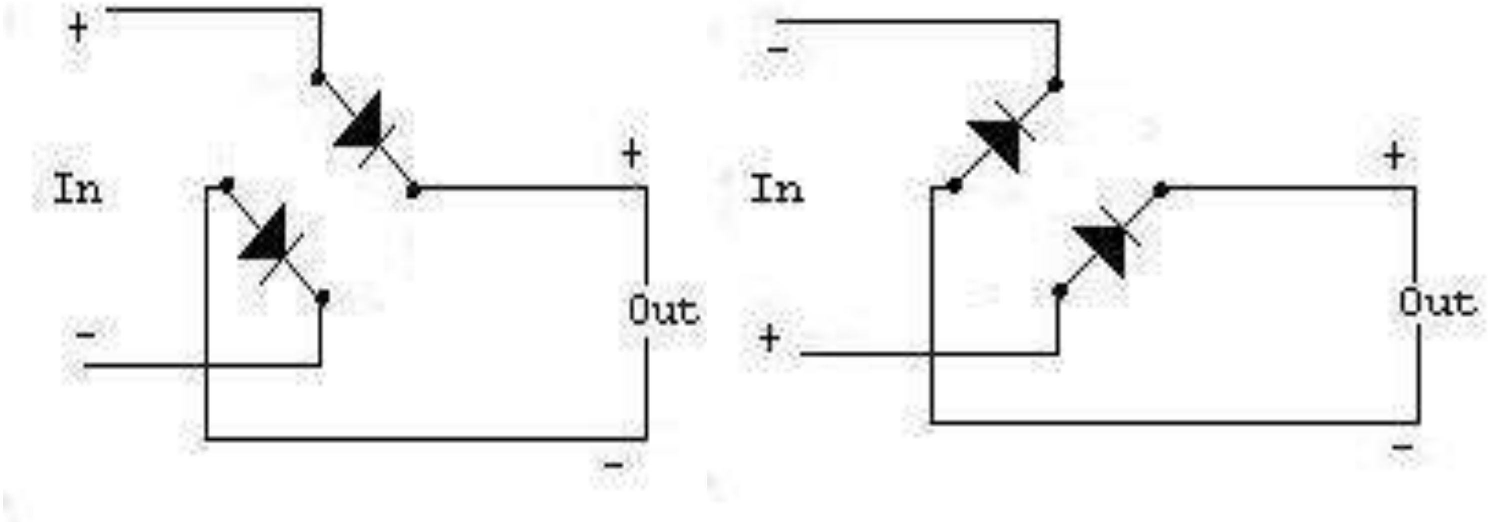
- A bridge rectifier makes use of four diodes in a bridge arrangement to achieve full-wave rectification. This is a widely used configuration, both with individual diodes wired as shown and with single component bridges where the diode bridge is wired internally.

Bridge rectifier :

- Four rectifiers arranged this way are called a diode bridge or bridge rectifier:



Here's what the circuit looks like to the signal as it alternates:



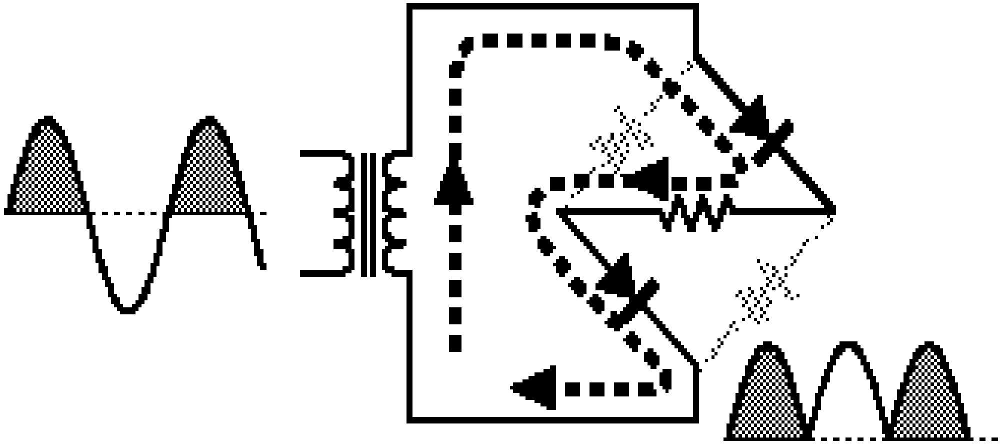
So, if we feed our AC signal into a full wave rectifier, we'll see both halves of the wave above 0 Volts.

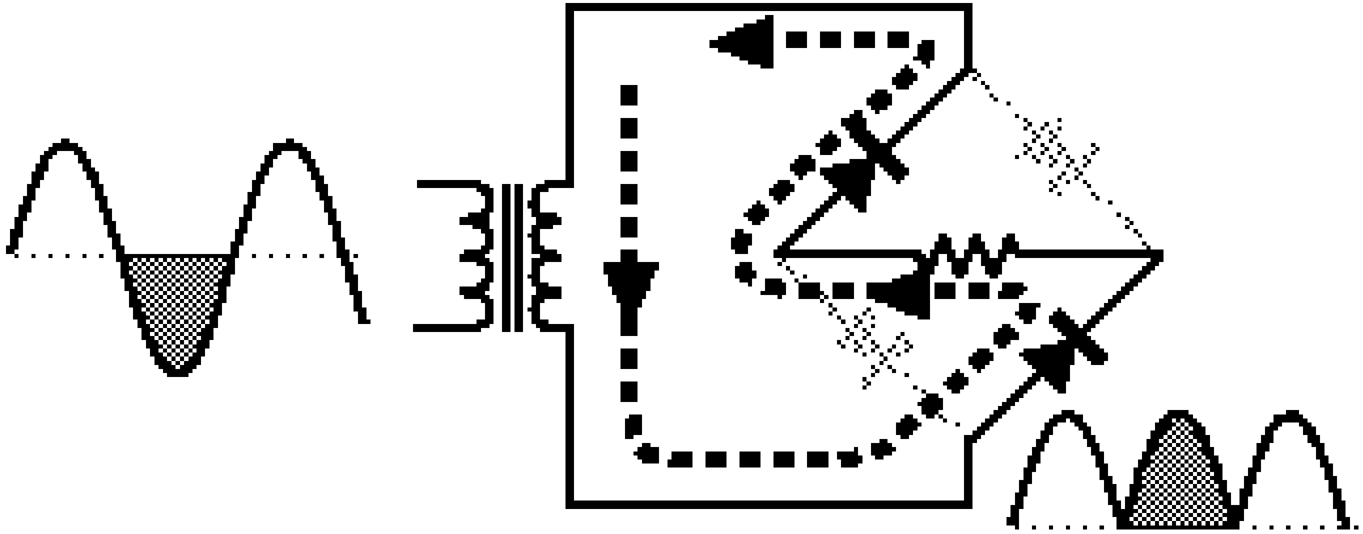
Since the signal passes through two diodes, the voltage out will be lower by two diode drops, or 1.2 Volts.

Current Flow in the Bridge Rectifier

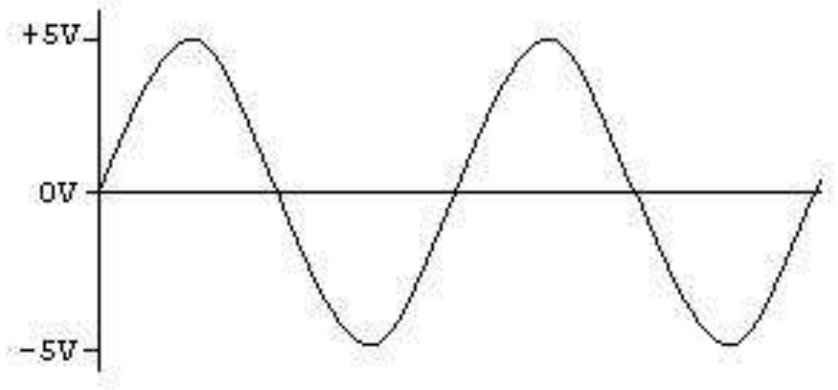
- For both positive and negative swings of the transformer, there is a forward path through the diode bridge. Both conduction paths cause current to flow in the same direction through the load resistor, accomplishing full-wave rectification

- While one set of diodes is forward biased, the other set is reverse biased and effectively eliminated from the circuit.

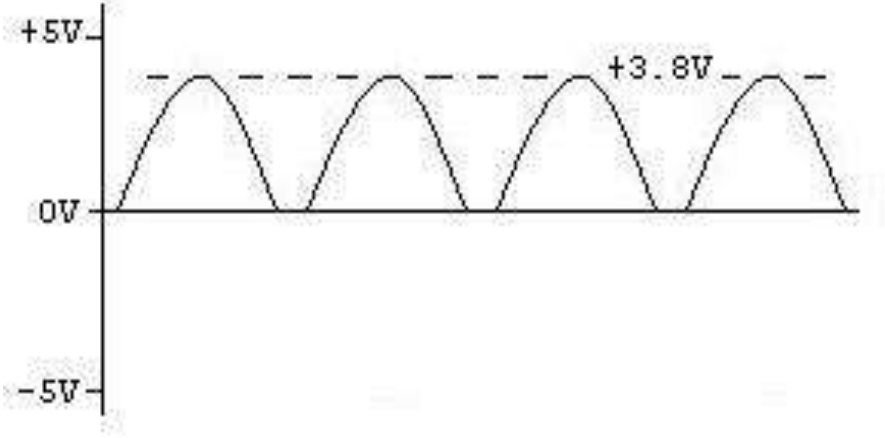




AC Wave In:



AC Wave Out (Full-Wave Rectified):



Applications :

- The primary application of rectifiers is to derive DC power from an AC supply.
- Rectifiers also find a use in detection of amplitude modulated radio signals.
- Rectifiers are also used to supply polarised voltage for welding.

LECTURE 4:

Problems :

LECTURE 5 :

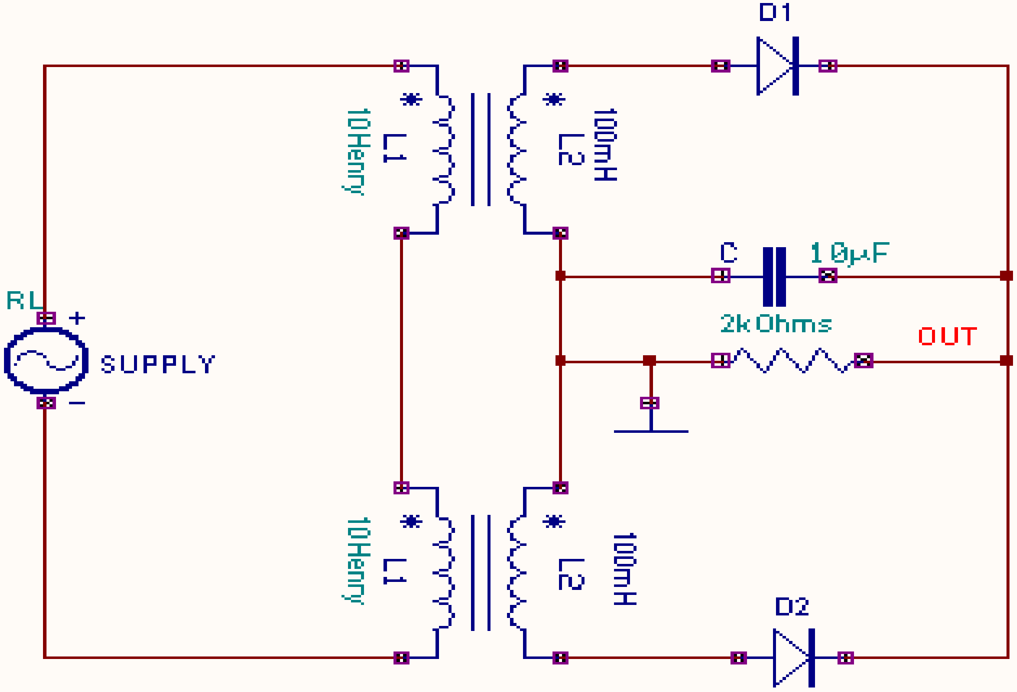
TOPIC TO BE COVERED :

- FILTERS : INDUCTOR FILTER

Filters

The output of the Full Wave Rectifier contains both ac and dc components. A majority of the applications, which cannot tolerate a high value ripple, necessitates further processing of the rectified output. The undesirable ac components i.e. the ripple, can be minimized using filters.

FullWave Rectifier with Filter

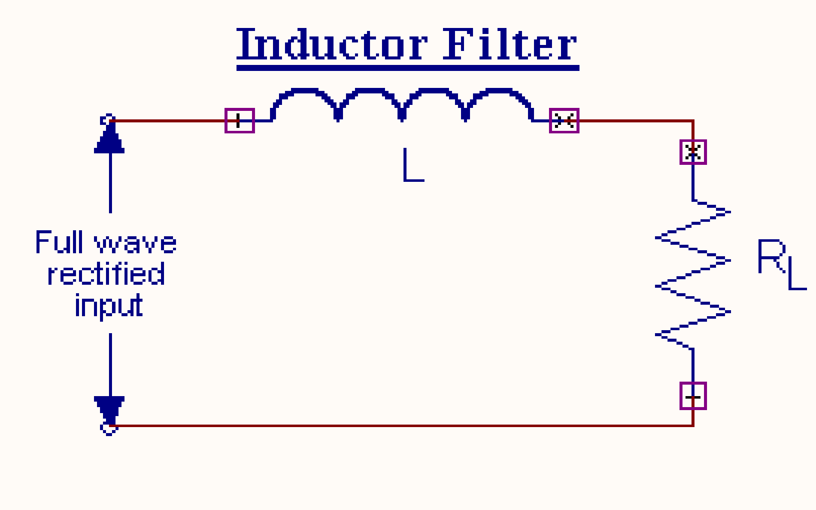


- The output of the rectifier is fed as input to the filter. The output of the filter is not a perfect dc, but it also contains small ac components. Some important filters are
  - Inductor Filter
  - Capacitor Filter
  - LC Filter
  - CLC or p Filter

INDUCTOR FILTERS :

- **INDUCTOR FILTERS** use an inductor called a choke to filter the pulsating dc input. Because of the impedance offered to circuit current, the output of the filter is at a lower amplitude than the input.

The figure shows an inductor filter. When the output of the rectifier passes through an inductor, it blocks the ac component and allows only the dc component to reach the load.



- Ripple factor of the inductor filter is given by

$$\gamma = \frac{R_L}{3\sqrt{2}\,\omega L}$$

- The operation of the inductor filter depends on its property to oppose any change of current passing through it. To analyze this filter for full wave, the Fourier series can be written as

$$V_o = \frac{2V_m}{\pi} - \frac{4V_m}{\pi}\left[\frac{1}{3}\cos 2\omega t + \frac{1}{15}\cos 4\omega t + \frac{1}{35}\cos 6\omega t + \cdots\right]$$

The dc component is $\frac{2V_m}{\pi}$.

Assuming the third and higher terms contribute little output, the output voltage is

$$V_o = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t$$

The impedance of series combination of L and RL at 2w is

$$Z = \sqrt{R_L{}^2 + (2\omega L)^2} = \sqrt{R_L{}^2 + 4\omega^2 L^2}$$

- Therefore for the ac component

$$I_m = \frac{V_m}{\sqrt{R_L^{\,2} + 4\omega^2 L^2}}$$

Therefore, the resulting current *i* is given by

$$i = \frac{2V_m}{\pi R_L} - \frac{4V_m}{3\pi}\frac{\cos(2\omega t - \varphi)}{\sqrt{R_L^{\,2} + 4\omega^2 L^2}} \quad where \quad \varphi = \tan^{-1}\left(\frac{2\omega L}{R_L}\right)$$

- The ripple factor which can be defined as the ratio of the rms value of the ripple to the dc value of the wave, is

$$\gamma = \frac{\dfrac{4V_m}{3\pi\sqrt{2}\sqrt{R_L^{\,2} + 4\omega^2 L^2}}}{\dfrac{2V_m}{\pi R_L}} = \frac{2}{3\sqrt{2}} \frac{1}{\sqrt{1 + \dfrac{4\omega^2 L^2}{R_L^{\,2}}}}$$

- If $\frac{4\omega^2 L^2}{R_L{}^2} >> 1$ mplified expression for γ is

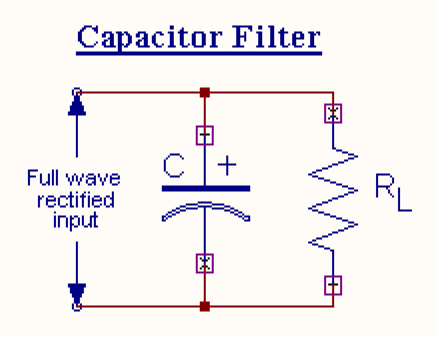
$$\gamma = \frac{R_L}{3\sqrt{2}\,\omega L}$$

LECTURE 6:

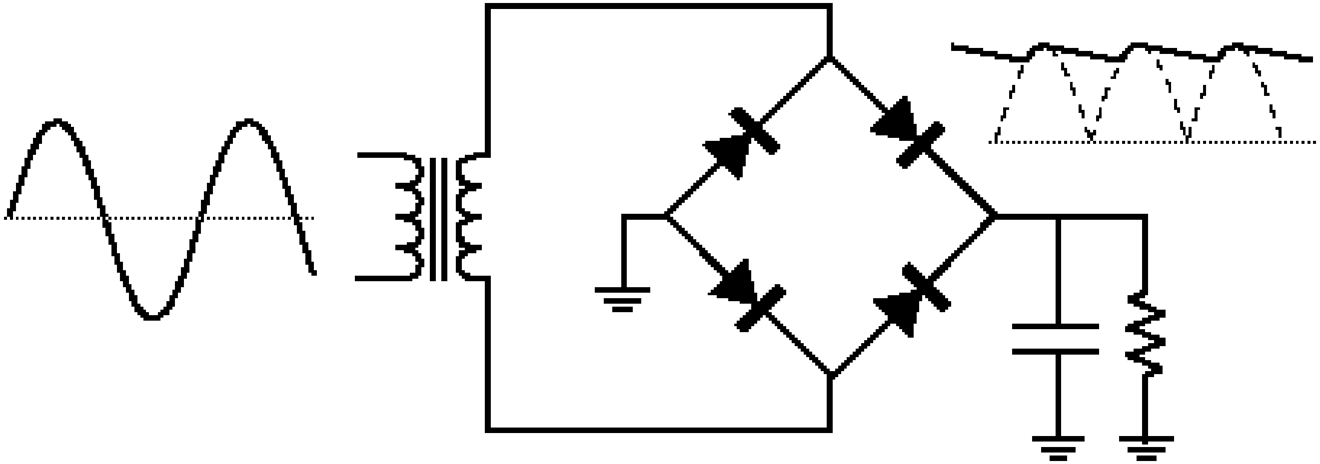
- TOPIC TO BE COVERED:
- CAPACITOR FILTER

capacitor filter :

- **A Single Capacitor** : If we place a capacitor at the output of the full-wave rectifier as shown to the left, the capacitor will charge to the peak voltage each half-cycle, and then will discharge more slowly through the load while the rectified voltage drops back to zero before beginning the next half-cycle. Thus, the capacitor helps to fill in the gaps between the peaks, as shown in red in the first figure to the right.


Capacitor Filter
Full wave rectified input
C
+
R_L

Bridge Rectifier, RC Filter

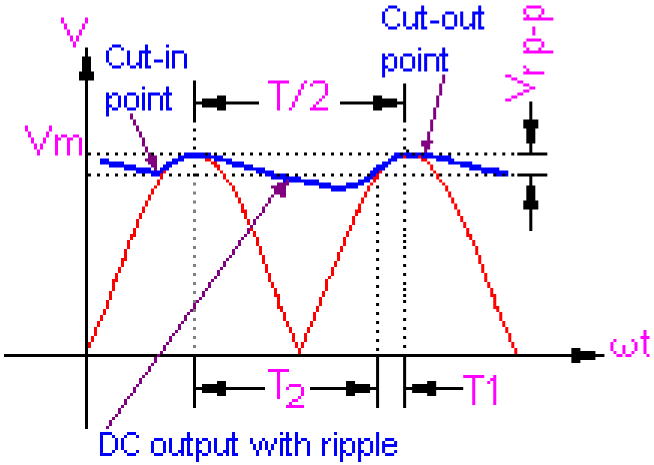


- A capacitor filter connected directly across the load is shown above. The property of a capacitor is that it allows ac component and blocks dc component. The operation of the capacitor filter is to short the ripple to ground but leave the dc to appear at output when it is connected across the pulsating dc voltage.

- The charge it has acquired $= V_{r\,p-p} \times C$

The charge it has lost $= I_{d.c.} \times T_2$

Ripple Voltage Triangular Waveform



$$\therefore V_{r\,p-p} \times C = I_{d.c.} \times T_2$$

If the value of the capacitor is fairly large, or the value of the load resistance is very large, then it can be assumed that the time T2 is equal to half the periodic time of the waveform.

$$T_2 = \frac{T}{2} = \frac{1}{2f}, \quad then \quad V_{r\,p-p} = \frac{I_{d.c.}}{2fC}$$

From the above assumptions, the ripple waveform will be triangular and its rms value is given by

$$V_{r\ rms} = \frac{V_{r\ p-p}}{2\sqrt{3}}$$

$$V_{r\ rms} = \frac{I_{d.c.}}{4\sqrt{3} f\ C}$$

$$= \frac{V_{d.c.}}{4\sqrt{3} f\ C\ R_L}, \quad \because I_{d.c.} = \frac{V_{d.c.}}{R_L}$$

$$\therefore Ripple, \gamma = \frac{V_{r\ rms}}{V_{d.c.}} = \frac{1}{4\sqrt{3} f\ C\ R_L}, \quad \because I_{d.c.} = \frac{V_{d.c.}}{R_L}$$

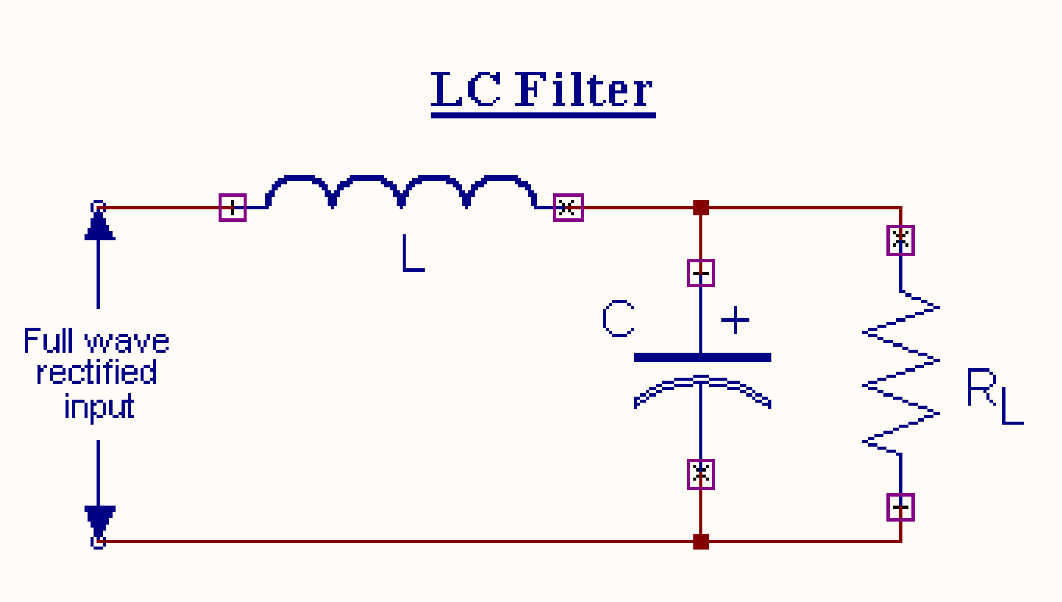
LECTURE 7:

- TOPIC TO BE COVERED :

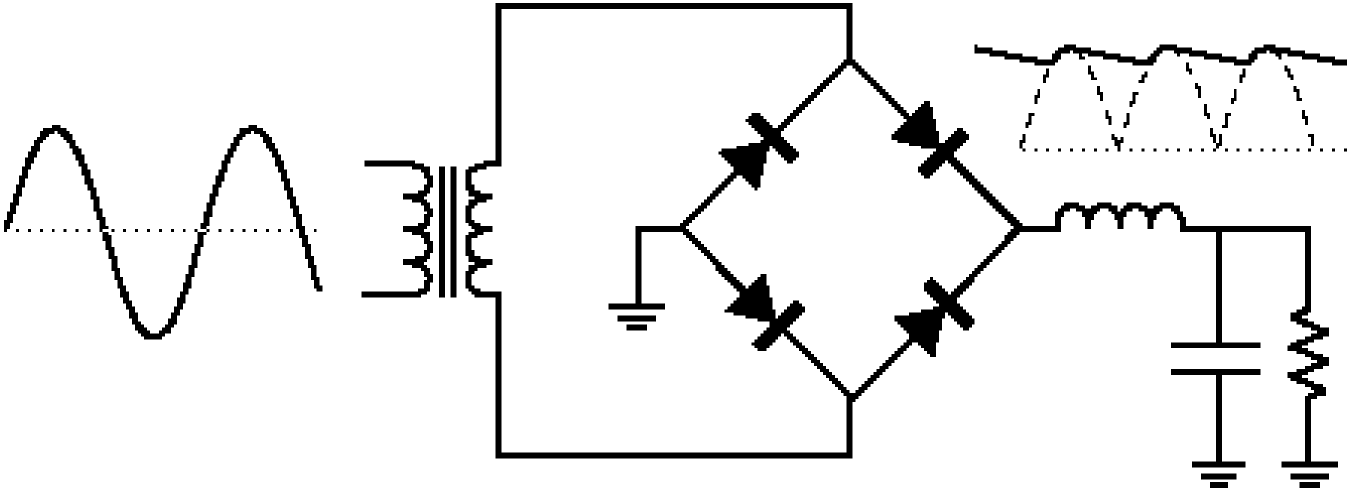
➢ *LC Filter*

LC Filter

LC Filter: - The ripple factor is directly proportional to the load resistance RL in the inductor filter and inversely proportional to *RL* in the capacitor filter. Therefore if these two filters are combined as LC filter or L section filter as shown in figure the ripple factor will be independent of *RL*.


LC Filter
L
C
+
R_L
Full wave rectified input

Bridge Rectifier, LC Filter



- From Fourier series, the output voltage can be expressed as

$$V_o = \frac{2V_m}{\pi} - \frac{4V_m}{3\pi}\cos 2\omega t$$

The dc output voltage

$$V_{dc} = \frac{2V_m}{\pi}$$

$$\therefore V_{r\,rms} = I_{rms} \cdot X_C = \frac{\sqrt{2}}{3} \cdot V_{dc} \cdot \frac{X_C}{X_L}$$

The ripple factor

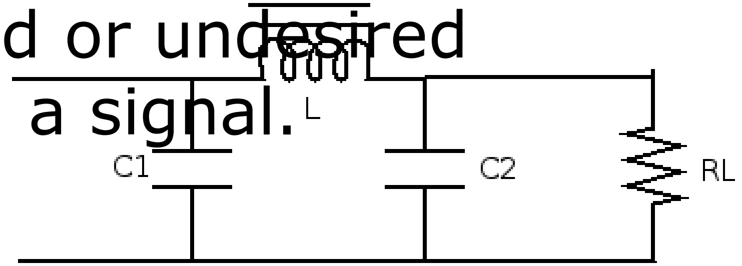
$$\gamma = \frac{V_{r,rms}}{V_{dc}} = \frac{\sqrt{2}}{3} \cdot \frac{X_C}{X_L}$$

$$= \frac{\sqrt{2}}{3} \cdot \frac{1}{4\,\omega^2 CL} \quad \because X_C = \frac{1}{2\,\omega\, C} \quad \& \quad X_L = 2\,\omega\, L$$

LECTURE 8 :

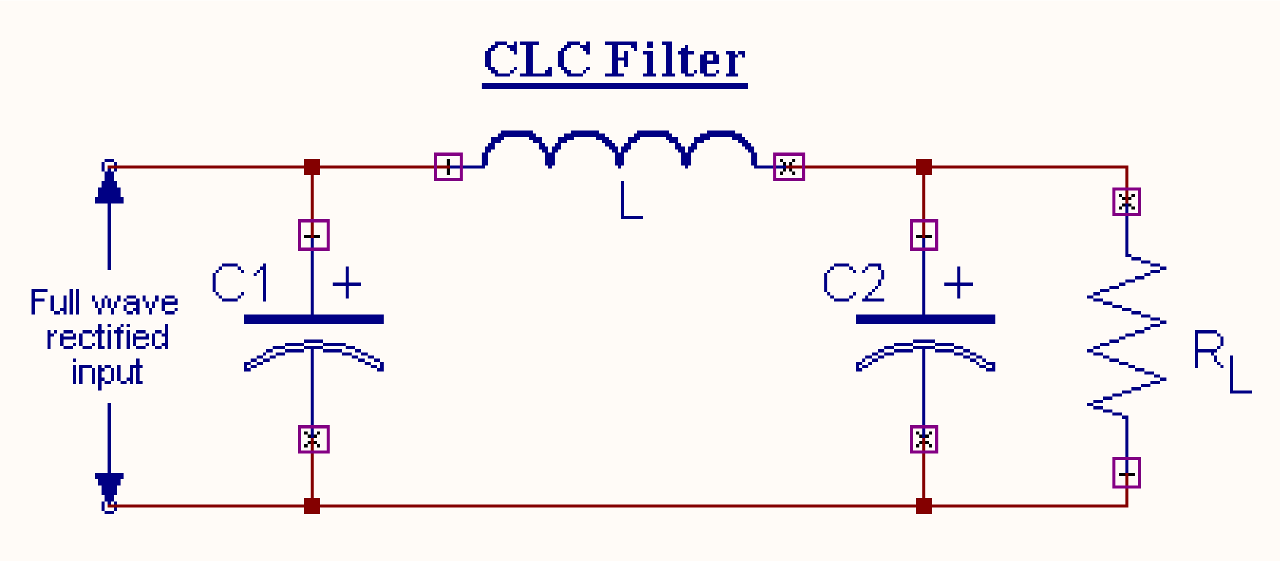
- TOPIC TO BE COVERED:
- CLC FILTER

- The **capacitor-input filter**, also called "Pi" filter due to its shape that looks like the Greek letter pi, is a type of electronic filter. Filter circuits are used to remove unwanted or undesired frequencies from a signal.



- A typical capacitor input filter consists of a filter capacitor C1, connected across the rectifier output, a choke L, in series and another filter capacitor connected across the load.

CLC or þ Filter



- The above figure shows CLC or p type filter, which basically consists of a capacitor filter, followed by LC section. This filter offers a fairly smooth output and is characterized by highly peaked diode currents and poor regulation. As in L section filter the analysis is obtained as follows.

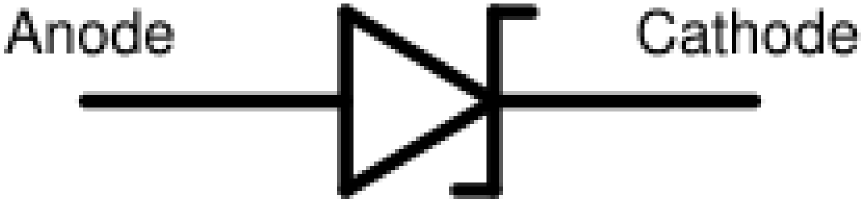
$$\gamma = \sqrt{2}\,\frac{X_{c1}}{R_L}\cdot\frac{X_{c2}}{X_L}$$

LECTURE 9 :

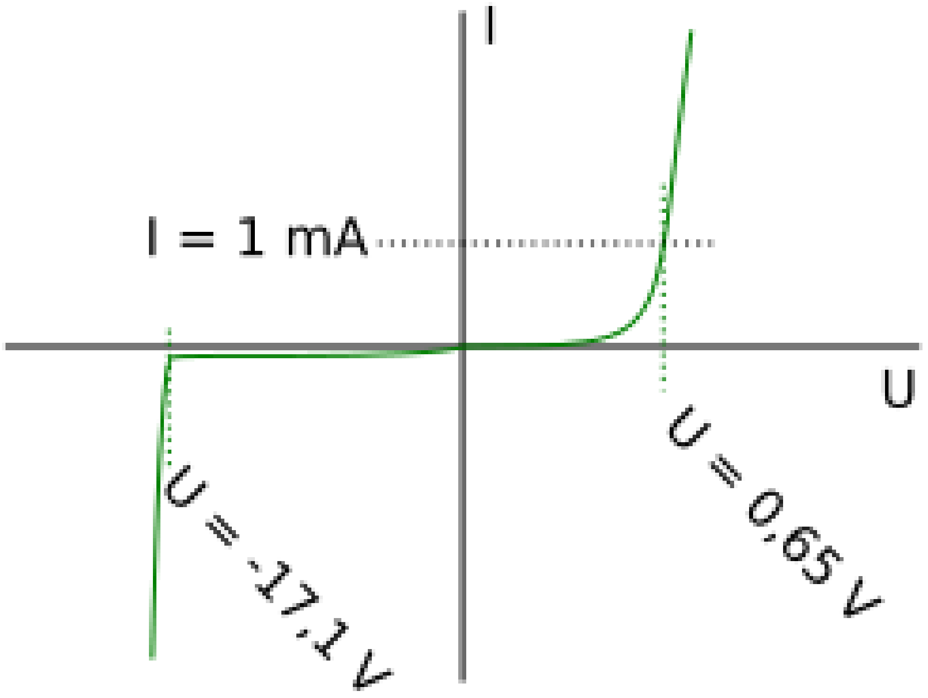
- TOPIC TO BE COVERED :

➢ Zener diode : CHARACTERISTICS & SPECIFICATION

Zener diode



Zener diode schematic symbol



Current-voltage characteristic of a Zener diode with a breakdown voltage of 17 volt.

- A **Zener diode** is a type of diode that permits current to flow in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the breakdown voltage known as "Zener knee voltage" or "Zener voltage"

- A **Zener diode** exhibits almost the same properties, except the device is specially designed so as to have a greatly reduced breakdown voltage, the so-called **Zener voltage**.
- A Zener diode contains a heavily doped p-n junction allowing electrons to tunnel from the valence band of the p-type material to the conduction band of the n-type material

- A reverse-biased Zener diode will exhibit a controlled breakdown and let the current flow to keep the voltage across the Zener diode at the Zener voltage.
- the Zener diode is typically used to generate a reference voltage for an amplifier stage, or as a voltage stabilizer for low-current applications.

- The breakdown voltage can be controlled quite accurately in the doping process. While tolerances within 0.05% are available, the most widely used tolerances are 5% and 10%.

Uses

- Zener diodes are widely used to regulate the voltage across a circuit.
- When connected in parallel with a variable voltage source so that it is reverse biased, a zener diode conducts when the voltage reaches the diode's reverse breakdown voltage. From that point it keeps the voltage at that value.

LECTURE 10:

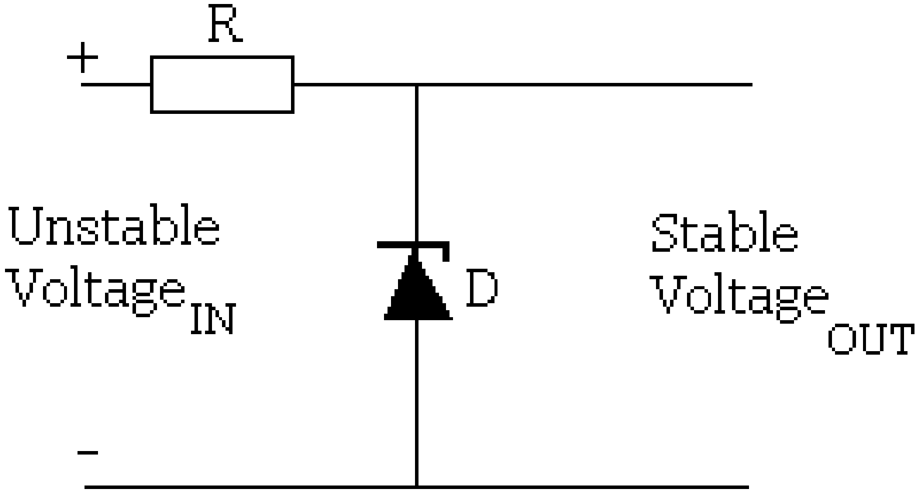
- TOPIC TO BE COVERED :
- Zener Diode As Voltage Regulator

Zener Diode As Voltage Regulator

A Zener Diode is an electronic component which can be used to make a very simple **voltage regulator circuit**.

This circuit enables a fixed stable voltage to be taken from an unstable voltage source such as the battery bank of a **renewable energy** system which will fluctuate depending on the state of charge of the bank.

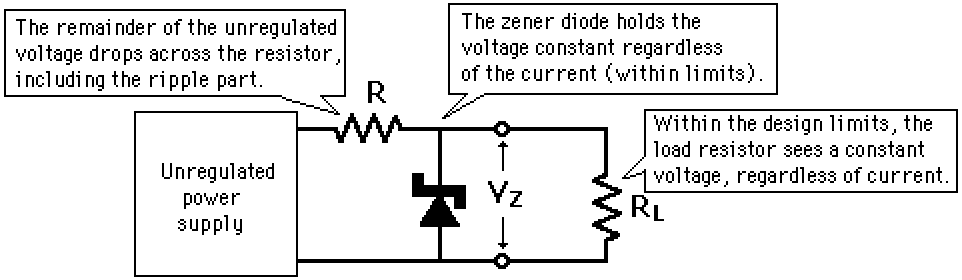
Zener Diode Voltage Regulator Circuit



fictured above is a very simple **voltage regulator** circuit requiring just one **zener diode** and one **resistor**.

- As the input voltage increases the current through the **Zener diode** increases but the **voltage drop** remains constant - a feature of zener diodes.
- Therefore since the current in the circuit has increased the voltage drop across the **resistor** increases by an amount equal to the difference between the input voltage and the zener voltage of the diode.

- The constant reverse voltage of the zener diode makes it a valuable component for the regulation of the output voltage against both variations in the input voltage from an unregulated power supply or variations in the load resistance. The current through the zener will change to keep the voltage at within the limits of the threshold of zener action and the maximum power it can dissipate



The remainder of the unregulated voltage drops across the resistor, including the ripple part.

The zener diode holds the voltage constant regardless of the current (within limits).

Within the design limits, the load resistor sees a constant voltage, regardless of current.

Problems:

UNIT 3

TRANSISTOR

LECTURE 1:

- TOPIC TO BE COVERED :

➢ Transistor :Introduction

Transistor

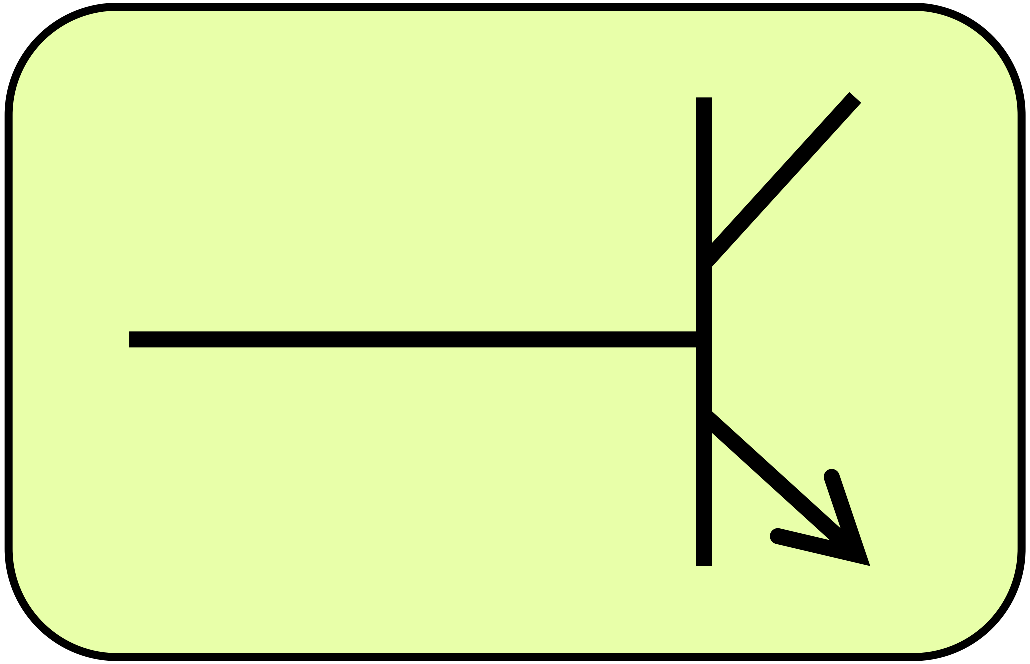
The first solid-state device discussed was the two-element semiconductor diode. The next device on our list is even more unique. It not only has one more element than the diode but it can amplify as well. Semiconductor devices that have-three or more elements are called TRANSISTORS. The term transistor was derived from the words TRANSfer and resISTOR. This term was adopted because it best describes the operation of the transistor - the transfer of an input signal current from a low-resistance circuit to a high- resistance circuit.

The three elements of the two-junction transistor are :

- The EMITTER, which gives off, or emits," current carriers (electrons or holes).
- The BASE, which controls the flow of current carriers.
- The COLLECTOR, which collects the current carriers.

Introducing Transistors

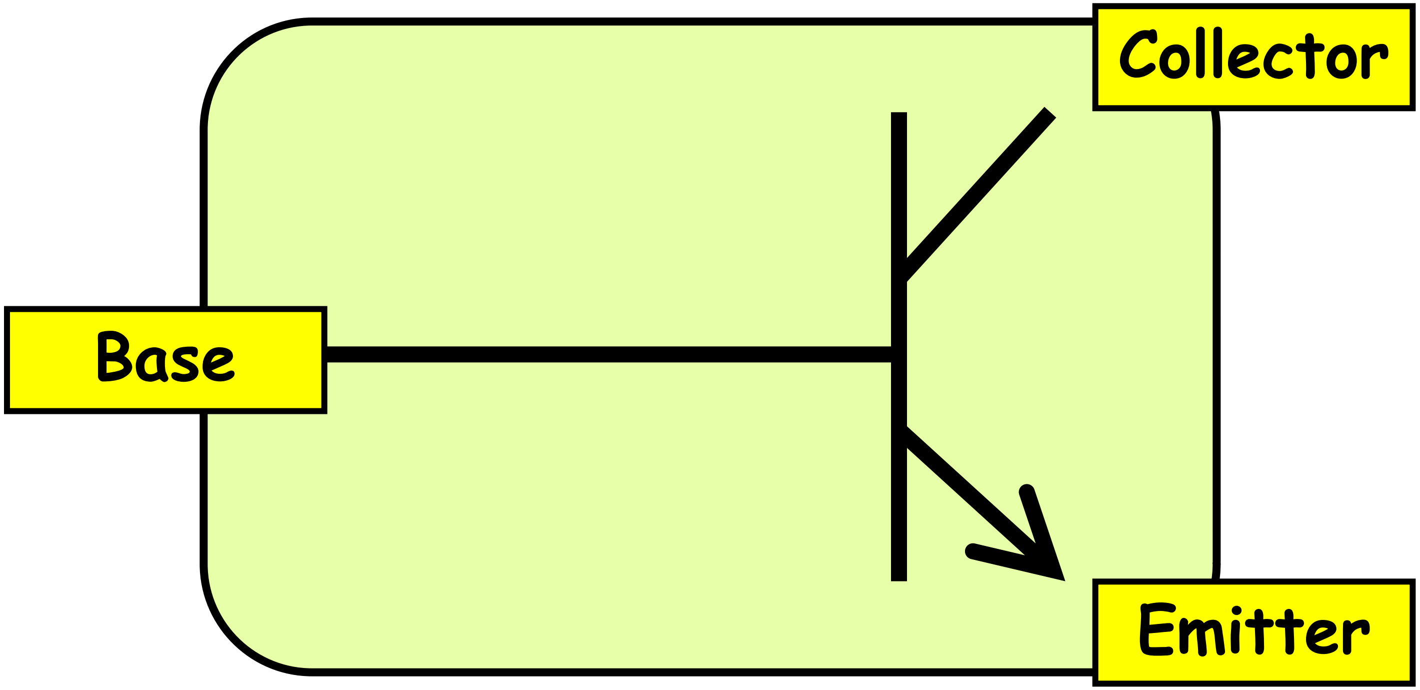
- Transistors are **process** devices.



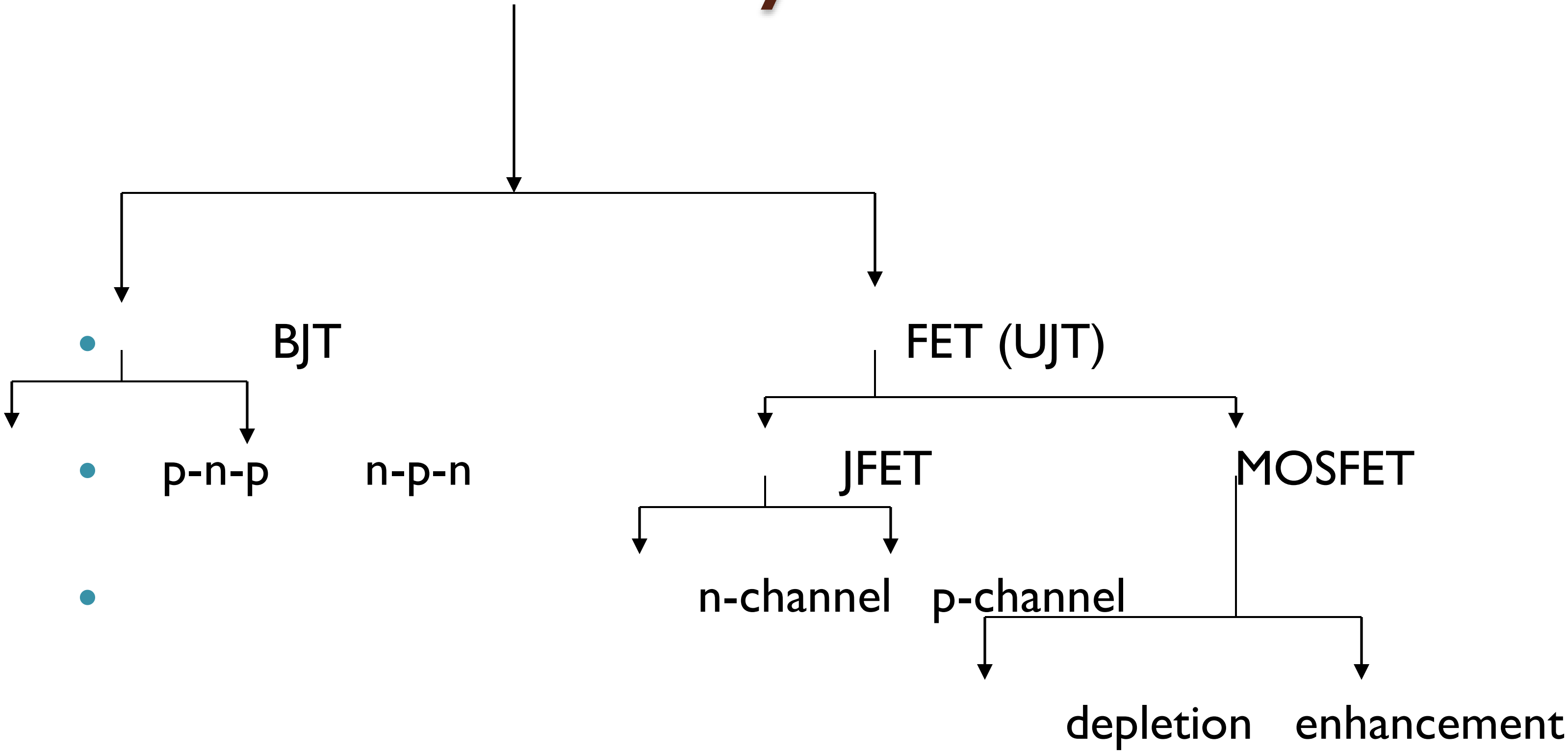
- **This is the symbol for an NPN transistor.**[3]

Transistor Terminals

- Transistors have three terminals:



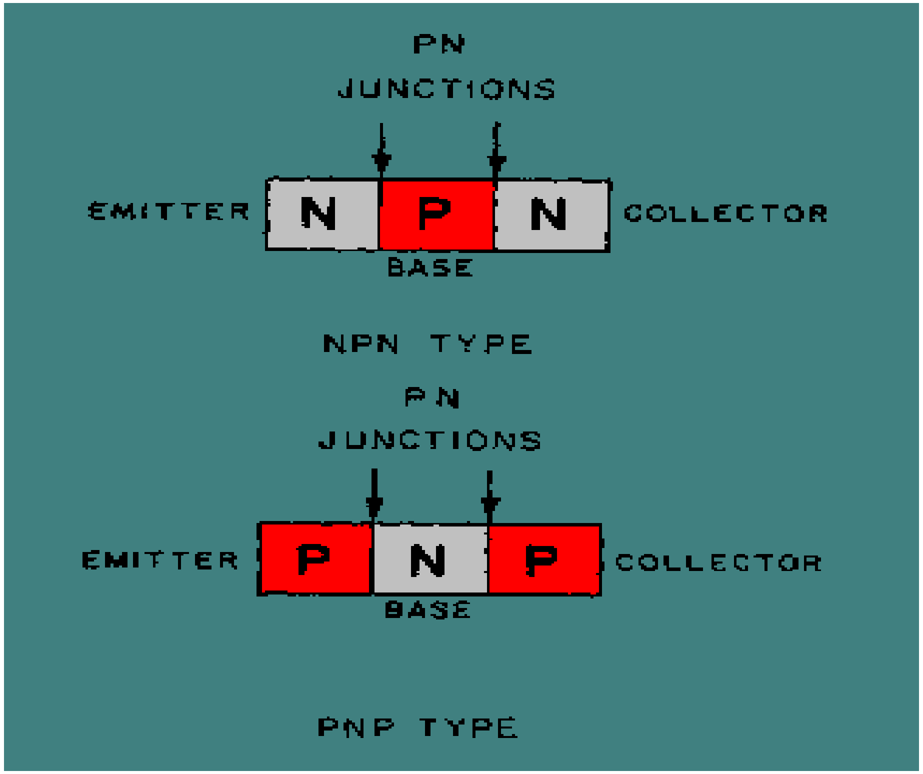
Transistor family



- BJT FET (UJT)
- p-n-p n-p-n JFET MOSFET
- n-channel p-channel

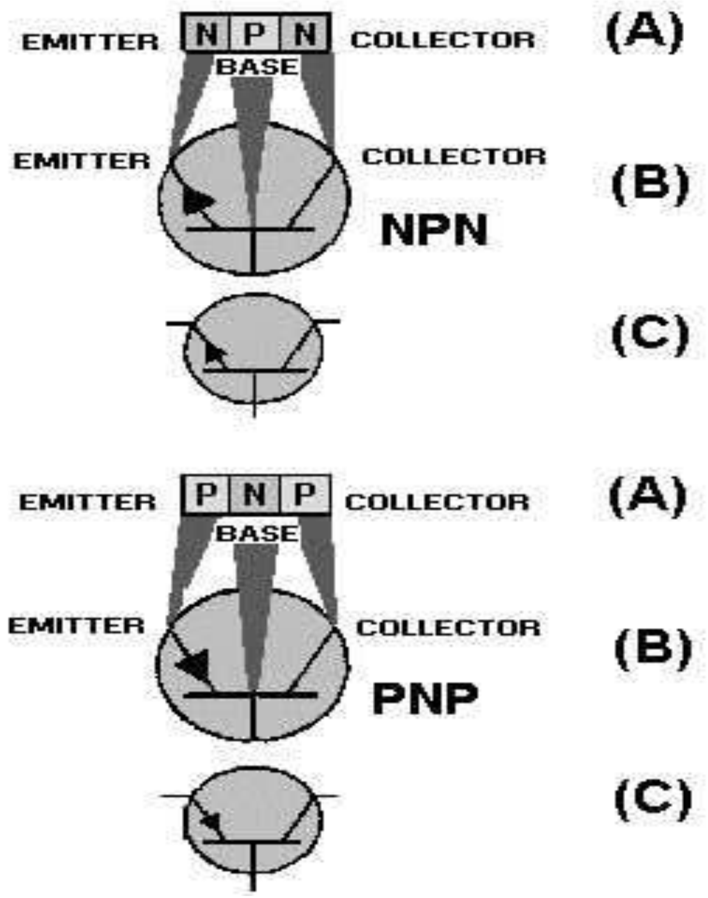
depletion enhancement

- Transistors are three-terminal semiconductor devices



Figure—Transistor block diagrams

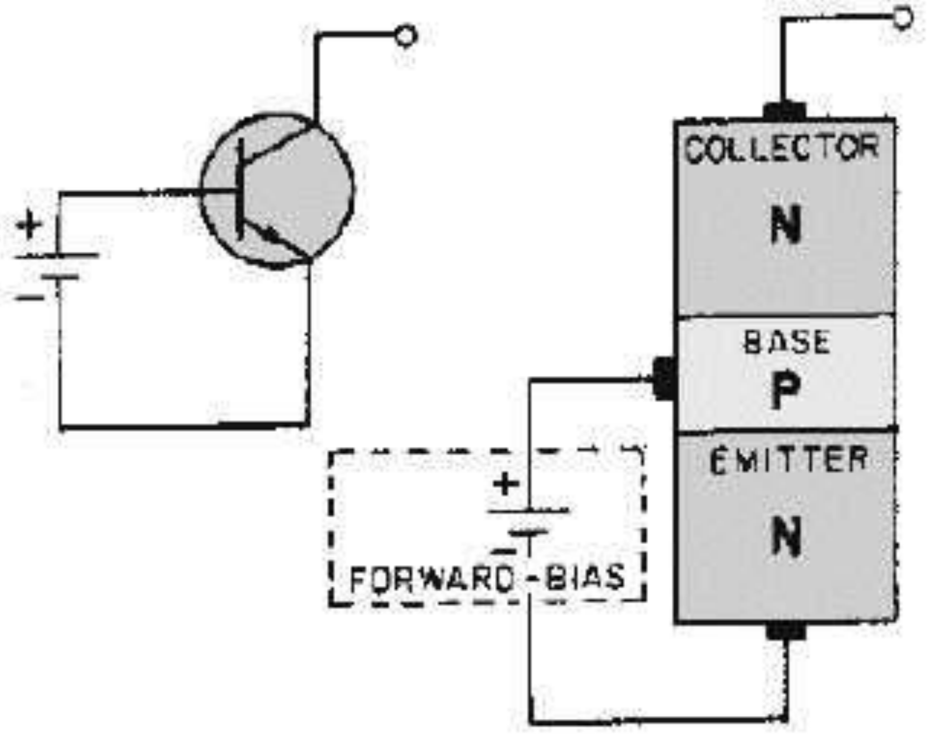
Construction :



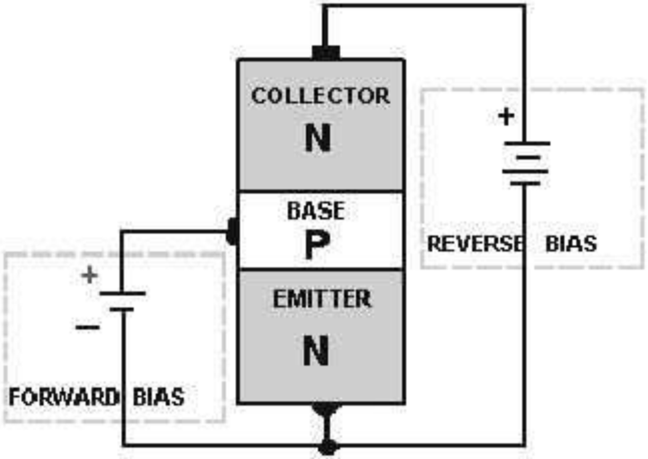
TRANSISTOR THEORY

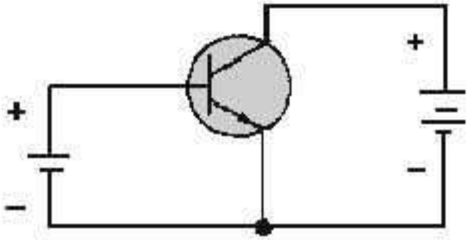
- **NPN Transistor Operation**

  Just as in the case of the PN junction diode, the N material comprising the two end sections of the NP_N transistor contains a number of free electrons, while the center P section contains an excess number of holes.


+
−
COLLECTOR
N
BASE
P
EMITTER
N
+
−
FORWARD-BIAS

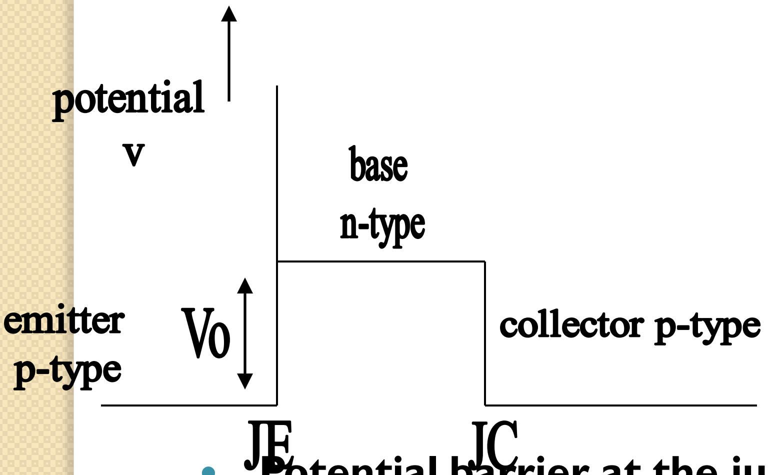
- The emitter, which is the first letter in the NPN sequence, is connected to the negative side of the battery while the base, which is the second letter (NPN), is connected to the positive side.
- However, since the second PN junction is required to be reverse biased for proper transistor operation, the collector must be connected to an opposite polarity voltage (positive) than that indicated by its letter designation(NPN). The voltage on the collector must also be more positive than the base, as shown below:


COLLECTOR
N
BASE
P
EMITTER
N
+
−
FORWARD BIAS
+
REVERSE BIAS

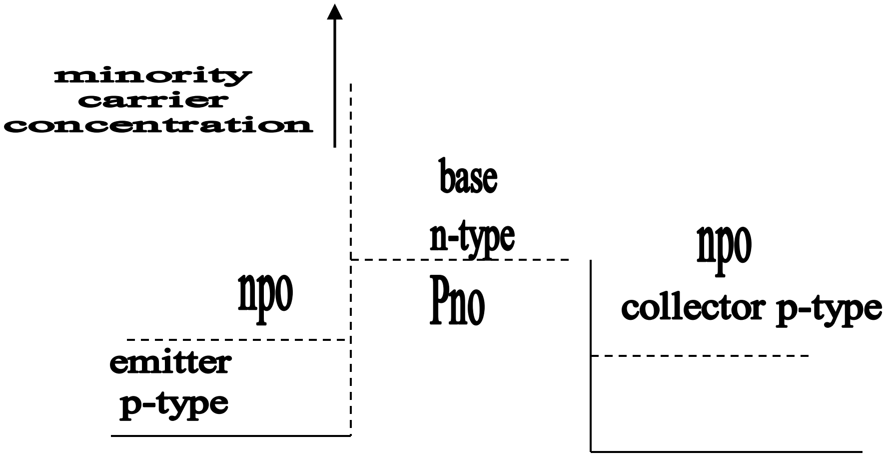

+
−
+
−

Open ckted Transistor

- Consider the xsistor with no external biasing voltages,



- Potential barrier at the junc^n



minority carrier density

- Under te open ckt condition , the minority carrier concentration in each section of xsistor is constant & is equal to the thermal equilibrium value .
- Thus n-type base has minority carrier concentration of P_{no} while p-type emitter & collector regions have minority carrier electron $conc^n$ n_{po}

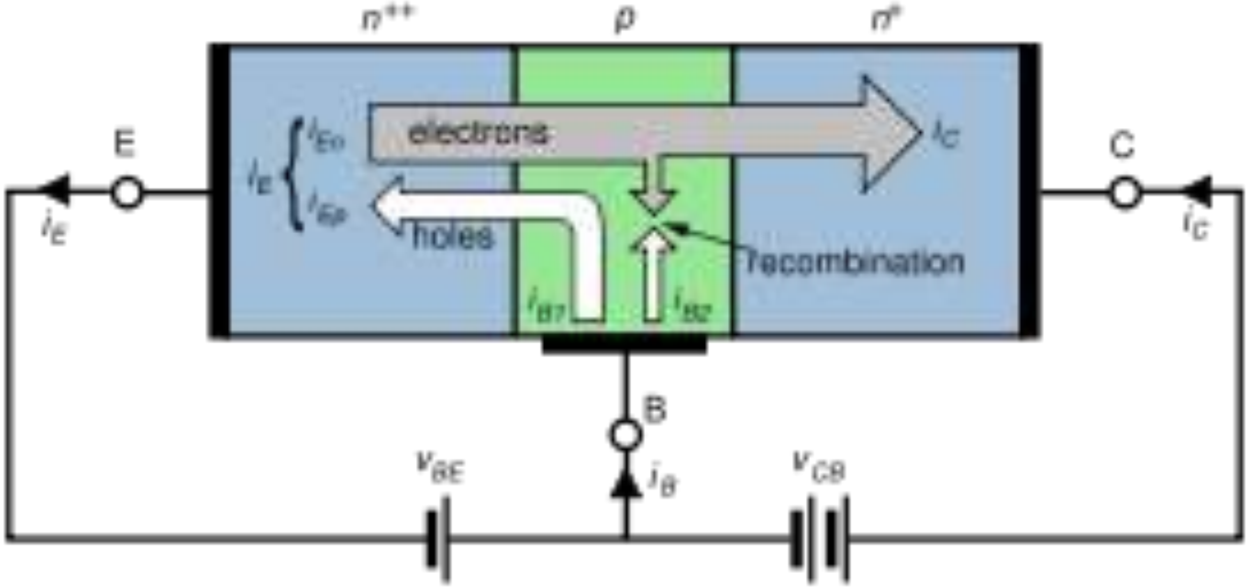
- **Regions of operation**

  Bipolar transistors have five distinct regions of operation, defined mostly by applied bias:
- **Forward-active** (or simply, **active**): The emitter-base junction is forward biased and the base-collector junction is reverse biased..
- **Reverse-active** (or **inverse-active** or **inverted**): By reversing the biasing conditions of the forward-active region, a bipolar transistor goes into reverse-active mode. In this mode, the emitter and collector regions switch roles.
- **Saturation**: With both junctions forward-biased, a BJT is in saturation mode and facilitates high current conduction from the emitter to the collector.
- **Cutoff**: In cutoff, biasing conditions opposite of saturation (both junctions reverse biased) are present. There is very little current flow, which corresponds to a logical "off", or an open switch.
- **Avalanche breakdown region**

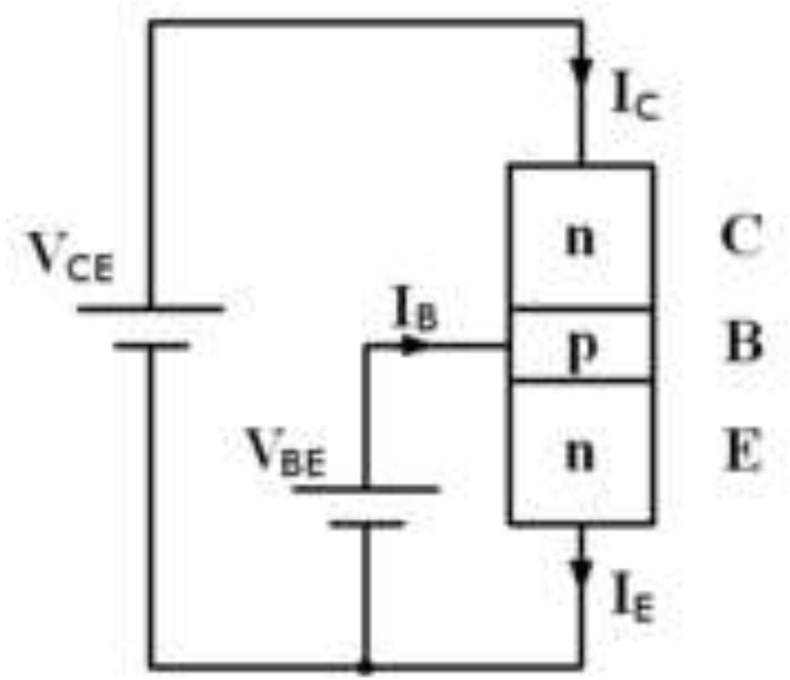
LECTURE 2:

- TOPIC TO BE COVERED :
- Transistor current component

Transistor current component



Transistors in circuits



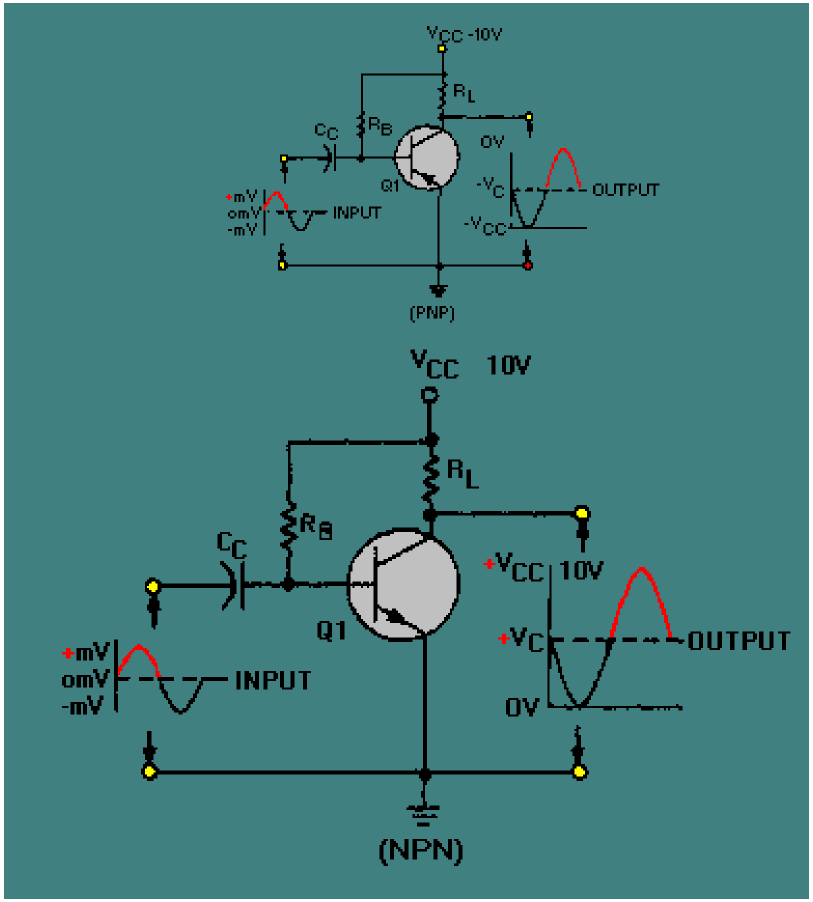
Structure and use of npn transistor

- Because of the electric field existing between base and collector (caused by *VCE*), the majority of these electrons cross the upper p-n junction into the collector to form the collector current, *IC*.
- The remainder of the electrons recombine with holes, the majority carriers in the base, making a current through the base connection to form the base current, *IB*

- As shown in the diagram, the emitter current, *IE*, is the total transistor current which is the sum of the other terminal currents. That is:

$$I_E = I_B + I_C$$

The basic transistor amplifier



- With Q1 properly biased, direct current flows continuously, with or without an input signal, throughout the entire circuit
- It is introduced into the circuit by the coupling capacitor and is applied between the base and emitter.

- As the input signal goes positive, the voltage across the emitter-base junction becomes more positive.
- This in effect increases forward bias, which causes base current to increase at the same rate as that of the input sine wave.

LECTURE 3:

- TOPIC TO BE COVERED :

➤ TRANSISTOR CONFIGURATIONS

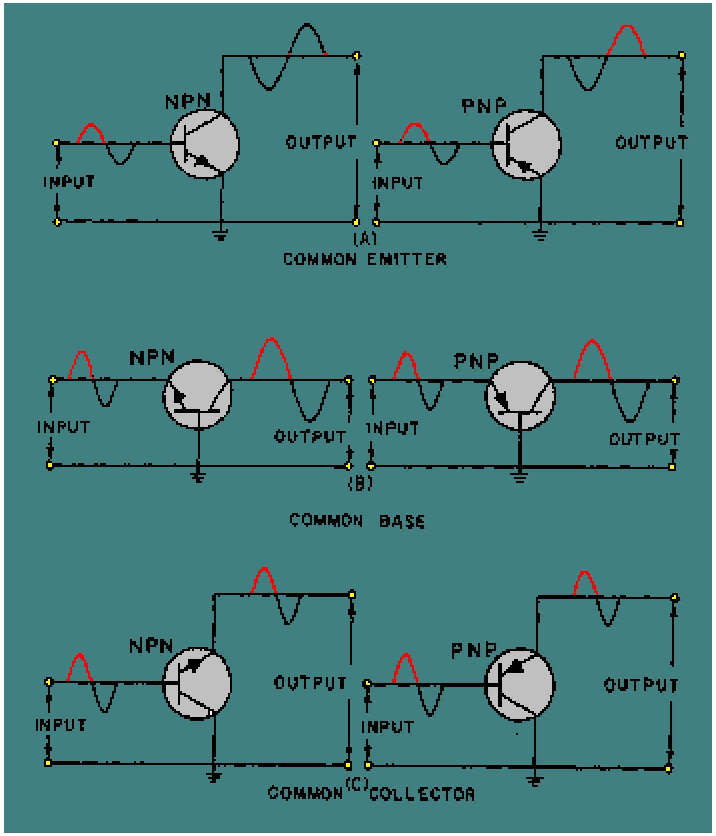
TRANSISTOR CONFIGURATIONS

A transistor may be connected in any one of three basic configurations :

common emitter (CE), common base (CB), and common collector (CC). The term common is used to denote the element that is common to both input and output circuits.

Because the common element is often grounded, these configurations are frequently referred to as grounded emitter, grounded base, and grounded collector

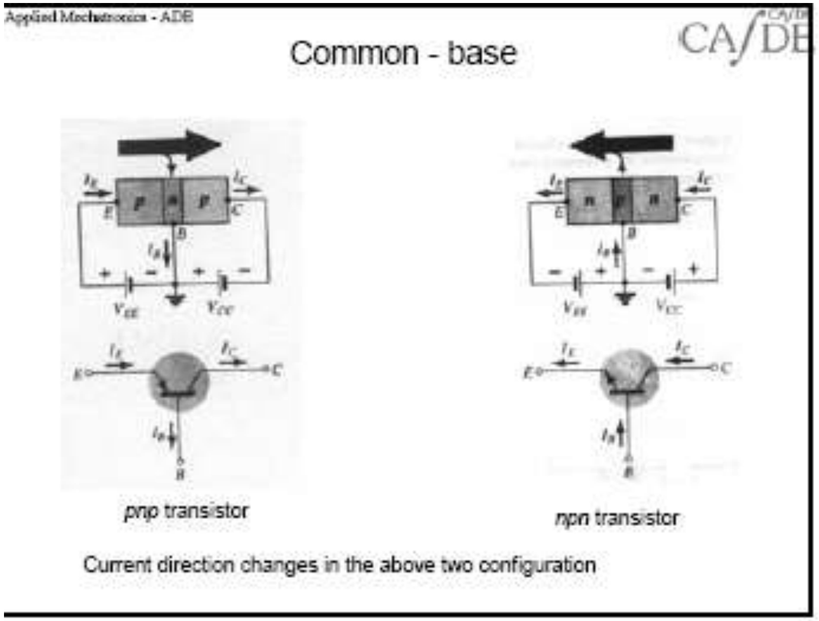
Transistor configurations.



- An easy way to identify a specific transistor configuration is to follow three simple steps:
- Identify the element (emitter, base, or collector) to which the input signal is applied.
- Identify the element (emitter, base, or collector) from which the output signal is taken.
- The remaining element is the common element, and gives the configuration its name.

Common Base

- In the common-base configuration, the input signal is applied to the emitter, the output is taken from the collector, and the base is the element common to both input and output. Since the input is applied to the emitter, it causes the emitter-base junction to react in the same manner as it did in the common-emitter circuit.



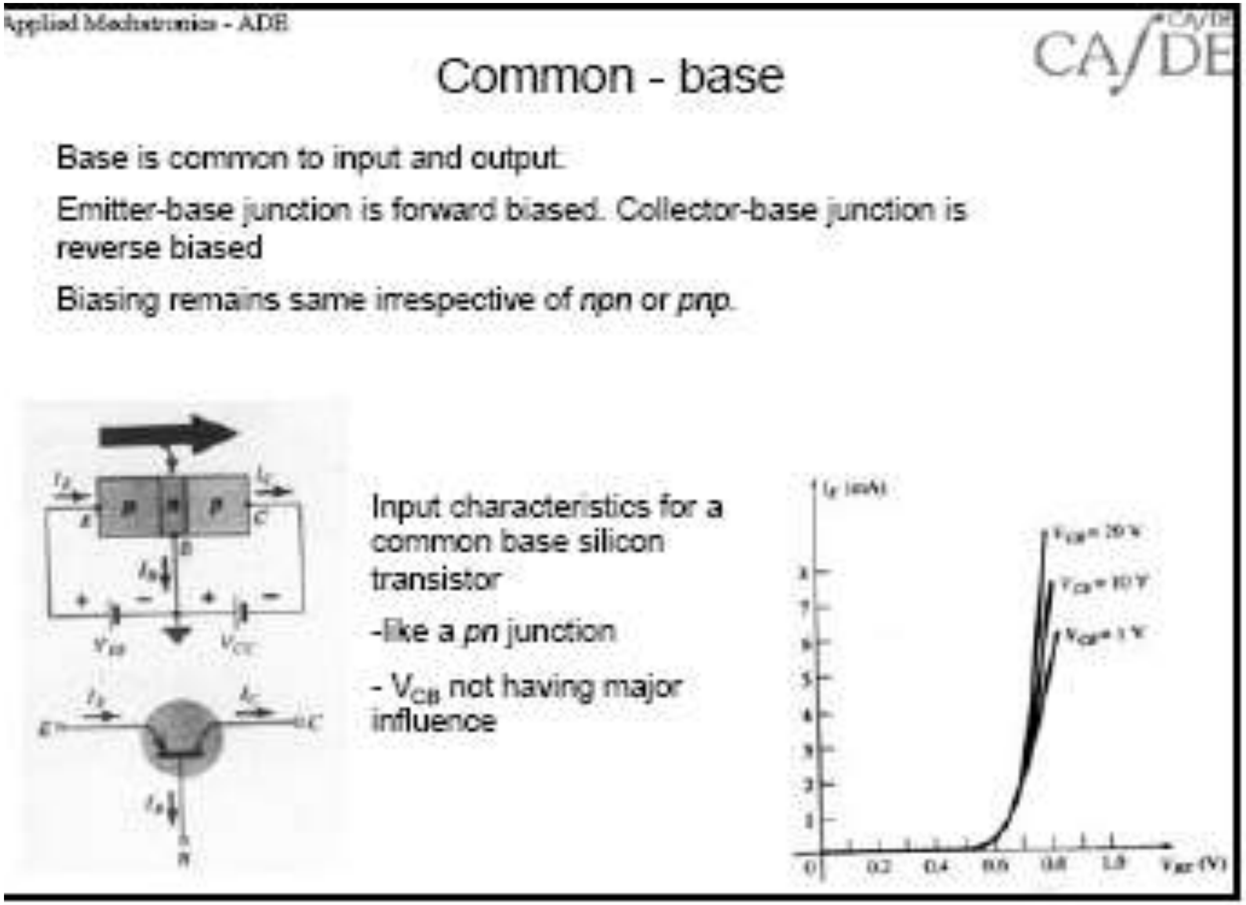
Applied Mechatronics - ADE

Common - base

pnp transistor

npn transistor

Current direction changes in the above two configuration



Applied Mechatronics - ADE

Common - base

Base is common to input and output.

Emitter-base junction is forward biased. Collector-base junction is reverse biased

Biasing remains same irrespective of *npn* or *pnp*.

Input characteristics for a common base silicon transistor

-like a *pn* junction

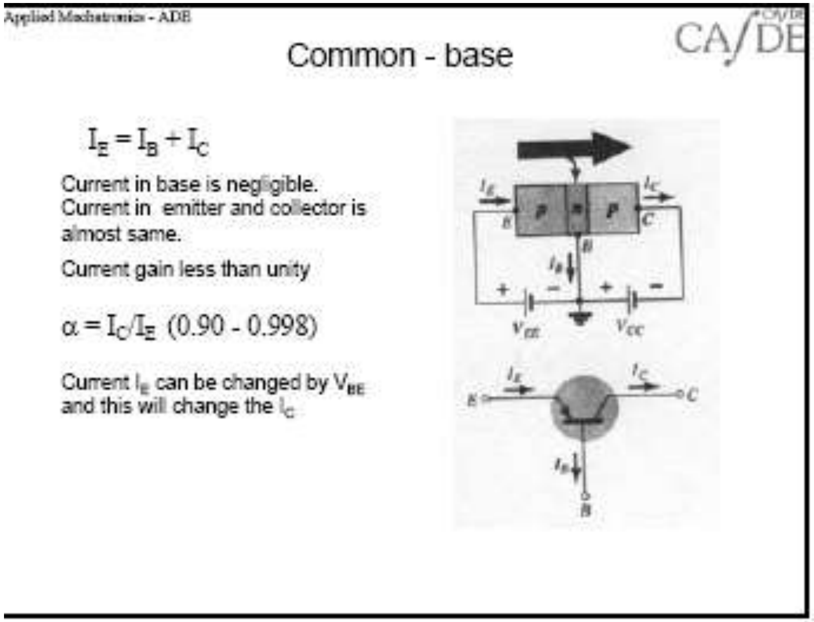
- V_{CB} not having major influence

- The current gain in the common-base circuit is calculated in a method similar to that of the common emitter except that the input current is I_E not I_B and the term ALPHA (a) is used in place of beta for gain .
- Alpha is calculated using the formula:

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

- To find alpha (a) when given beta (b), use the following formula to convert b to a for use with the common-base configuration:

$$\alpha = \frac{\beta}{\beta + 1}$$



Applied Mechatronics - ADE

Common - base

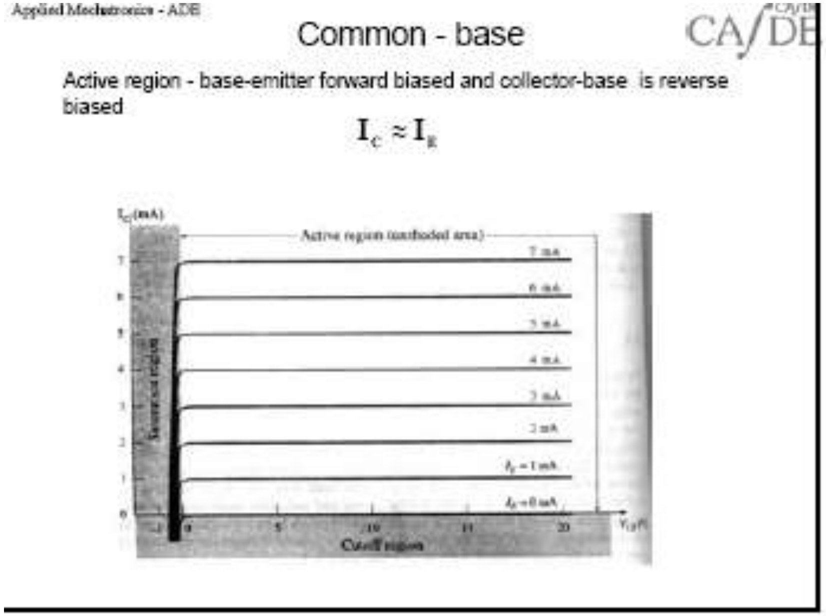
$I_E = I_B + I_C$

Current in base is negligible.
Current in emitter and collector is almost same.

Current gain less than unity

$\alpha = I_C/I_E$ (0.90 - 0.998)

Current I_E can be changed by V_{BE} and this will change the I_C



Applied Mechatronics - ADE

Common - base

Active region - base-emitter forward biased and collector-base is reverse biased

$$\mathbf{I}_C \approx \mathbf{I}_E$$

Common Collector

- In the common-collector circuit, the input signal is applied to the base, the output is taken from the emitter, and the collector is the element common to both input and output.
- The common collector is also referred to as an emitter-follower because the output developed on the emitter follows the input signal applied to the base.

- The common-collector current gain, gamma (g), is defined as

$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

- and is related to collector-to-base current gain, beta (b), of the common-emitter circuit by the formula:

$$\gamma = \beta + 1$$

LECTURE 4:

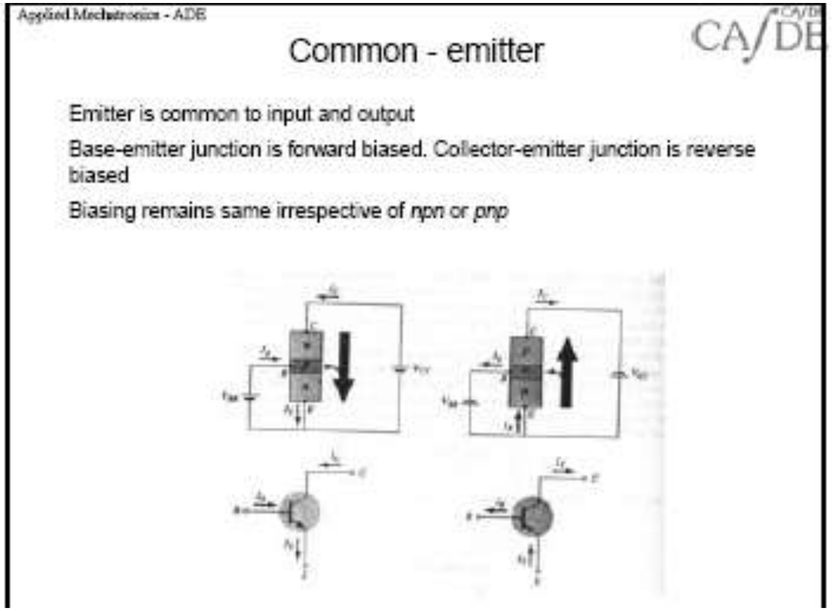
- TOPIC TO BE COVERED :

➢ Common Emitter

Common Emitter

The common-emitter configuration (CE) is the arrangement most frequently used in practical amplifier circuits, since it provides good voltage, current, and power gain.

Since the input signal is applied to the base-emitter circuit and the output is taken from the collector-emitter circuit, the emitter is the element common to both input and output.

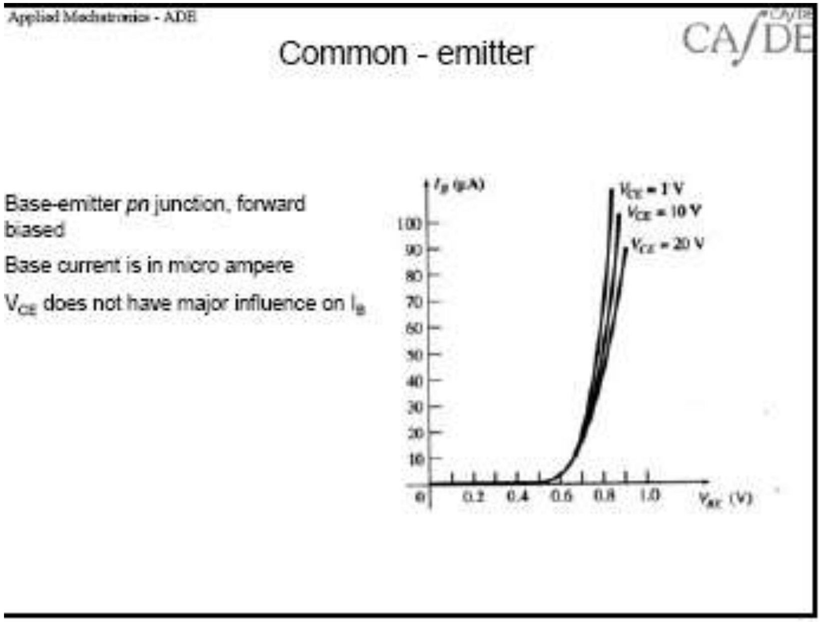


Applied Mechatronics - ADE

CA/DE

Common - emitter

- Emitter is common to input and output
- Base-emitter junction is forward biased. Collector-emitter junction is reverse biased
- Biasing remains same irrespective of *npn* or *pnp*



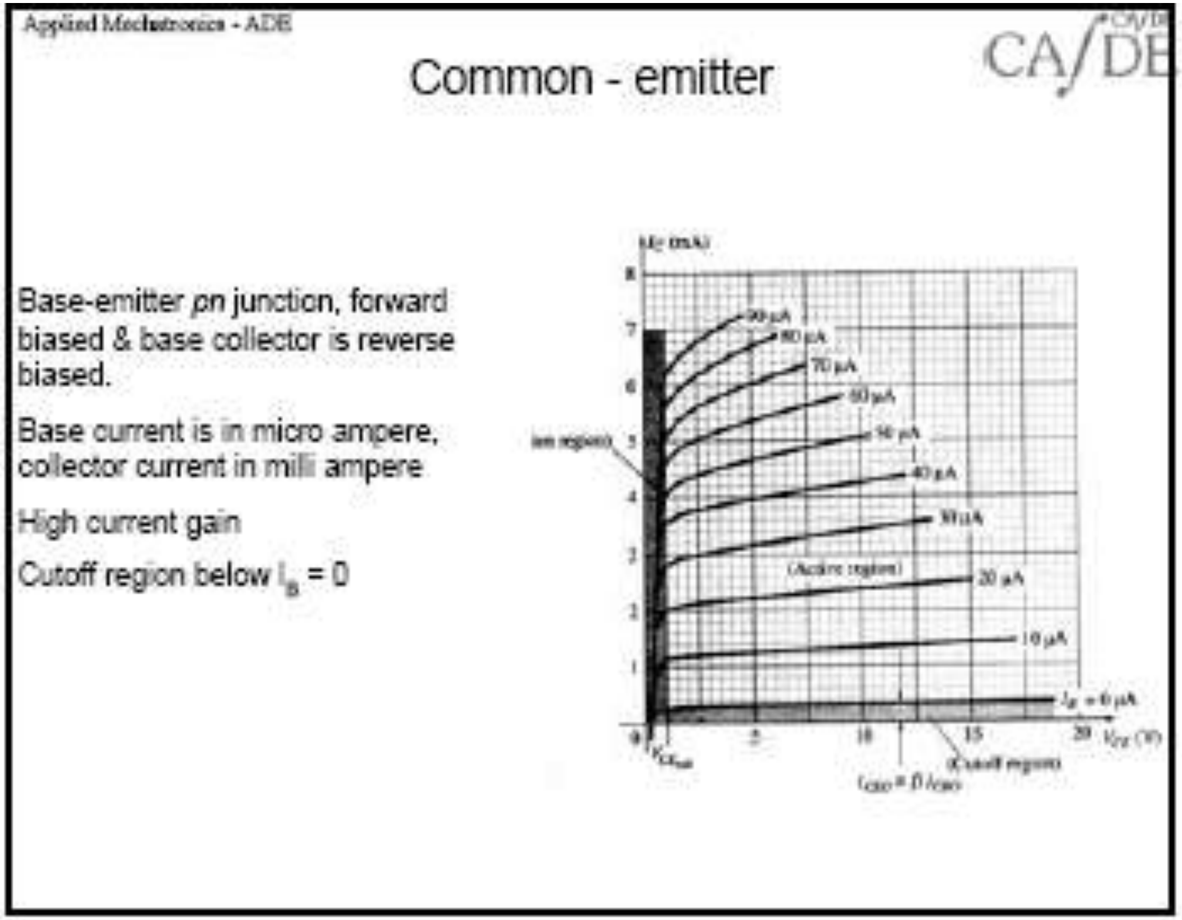
Applied Mechatronics - ADE

Common - emitter

Base-emitter *pn* junction, forward biased

Base current is in micro ampere

V_{CE} does not have major influence on I_B



Applied Mechatronics - ADE

Common - emitter

- Base-emitter *pn* junction, forward biased & base collector is reverse biased.
- Base current is in micro ampere, collector current in milli ampere
- High current gain
- Cutoff region below $I_B = 0$

- The common-emitter is the most popular of the three transistor configurations because it has the best combination of current and voltage gain

- The current gain in the common-emitter circuit is called BETA (b).
- Beta is the relationship of collector current (output current) to base current (input current). To calculate beta, use the following formula:

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

- The current gain in the common-emitter circuit is called BETA (b).
- Beta is the relationship of collector current (output current) to base current (input current).
- To calculate beta, use the following formula:

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

- The resistance gain of the common emitter can be found in a method similar to the one used for finding beta:

$$R = \frac{R_{out}}{R_{in}}$$

Transistor Configuration Comparison Chart

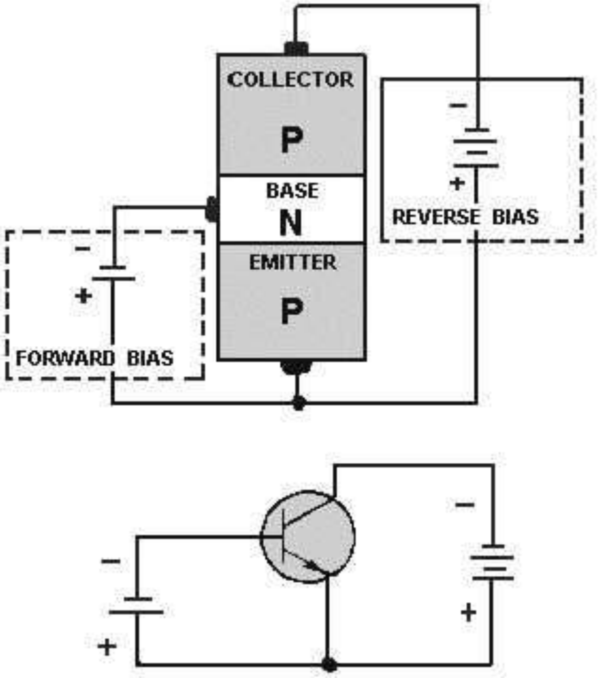
AMPLIFIER TYPE	**COMMON BASE**	**COMMON EMITTER**	**COMMON COLLECTOR**
Input/Output Phase Relationship	0°	180°	0°
Voltage Gain	High	Medium	Low
Current Gain	Low(a)	Medium(b)	High(g)
Power Gain	Low	High	Medium
Input Resistance	Low	Medium	High
Output Resistance	High	Medium	Low

LECTURE 5:

- TOPIC TO BE COVERED :

➢ Typical transistor junction voltages

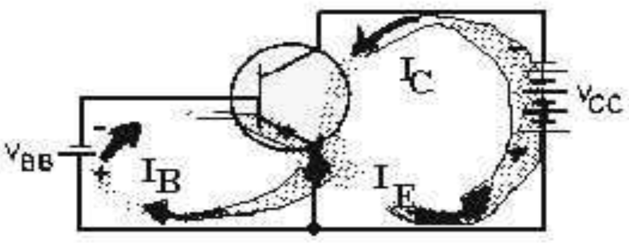
Typical transistor junction voltages

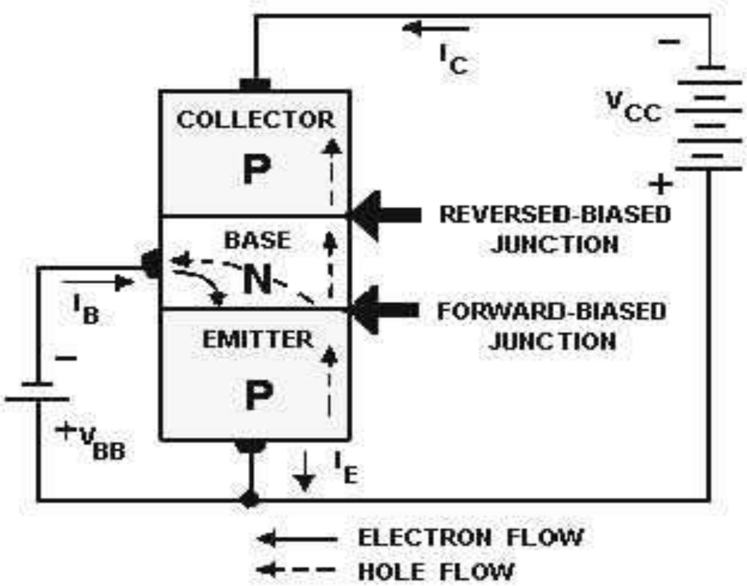


A properly biased PNP transistor.

PNP JUNCTION INTERACTION.—

- The interaction between the forward- and reverse-biased junctions in a PNP transistor is very similar to that in an NPN transistor, except that in the PNP transistor, the majority current carriers are holes.
- In the PNP transistor shown in figure the positive voltage on the emitter repels the holes toward the base


V_{BB}
-
+
I_B
I_C
V_{CC}
I_E


I_C
-
V_{CC}
+
COLLECTOR
P
BASE
N
EMITTER
P
REVERSED-BIASED JUNCTION
FORWARD-BIASED JUNCTION
I_B
-
+V_{BB}
I_E
ELECTRON FLOW
HOLE FLOW

- Once in the base, the holes combine with base electrons.
- The base region is made very thin to prevent the recombination of holes with electrons. Therefore, well over 90 percent of the holes that enter the base become attracted to the large negative collector voltage and pass right through the base.

- for each electron and hole that combine in the base region, another electron leaves the negative terminal of the base battery (V BB) and enters the base as base current (IB).
- At the same time an electron leaves the negative terminal of the battery, another electron leaves the emitter as IE (creating a new hole) and enters the positive terminal of VBB.

- At the same time an electron leaves the negative terminal of the battery, another electron leaves the emitter as IE (creating a new hole) and enters the positive terminal of VBB.
- Meanwhile, in the collector circuit, electrons from the collector battery (VCC) enter the collector as Ic and combine with the excess holes from the base.

- For each hole that is neutralized in the collector by an electron, another electron leaves the emitter and starts its way back to the positive terminal of VCC.
- The combination of the current in both of these loops (IB + IC) results in total transistor current (IE).

- The most important thing to remember about the two different types of transistors is that the emitter-base voltage of the PNP transistor has the same controlling effect on collector current as that of the NPN transistor.

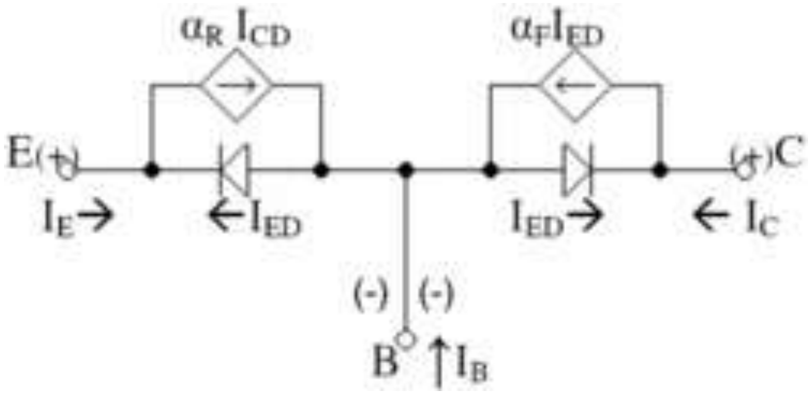
LECTURE 6:

- TOPIC TO BE COVERED :

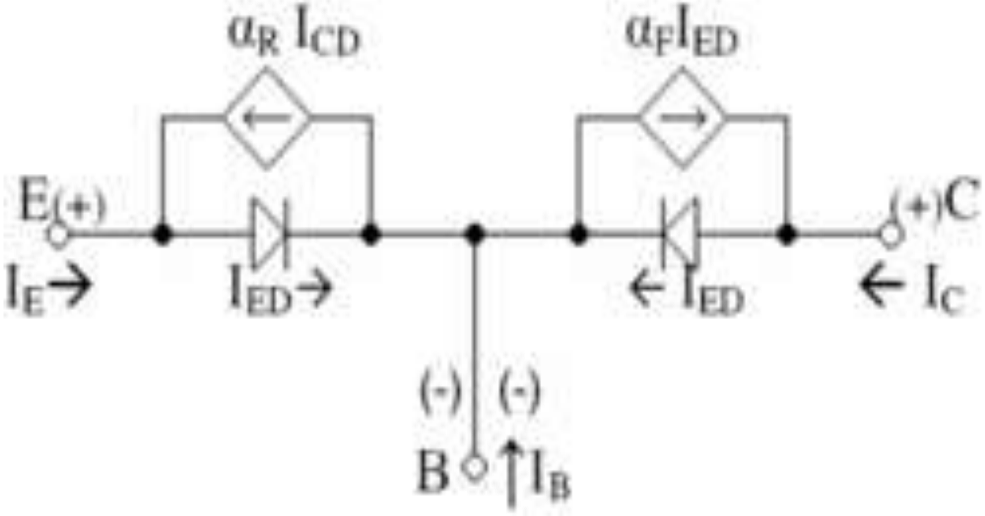
➢ Ebers–Moll model

Ebers–Moll model

The DC emitter and collector currents in active mode are well modeled by an approximation to the Ebers–Moll model:



Ebers-Moll Model for NPN Transistor



Ebers-Moll Model for PNP Transistor

$$I_{\mathrm{E}} = I_{\mathrm{ES}}\left(e^{\frac{V_{\mathrm{BE}}}{V_{\mathrm{T}}}} - 1\right)$$

$$I_{\mathrm{C}} = \alpha_T I_{\mathrm{ES}}\left(e^{\frac{V_{\mathrm{BE}}}{V_{\mathrm{T}}}} - 1\right)$$

- The base internal current is mainly by diffusion and

W'

$$J_n(Base) = \frac{qD_n n_{bo}}{W} e^{\frac{V_{EB}}{V_T}}$$

- *V*T imately 26 mV at 300 K ~ room temperature).
- *I*E is the emitter current
- *I*C is the collector current

- α_T is the common base forward short circuit current gain (0.98 to 0.998)
- I_{ES} is the reverse saturation current of the base–emitter diode (on the order of 10^{-15} to 10^{-12} amperes)
- V_{BE} is the base–emitter voltage
- D_n is the diffusion constant for electrons in the p-type base
- W is the base width

- In a typical configuration, a very small signal current flows through the base–emitter junction to control the emitter–collector current. β is related to α through the following relations:

$$\alpha_T = \frac{I_{\mathrm{C}}}{I_{\mathrm{E}}}$$

$$\beta_F = \frac{I_\mathrm{C}}{I_\mathrm{B}}$$

$$\beta_F = \frac{\alpha_T}{1 - \alpha_T} \iff \alpha_T = \frac{\beta_F}{\beta_F + 1}$$

Emitter Efficiency :

$$\eta = \frac{J_n(Base)}{J_E}$$

- Ebers-Moll equations used to describe the three currents in any operating region are given below.

$$i_{\mathrm{C}} = I_{\mathrm{S}}\left(e^{\frac{V_{\mathrm{BE}}}{V_{\mathrm{T}}}} - e^{\frac{V_{\mathrm{BC}}}{V_{\mathrm{T}}}}\right) - \frac{I_{\mathrm{S}}}{\beta_{\mathrm{R}}}\left(e^{\frac{V_{\mathrm{BC}}}{V_{\mathrm{T}}}} - 1\right)$$

$$i_{\mathrm{B}} = \frac{I_{\mathrm{S}}}{\beta_{\mathrm{F}}}\left(e^{\frac{V_{\mathrm{BE}}}{V_{\mathrm{T}}}} - 1\right) + \frac{I_{\mathrm{S}}}{\beta_{\mathrm{R}}}\left(e^{\frac{V_{\mathrm{BC}}}{V_{\mathrm{T}}}} - 1\right)$$

$$i_{\mathrm{E}} = I_{\mathrm{S}}\left(e^{\frac{V_{\mathrm{BE}}}{V_{\mathrm{T}}}} - e^{\frac{V_{\mathrm{BC}}}{V_{\mathrm{T}}}}\right) + \frac{I_{\mathrm{S}}}{\beta_{\mathrm{F}}}\left(e^{\frac{V_{\mathrm{BE}}}{V_{\mathrm{T}}}} - 1\right)$$

- Where
- i_C is the collector current
- i_B is the base current
- i_E is the emitter current
- β_F is the forward common emitter current gain (20 to 500)
- β_R is the reverse common emitter current gain (0 to 20)

- IS is the reverse saturation current (on the order of 10−15 to 10−12 amperes)
- VT is the thermal voltage (approximately 26 mV at 300 K ≈ room temperature).
- VBE is the base–emitter voltage
- VBC is the base–collector voltage

LECTURE 7:

- TOPIC TO BE COVERED :

➢ **Early effect**

Early effect

- The **Early effect** is the variation in the width of the base in a BJT due to a variation in the applied base-to-collector voltage, named after its discoverer James M. Early. A greater reverse bias across the collector–base junction, for example, increases the collector–base depletion width, decreasing the width of the charge neutral portion of the base.

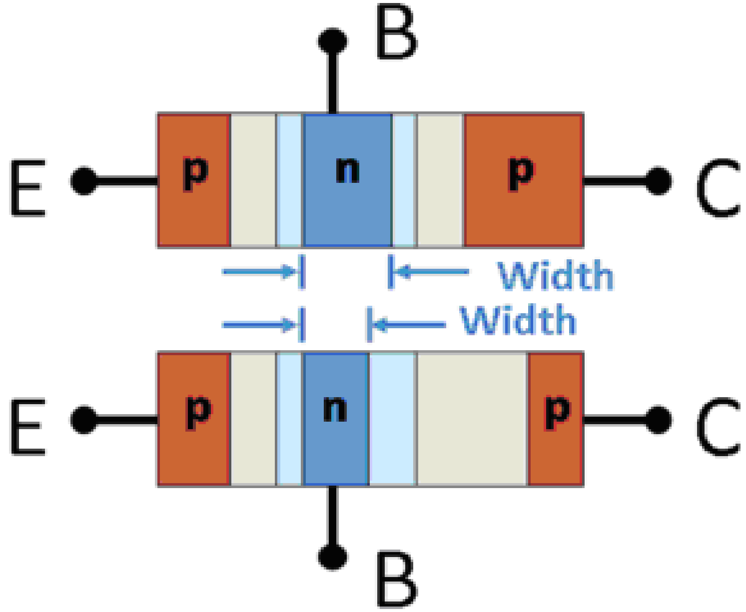


Figure 1. Top: pnp base width for low collector–base reverse bias;
Bottom: narrower pnp base width for large collector–base reverse bias. Light colors are depleted regions.

- As the applied collector–base voltage (*VBC*) varies, the collector–base depletion region varies in size.
- An increase in the collector–base voltage, for example, causes a greater reverse bias across the collector–base junction, increasing the collector–base depletion region width, and decreasing the width of the base.

- This variation in base width often is called the "Early effect" .Narrowing of the base width has two consequences:
- There is a lesser chance for recombination within the "smaller" base region.
- The charge gradient is increased across the base, and consequently, the current of minority carriers injected across the emitter junction increases.

- In the forward active region the Early effect modifies the collector current (*i*C) and the forward common emitter current gain (βF) as given by the following equations:

$$i_C = I_S e^{\frac{v_{BE}}{v_T}} \left(1 + \frac{V_{CB}}{V_A}\right)$$

$$\beta_F = \beta_{F0} \left(1 + \frac{V_{CB}}{V_A}\right)$$

Where,

- *V*CB is the collector–base voltage
- *V*A is the Early voltage (15 V to 150 V)
- βF0 is forward common-emitter current gain when *VCB* = 0 V

Punchthrough

- When the base–collector voltage reaches a certain (device specific) value, the base–collector depletion region boundary meets the base–emitter depletion region boundary. When in this state the transistor effectively has no base. The device thus loses all gain when in this state.

Problems :

Problems :

Problems :

Problems :

UNIT 4

TRANSISTOR BIASING

LECTURE 1:

- TOPIC TO BE COVERED :

➢ **Transistor Bias Stabilization**

Transistor Bias Stabilization

- **Used to compensate for temperature effects which affects semiconductor operation. As temperature increases, free electrons gain energy and leave their lattice structures which causes current to increase.**

Transistor biasing :

Requirements upon biasing circuit :

The operating point of a device, also known as bias point or quiescent point (or simply Q-point), is the DC voltage and/or current which, when applied to a device, causes it to operate in a certain desired fashion.

1. For analog circuit operation, the Q-point is placed so the transistor stays in <u>**active mode**</u> (does not shift to operation in the saturation region or cut-off region) when input is applied. For digital operation, the Q-point is placed so the transistor does the contrary - switches from "on" to "off" state. Often, Q-point is established near the center of active region of transistor characteristic to allow similar signal swings in positive and negative directions.

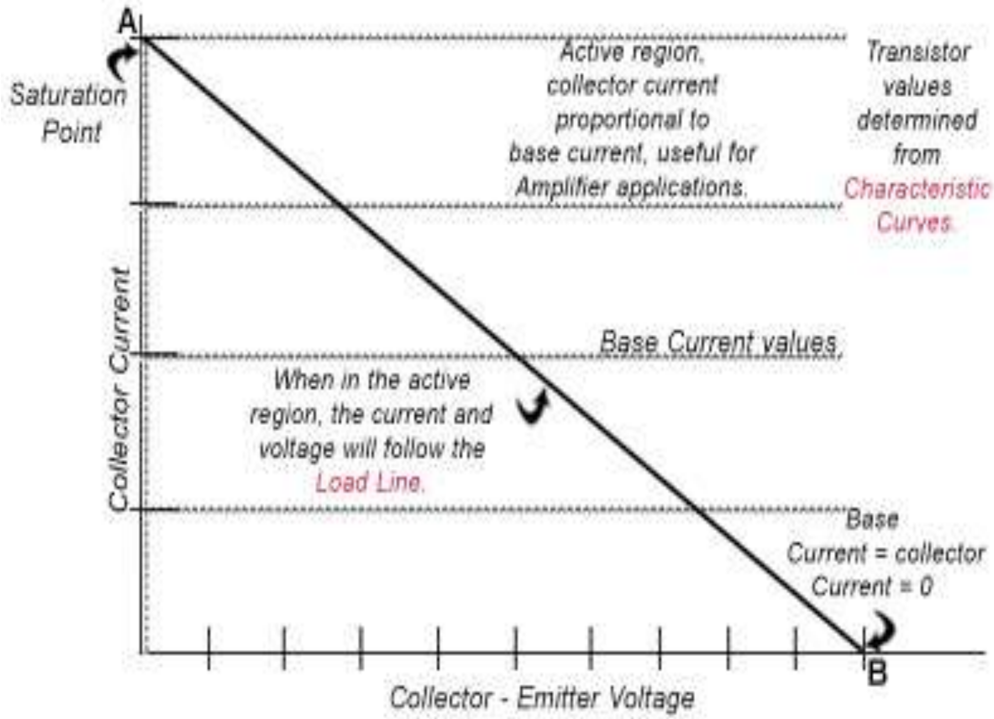
- Q-point should be stable. In particular, it should be insensitive to variations in transistor parameters (for example, should not shift if transistor is replaced by another of the same type), variations in temperature, variations in power supply voltage and so forth.
- The circuit must be practical: easily implemented and cost-effective.

Q-POINT

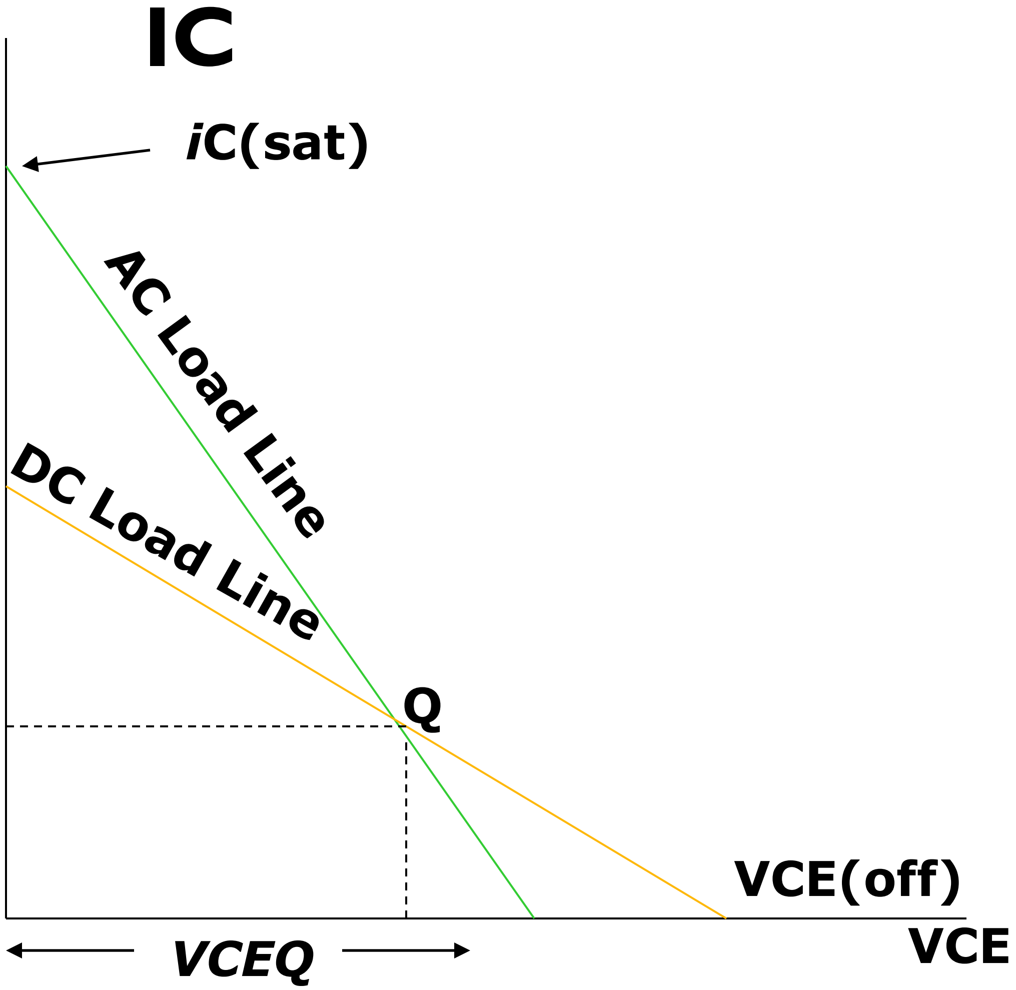
- The Q-point or operating point is established by the DC analysis which establishes the DC load line. The AC load line has a different slope then the DC load line and the two load lines intersect at the Q-point. In the common emitter amplifier, as you increase the frequency,the gain to go down and the phase shift to move away from -180 degrees. The Q-point remains unchanged.

DC & AC load line Analysis

- ***Load Lines***



- Every amplifier has two loads: a dc Load and an ac load.
- The dc load line represents all possible combinations of I_c and V_{CE}
- ***The ac load line*** represents all possible ***ac*** combinations of and i_c & V_{CE}.
- The dc load line will not follow the path of the ac load line as shown to the left. This is because the ac signal "sees" the ac equivalent circuit that includes r_C
- Note that the Q point is shared by both lines.

- 
IC
iC(sat)
AC Load Line
DC Load Line
Q
VCE(off)
VCE
VCEQ

- ***The ac Load Line***
- The ac load line uses $R_C \| R_L$ in its determination, and consequently, the ac load line will be than the dc load line.
- The ends of the ac load line are found using the formulas:

$$ic(\text{sat}) = ICQ + VCEQ$$

rc

$$v\ ce(\text{off}) = VCEQ + ICQ$$

rC

- Note that the Q point is in the centre of the dc loadline but not in the centre of the ac load line.
- The ac load line tells us what the maximum output voltage swing will be for the given amplifier.

LECTURE 2:

- TOPIC TO BE COVERED :
- Bias stability

Bias stability

One of the basic problems with transistor amplifiers is establishing and maintaining the proper values of quiescent current and voltage in the circuit.

This is accomplished by selecting the proper circuit-biasing conditions and ensuring these conditions are maintained despite variations in ambient (surrounding) temperature, which cause changes in amplification and even distortion (an unwanted change in a signal).

- Thus a need arises for a method to properly bias the transistor amplifier and at the same time stabilize its dc operating point (the no signal values of collector voltage and collector current).

Stabilty factor

- The Stabilty factor may be defined as the rate of change of collector current with respect to the revere saturation current keeping the CE current gain and base current as constant ,

$$S = \frac{dI_c}{dI_{co}} = \frac{\Delta I_c}{\Delta I_{co}}$$

- In defination of s, β, & V_{BE} are assumed to be constant while they vary with temp.

Hence we define two other stabilty constant : S_β & Sv

1. $S_\beta = \frac{dI_c}{d\beta} = \frac{\Delta I_c}{\Delta\beta}$

2. $Sv = \frac{dI_c}{dV_{BE}} = \frac{\Delta I_c}{\Delta V_{BE}}$

LECTURE 3:

- TOPIC TO BE COVERED :
- Types of bias circuit : Emitter bias

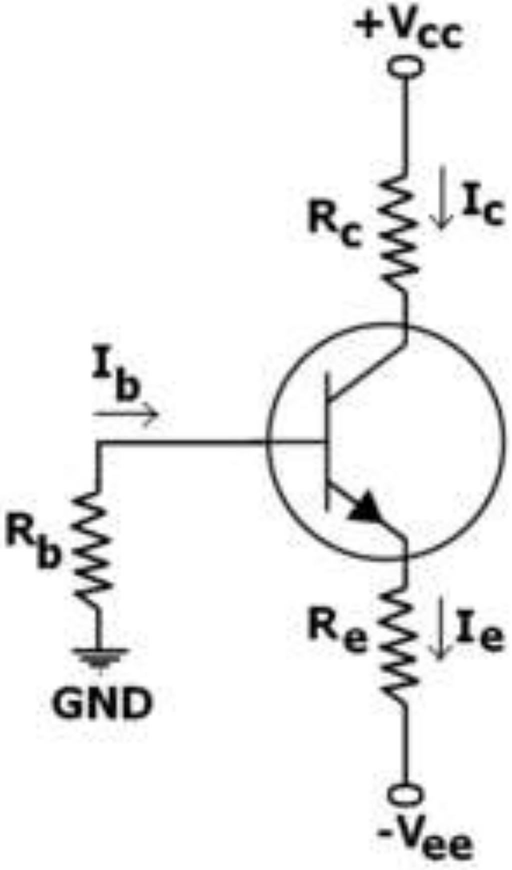
Types of bias circuit

- The following discussion treats four common biasing circuits used with bipolar transistors:
- Fixed bias
- Collector-to-base bias
- Voltage divider bias
- Emitter bias

Types of Bias Stabilization

- ***Self Bias***: A portion of the output is fed back to the input 180o out of phase. **This negative feedback will reduce overall amplifier gain.**
- ***Fixed Bias***: Uses resistor in parallel with Transistor emitter-base junction.
- ***Combination Bias***: This form of bias stabilization uses a combination of the emitter resistor form and a voltage divider. It is designed to compensate for both temperature effects as well as minor fluctuations in supply (bias) voltage.
- ***Emitter Resister Bias***: As temperature increases, current flow will increase. This will result in an increased voltage drop across the emitter resistor which opposes the potential on the emitter of the transistor.

Emitter bias



- When a split supply (dual power supply) is available, this biasing circuit is the most effective. The negative supply VEE is used to forward-bias the emitter junction through RE.
- The positive supply VCC is used to reverse-bias the collector junction. Only three resistors are necessary

- We know that,

  VB - VE = Vbe

- If RB is small enough, base voltage will be approximately zero. Therefore emitter current is,

  IE = (VEE - Vbe)/RE

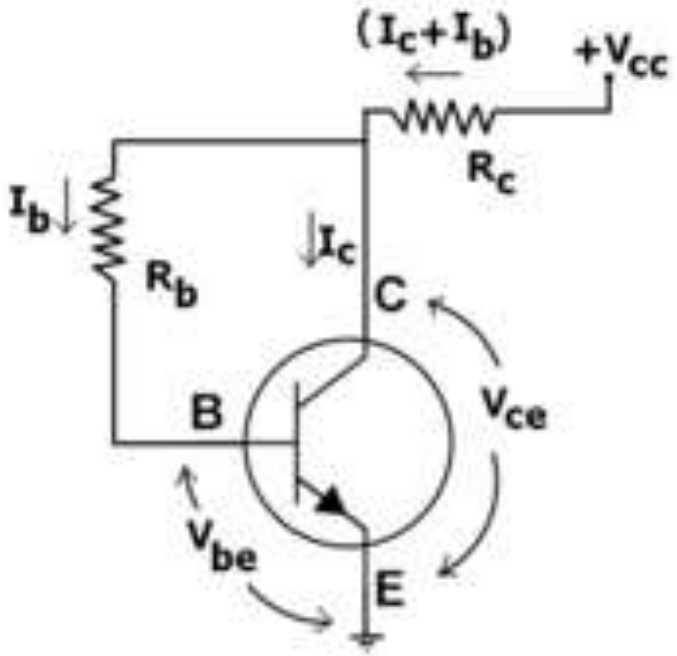
The operating point is independent of β if RE >> RB/β

- **Merit:**
- Good stability of operating point similar to voltage divider bias.
- **Demerit:**
- This type can only be used when a split (dual) power supply is available.

LECTURE 4:

- TOPIC TO BE COVERED :
- **Collector-to-base bias**

Collector-to-base bias



- In this form of biasing, the base resistor RB is connected to the collector instead of connecting it to the battery VCC.
- That means this circuit employs negative feedback to stabilize the operating point.

- From Kirchhoff's voltage law, the voltage across the base resistor is

$$VRb = VCC - (IC + Ib)RC - Vbe.$$

From Ohm's law, the base current is

$$Ib = VRb / Rb.$$

- For the given circuit,

$$IB = (VCC - Vbe) / (RB+\beta RC).$$

- **Merits:**
- Circuit stabilizes the operating point against variations in temperature and β (ie. replacement of transistor)
- **Demerits:**
- In this circuit, to keep IC independent of β the following condition must be met:

$$I_C = \beta I_B = \frac{\beta(V_{CC} - V_{be})}{R_B + \beta R_C} \approx \frac{(V_{CC} - V_{be})}{R_C}$$

which is approximately the case if
β RC >> RB.

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping RC fairly large, or making RB very low.
- If RC is of large value, high VCC is necessary. This increases cost as well as precautions necessary while handling.
- If RB is low, the reverse bias of the collector-base is small, which limits the range of collector voltage swing that leaves the transistor in active mode.

- The resistor RB causes an ac feedback, reducing the voltage gain of the amplifier. This undesirable effect is a trade-off for greater Q-point stability.

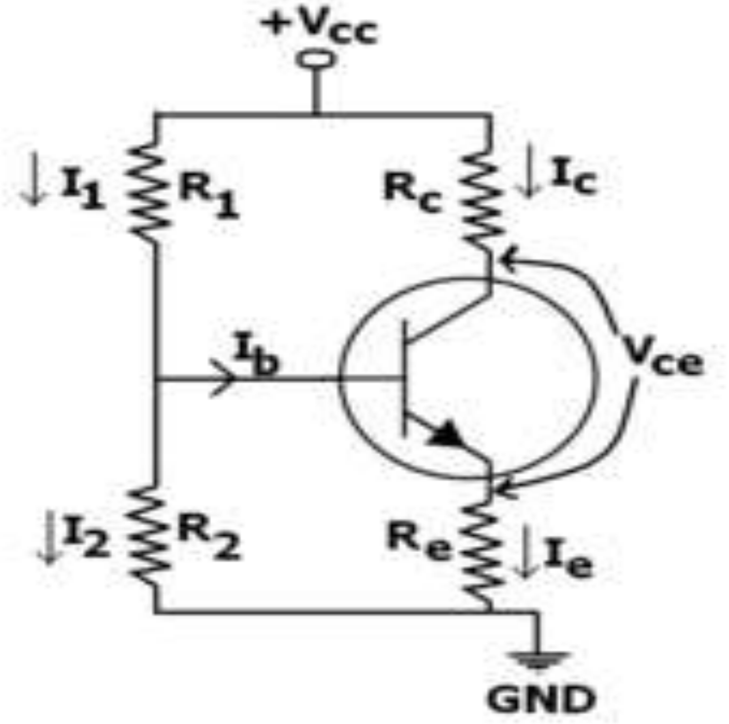
- **Usage:** The feedback also decreases the input impedance of the amplifier as seen from the base, which can be advantageous. Due to the gain reduction from feedback, this biasing form is used only when the trade-off for stability is warranted.

LECTURE 5:

- TOPIC TO BE COVERED :

- Voltage divider bias

Voltage divider bias



- In this form of biasing, the base resistor RB is connected to the collector instead of connecting it to the battery VCC.
- That means this circuit employs negative feedback to stabilize the operating point.

- From Kirchhoff's voltage law, the voltage across the base resistor is

  VRb = VCC - (IC + Ib)RC - Vbe.
- From Ohm's law, the base current is

  Ib = VRb / Rb.
- For the given circuit,

  IB = (VCC - Vbe) / (RB+βRC).

- **Merits:**
- Circuit stabilizes the operating point against variations in temperature and β (ie. replacement of transistor)
- **Demerits:**
- In this circuit, to keep IC independent of β the following condition must be met:

$$I_C = \beta I_B = \frac{\beta(V_{CC} - V_{be})}{R_B + \beta R_C} \approx \frac{(V_{CC} - V_{be})}{R_C}$$

which is approximately the case if

β RC >> RB.

As β-value is fixed for a given transistor, this relation can be satisfied either by keeping RC fairly large, or making RB very low.

If RC is of large value, high VCC is necessary. This increases cost as well as precautions necessary while handling.

If RB is low, the reverse bias of the collector-base is small, which limits the range of collector voltage swing that leaves the transistor in active mode.

- The resistor RB causes an ac feedback, reducing the voltage gain of the amplifier. This undesirable effect is a trade-off for greater Q-point stability.

- **Usage:** The feedback also decreases the input impedance of the amplifier as seen from the base, which can be advantageous. Due to the gain reduction from feedback, this biasing form is used only when the trade-off for stability is warranted.

LECTURE 6:

- TOPIC TO BE COVERED :

➢ Thermal runaway

Thermal runaway

Thermal runaway refers to a situation where an increase in temperature changes the conditions in a way that causes a further increase in temperature leading to a destructive result. It is a kind of positive feedback.

- Some bipolar transistors (notably germanium based bipolar transistors) increase significantly in leakage current as they increase in temperature. Depending on the design of the circuit, this increase in leakage current can increase the current flowing through the transistor and with it the power dissipation.

- This causes a further increase in C-E current. This is frequently seen in a push-pull stage of a class AB amplifier. If the transistors are biased to have minimal crossover distortion at room temperature, and the biasing is not made temperature-dependent, as the temperature rises, both transistors will be increasingly turned on, causing current and power to further increase, eventually destroying one or both devices.

- If multiple bipolar transistors are connected in parallel (which is typical in high current applications) one device will enter thermal runaway first, taking the current which originally was distributed across all the devices and exacerbating the problem.

- This effect is called ***current hogging***. Eventually one of two things will happen, either the circuit will stabilize or the transistor in thermal runaway will be destroyed by the heat. Hence current hogging term is related to thermal runaway.

Problem :

Problem :

UNIT 5

FET & MOSFET

LECTURE 1:

- TOPIC TO BE COVERED :

➢ Field Effect transistors – FETs : introduction

Field Effect transistors - FETs

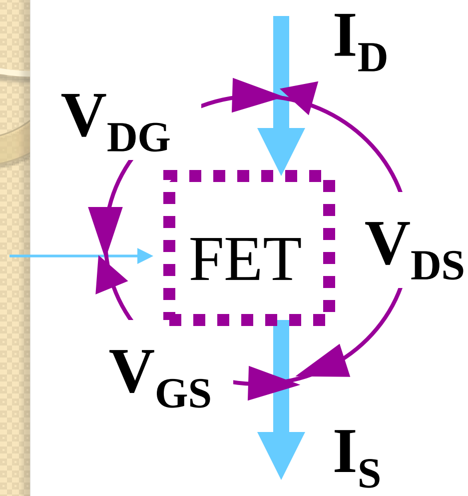
First, why are we using still another transistor? BJTs had a small problem - the input signal was a current I_B which was small but not that small. This was the control signal. Typically we would prefer that we control with a voltage directly.

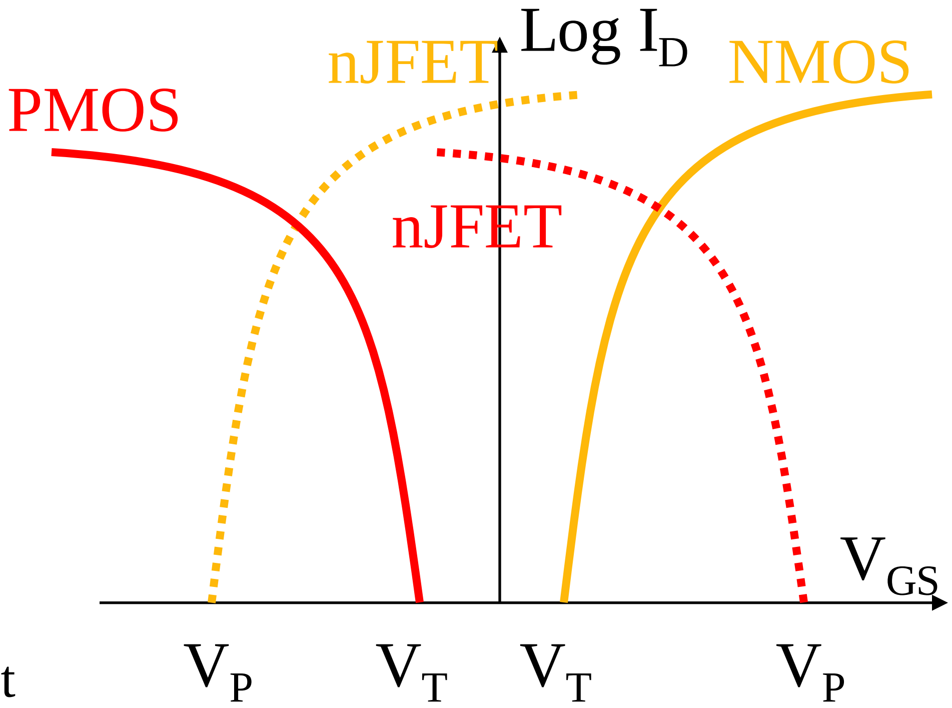
This has an added benefit. If the device control only depends on a voltage signal we can design it so it draws little or NO current! This means that when we attach it to something like a thermocouple, it will not disturb the input since it is drawing no power. In other words the input impedance of the circuit is large.

Comparison :

FET	BJT
Gate	Base
Drain	Collector
Source	Emitter
Gate Voltage	Base current
Drain current	Collector current
Drain-source voltage	Collector-Emitter Voltage

Flavors of FETs



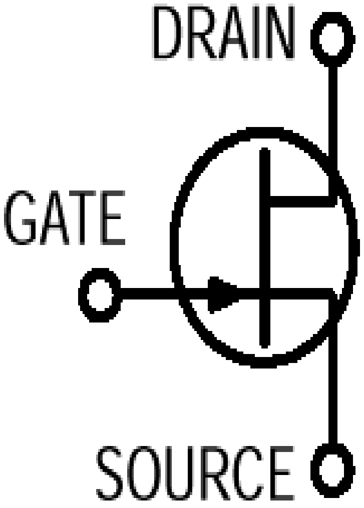


The basic way to think of an FET is that there is a current $I_D = I_S$ that is flowing through a channel that is controlled by a voltage V_{GS}. Since the channel offers resistance to the flow it has a voltage drop V_{DS}. These three parameters completely characterize the device.

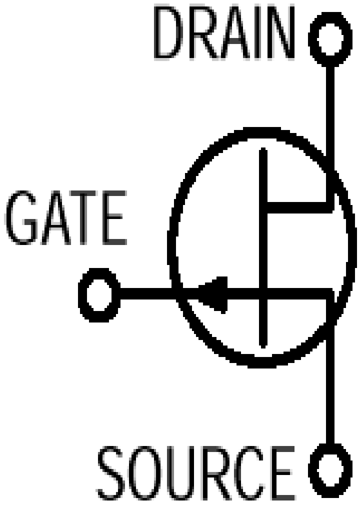
The above shows difference between different types of FETs. The important thing to note is that the shapes are the same! We will focus on the blue curves, where electrons are the carriers.

Junction FETs

2N5457
2N5458
2N5459

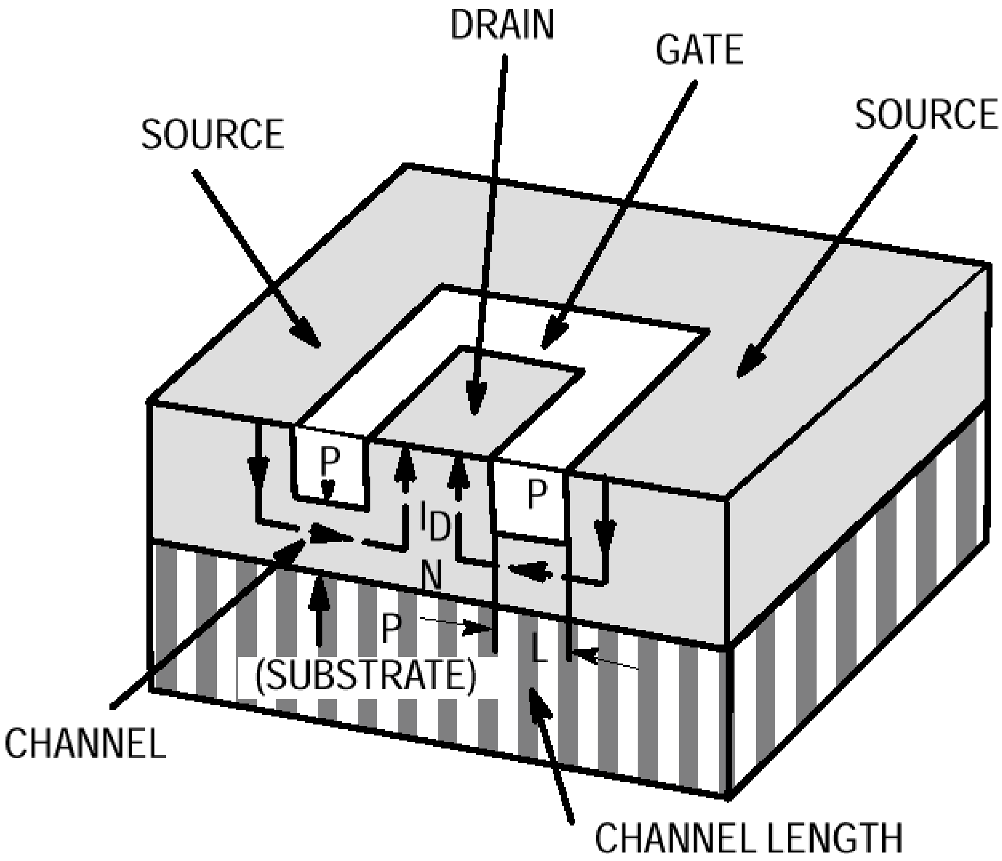


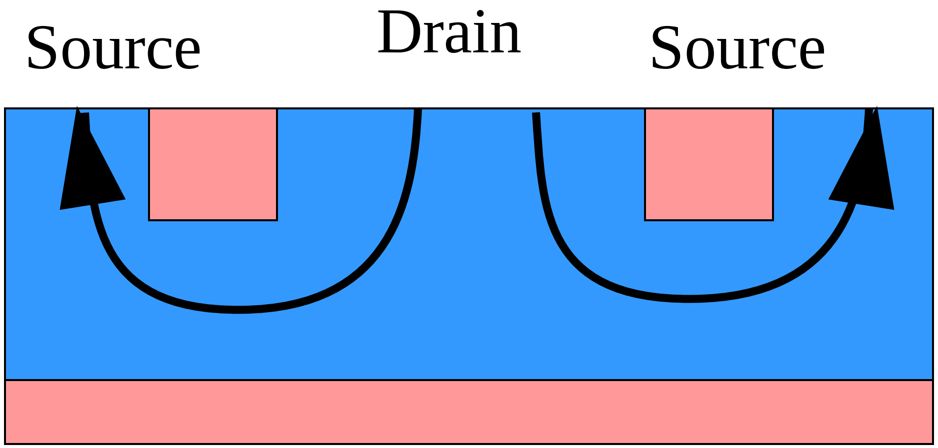
N-CHANNEL JFET



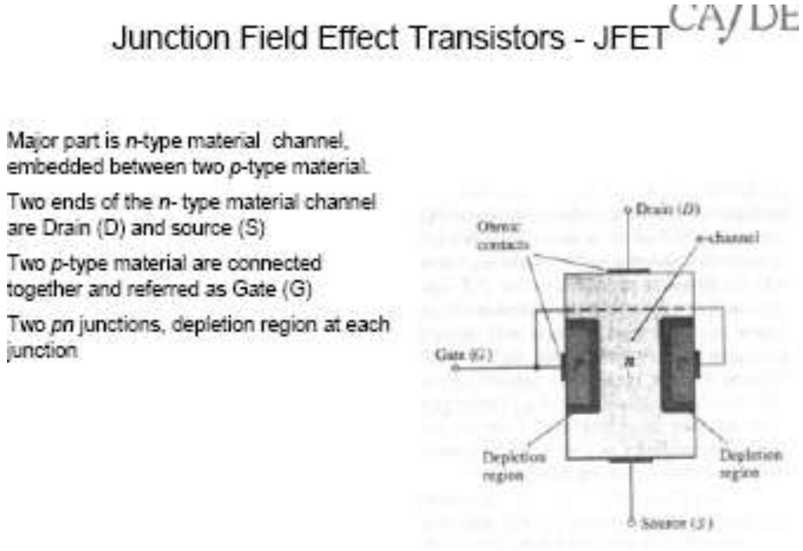
P-CHANNEL JFET

Junction FETs



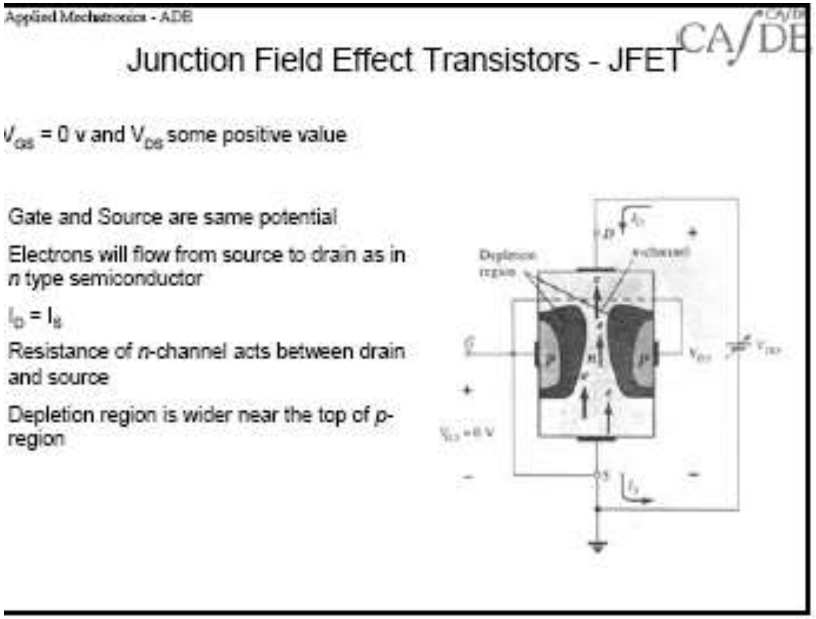


The arrows show current flow from the drain to source.



Junction Field Effect Transistors - JFET

- Major part is *n*-type material channel, embedded between two *p*-type material.
- Two ends of the *n*- type material channel are Drain (D) and source (S)
- Two *p*-type material are connected together and referred as Gate (G)
- Two *pn* junctions, depletion region at each junction

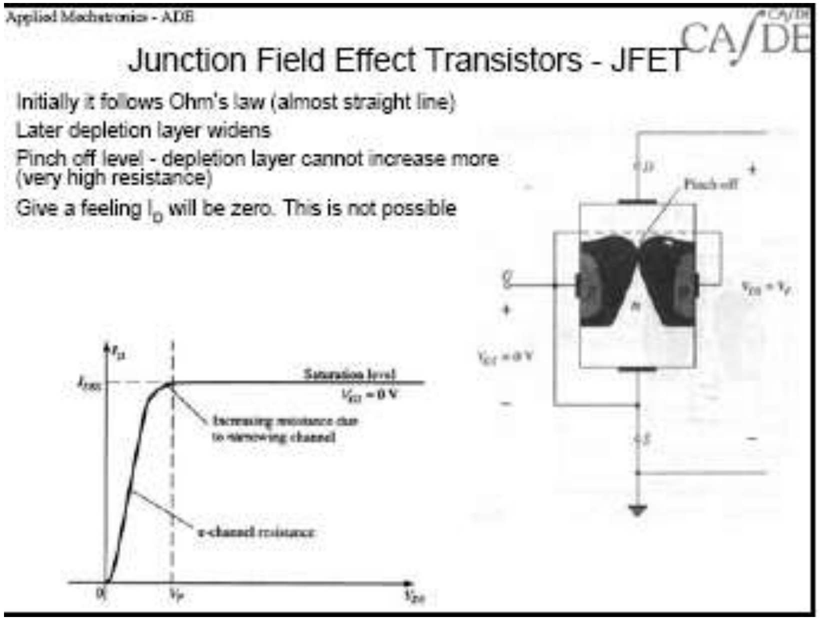


Applied Mechatronics - ADE

Junction Field Effect Transistors - JFET

V_{GS} = 0 v and V_{DS} some positive value

- Gate and Source are same potential
- Electrons will flow from source to drain as in *n* type semiconductor
- $I_D = I_S$
- Resistance of *n*-channel acts between drain and source
- Depletion region is wider near the top of *p*-region



Applied Mechatronics - ADE

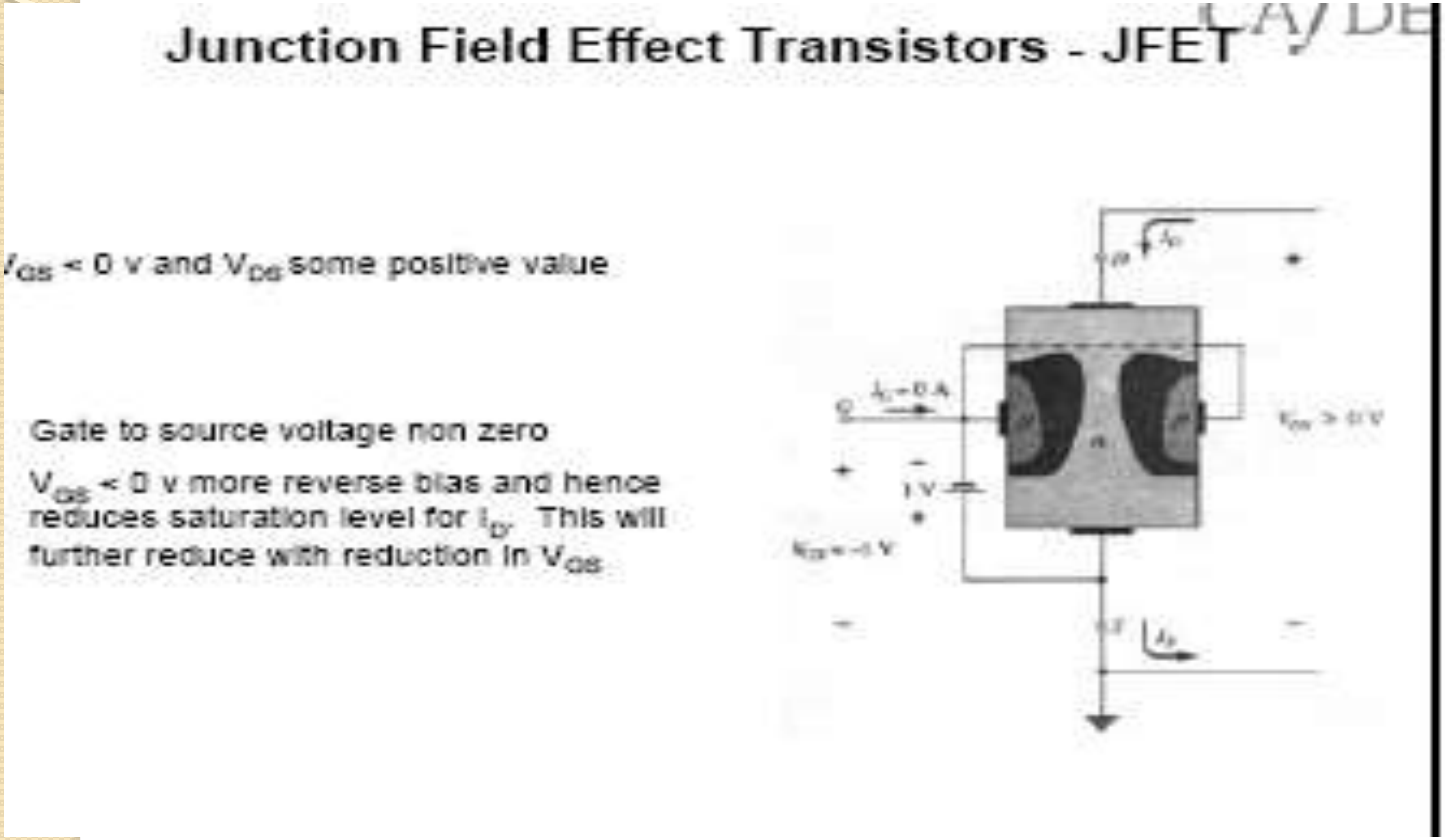
Junction Field Effect Transistors - JFET

Initially it follows Ohm's law (almost straight line)

Later depletion layer widens

Pinch off level - depletion layer cannot increase more (very high resistance)

Give a feeling I_D will be zero. This is not possible



Junction Field Effect Transistors - JFET

$/_{GS} < 0$ v and V_{DS} some positive value

Gate to source voltage non zero

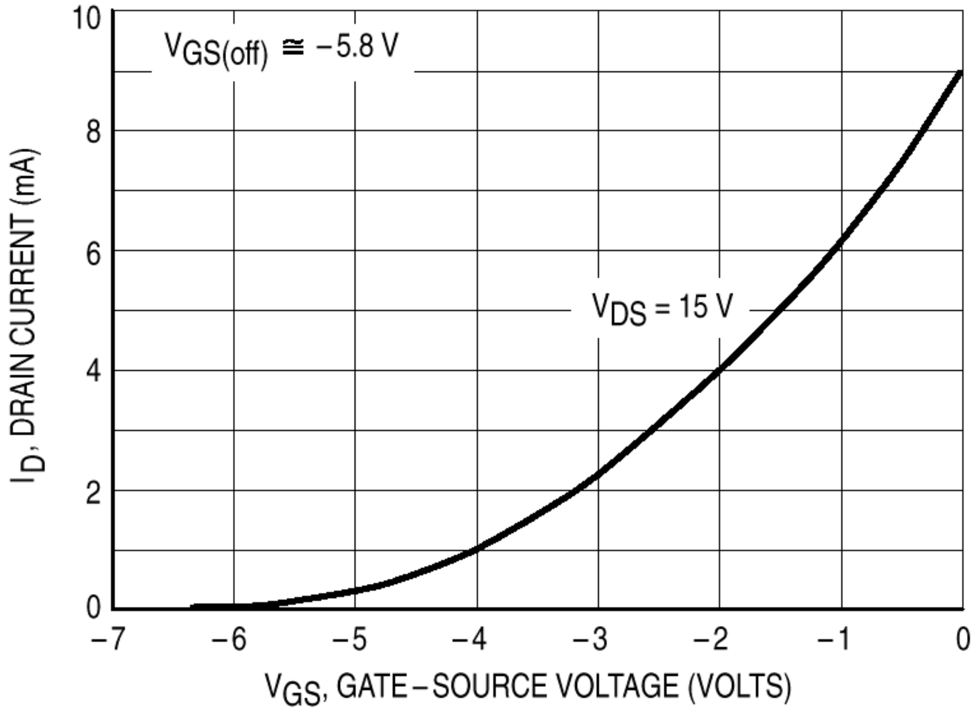
$V_{GS} < 0$ v more reverse bias and hence reduces saturation level for I_D. This will further reduce with reduction in V_{GS}

LECTURE 2:

- TOPIC TO BE COVERED :

➢ Junction FETs - characteristic curves

Junction FETs - characteristic curves



Here we see the results of make the GS junction more reverse biased. This is a parabola given by

$$I_D = k\left(V_{GS} - V_P\right)^2$$

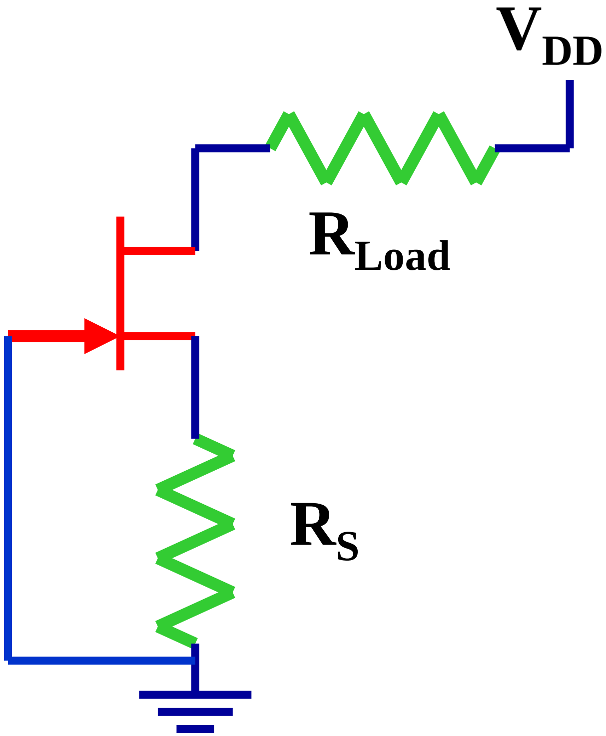
where *k* is a constant and *VP* is the pinch-off or threshold voltage. Note that the curve extends only to zero volts. This is because the junction is normally only reverse-biased to prevent damage if large current flow through the GS junction.

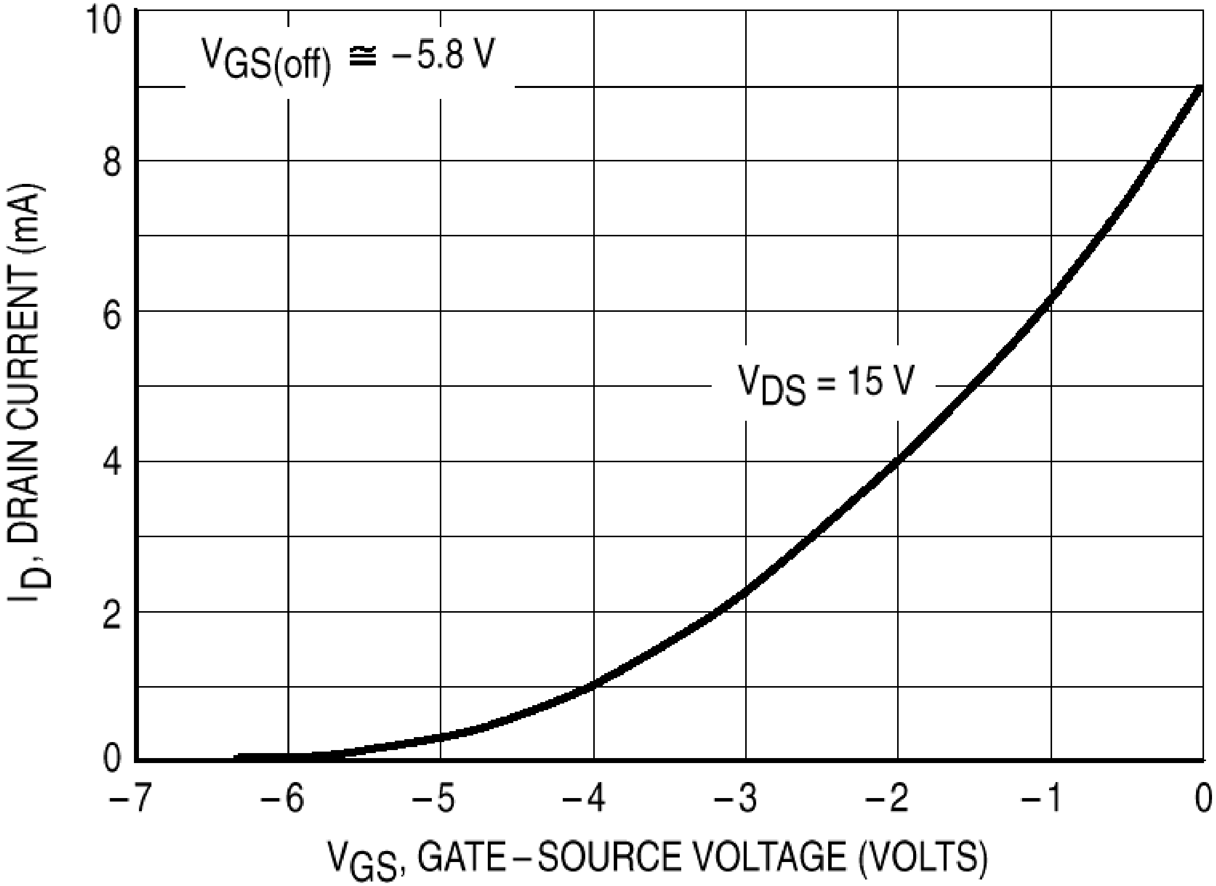
Regions of JFET operation:

- **Cut-off region:** The transistor is off. There is no conduction between the drain and the source when the gate-source voltage is greater than the cut-off voltage. ($I_D = 0$ for $V_{GS} > V_{GS,off}$)
- **Active region (also called the Saturation region):** The transistor is on. The drain current is controlled by the gate-source voltage (V_{GS}) and relatively insensitive to V_{DS}. In this region the transistor can be an amplifier.

- **Ohmic region:** The transistor is on, but behaves as a voltage controlled resistor. When V_{DS} is less than in the active region, the drain current is roughly proportional to the source-drain voltage and is controlled by the gate voltage.

Junction FET - current source



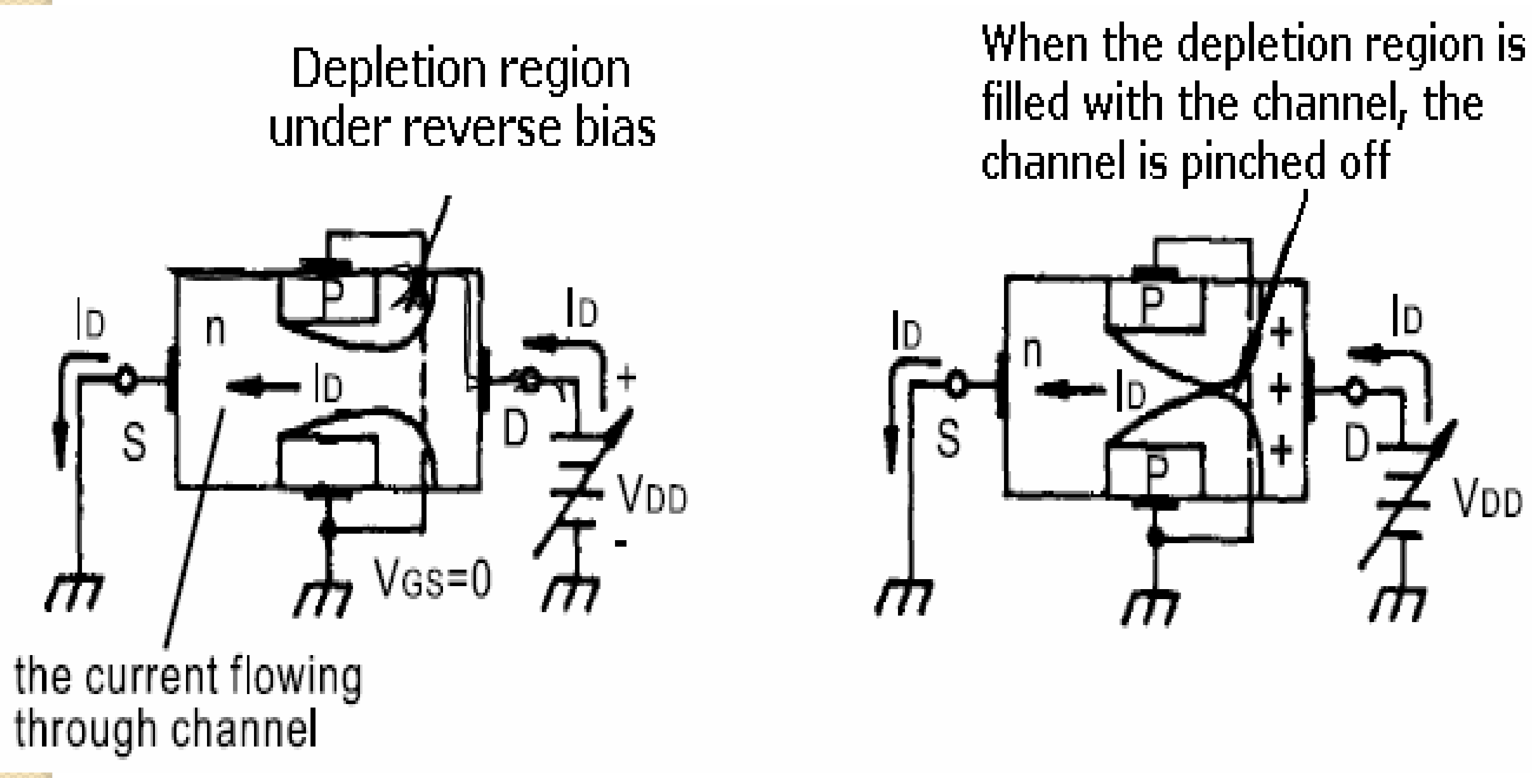

$V_{GS(off)} \cong -5.8$ V
$V_{DS} = 15$ V
I_D, DRAIN CURRENT (mA)
10
8
6
4
2
0
−7
−6
−5
−4
−3
−2
−1
0
V_{GS}, GATE−SOURCE VOLTAGE (VOLTS)

- The curve is not effected much by the value of VDS unless it gets too small. This means that we can apply a voltage to the gate and get exactly the same current for very different voltage drops across DS channel. The circuit above is a self-biased voltage controlled current source. If RS is 4k, then from the plot above 1 mA will flow resulting in VGS = -4 V. Regardless of the value of Rload (within the limits of the power supply VDD) exactly 1 mA will be delivered.
- The only downside of this circuit is that the load is not grounded on either end, but that can be fixed.

Common Specifications.

- ***I*DSS** is the drain current in the active region for *V*GS = 0. (*I*D source shorted to gate)
- ***V*GS,off** is the minimum *V*GS where *I*D = 0. *V*GS,off is negative for *n*-channel and positive for *p*-channel..
- **gm** is the transconductance, the change in *I*D with *V*GS and constant *V*DS.

- When Vgs = 0, the relation between Vds and Ids is shown in Fig below.From this figure we can clearly view that Id will be increased with Vds until it maintains at a constant value. This constant value is called Idss, wherein the footnote "ds" means the current from drain to source, and the last "s" means it is under the status that drain-gate are short-circuit (Vgs = 0).

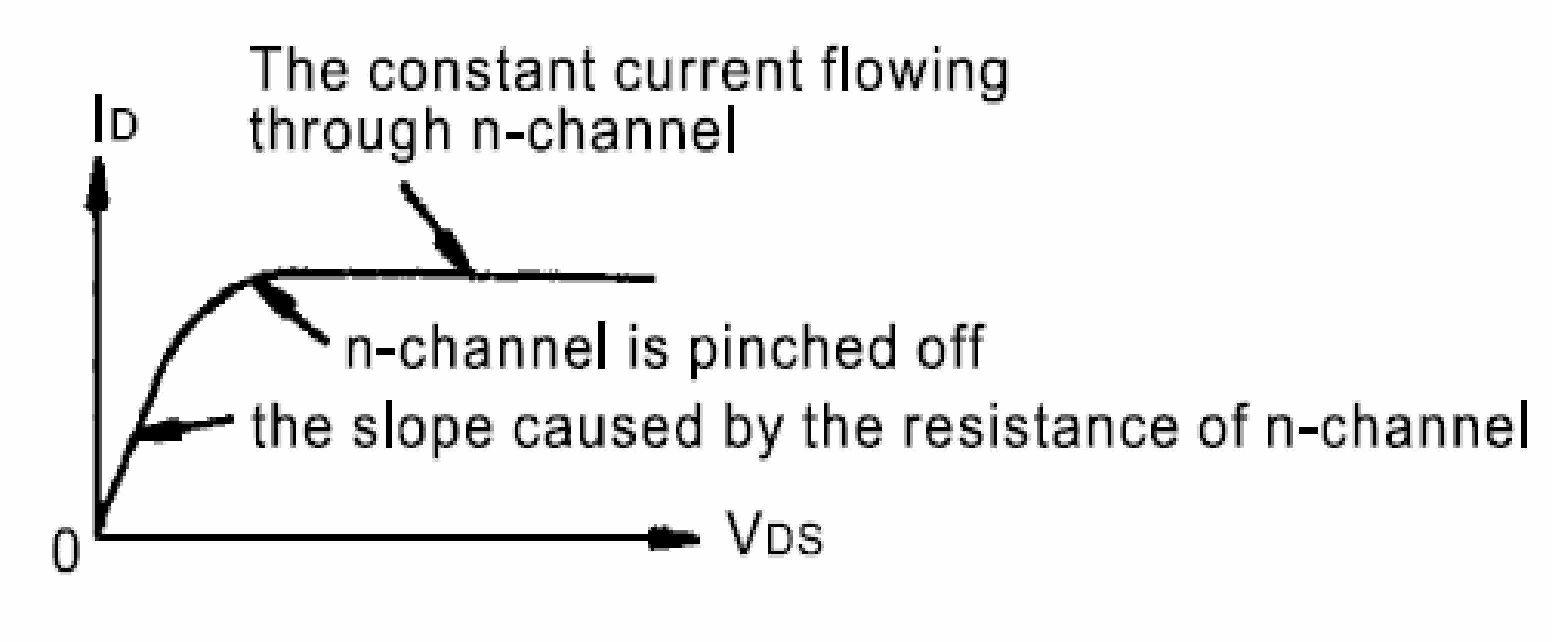


Depletion region under reverse bias

the current flowing through channel

When the depletion region is filled with the channel, the channel is pinched off

Pinch off voltage :

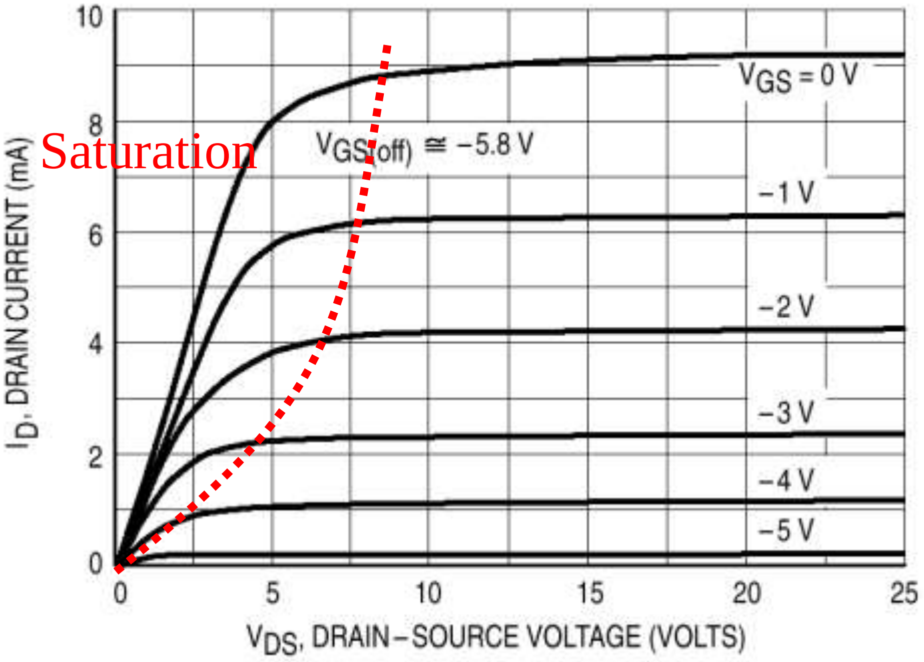


LECTURE 3:

- TOPIC TO BE COVERED :
- Transfer Characteristic Curve
- Drain-Source Characteristic Curve

Junction FETs - characteristic curves (2)

Linear



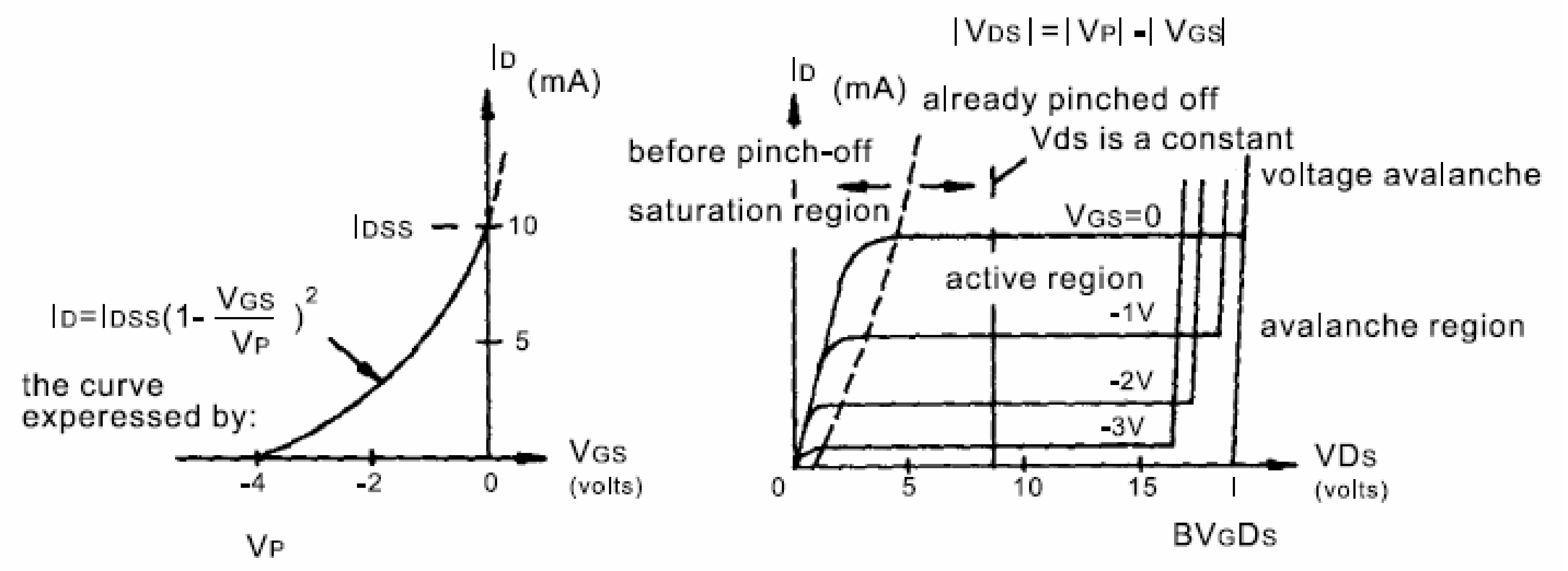
Linear $$I_D = k(V_{GS} - V_P)^2$$

Saturation $$I_D = 2k\left[(V_{GS} - V_P)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

Like the BJT there are two regions of operation - saturation and linear (also called triode). Amplifier applications live in the saturation region; switching and variable resistor applications live in the linear region.

Although we will not discuss amplifiers, note that the drain current is dependent on VGS in a linear fashion and could be used to make a circuit with voltage gain.

Transfer Characteristic Curve



- Another characteristic curve for JFET is transfer characteristic curve. This is a variation curve of drain current Id corresponding to gate-source voltage Vgs while the drain-source voltage Vds is constant.
- Two points, Idss and Vp are the most important points in this transfer characteristic curve. When these two points are fixed in the coordinate axes, the remaining points can be looked up from this transfer characteristic curve or can be solved from the formula

Id = Idss(1-Vgs/Vp)2.

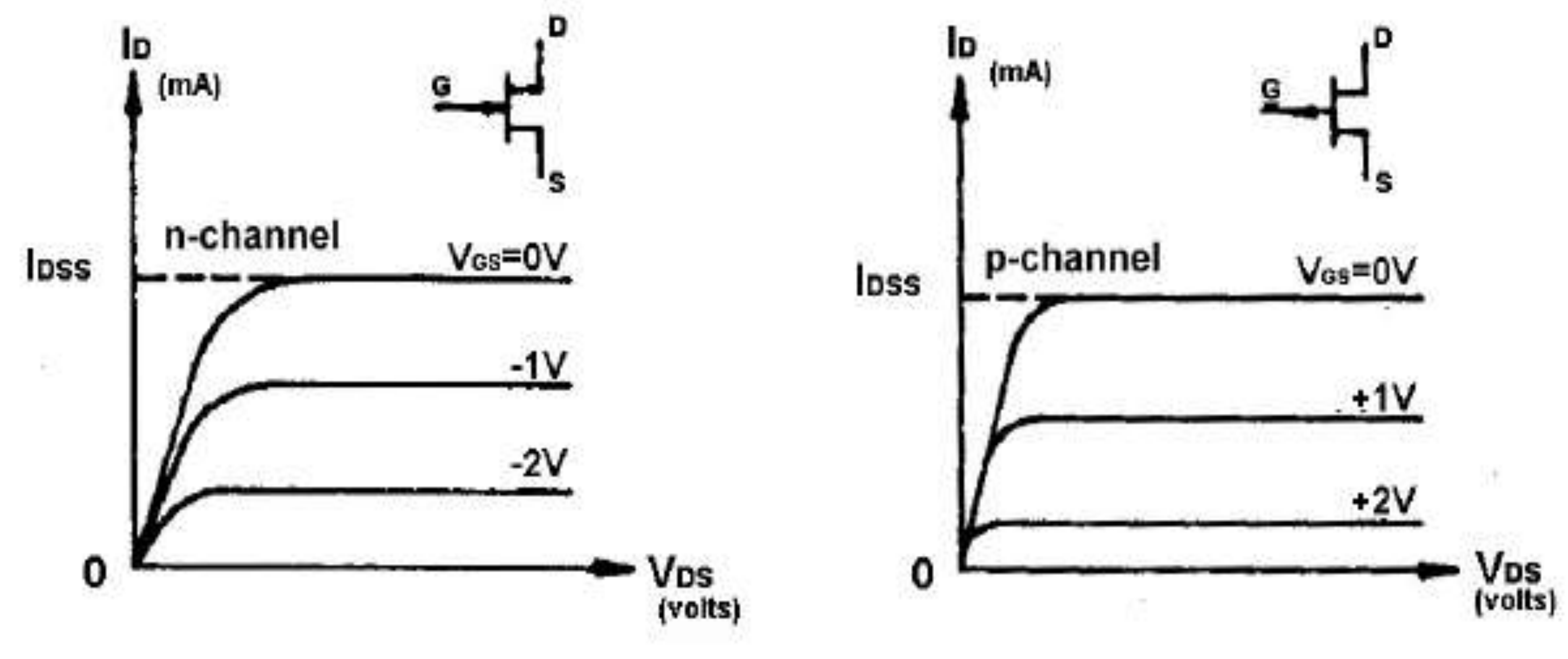
- From this formula,we can calculate

Vgs = 0, Id = Idss,

Id = 0,Vgs = Vp.

- The design of JFET is typically designed in the middle between Vp and Idss of the transfer curve .

Drain-Source Characteristic Curve



Drain-Source Characteristic Curve of JFET.

- If Vgs is increased (it's more negative to n-channel), depletion will be immediately generated in the channel so that the current required to pinch off the channel will be decreased. The curve corresponding to Vgs = -1V is shown in Fig .
- From this result we can find out that the gate voltage functions as a controller capable of decreasing the drain current (at a specific voltage Vds). If Vgs is more positive for p-channel JFET, the drain current will be decreased from Idss .If Vgs is continuously increased, the drain current will be decreased correspondingly. When Vgs reaches a certain value, the drain current will be decreased to zero and will be independent of the value of Vds.
- The gate-source voltage at this time is called pinch-off voltage which is usually denoted as Vp or Vgs (cutoff). From Fig we can find out that Vp is a negative voltage for n-channel FET and a positive voltage for p-channel FET.

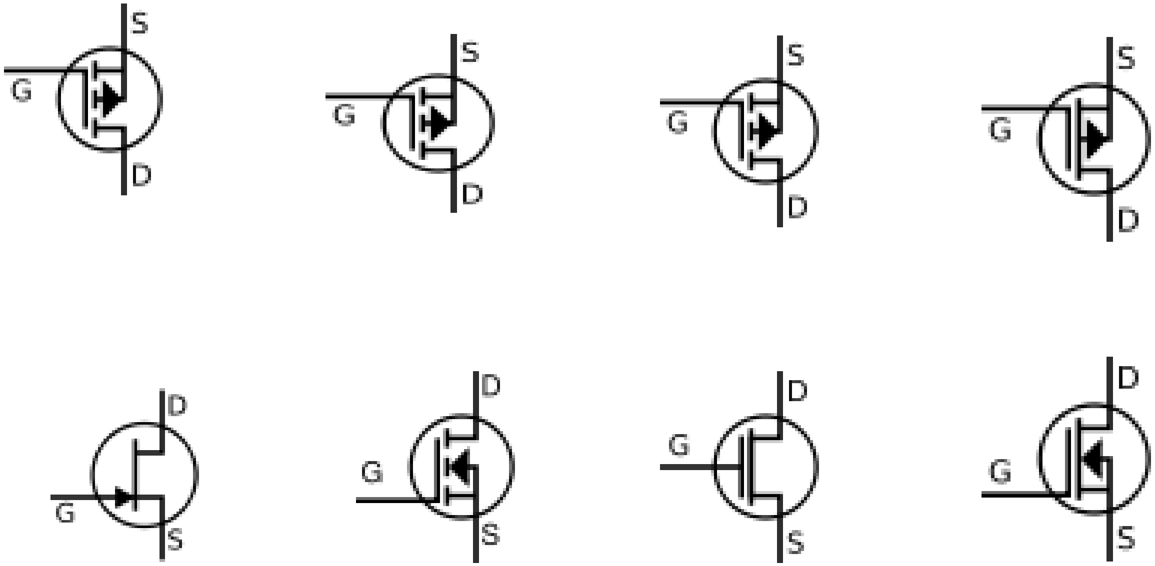
LECTURE 4:

- TOPIC TO BE COVERED :

➢ MOSFET : Introduction ,types & symbols

MOSFET

- The **metal–oxide–semiconductor field-effect transistor** (**MOSFET**, **MOS-FET**, or **MOS FET**) is a device used to amplify or switch electronic signals. It is by far the most common field-effect transistor in both digital and analog circuits. The MOSFET is composed of a channel of n-type or p-type semiconductor material (see article on semiconductor devices), and is accordingly called an NMOSFET or a PMOSFET (also commonly nMOSFET, pMOSFET).



P-channel

N-channel

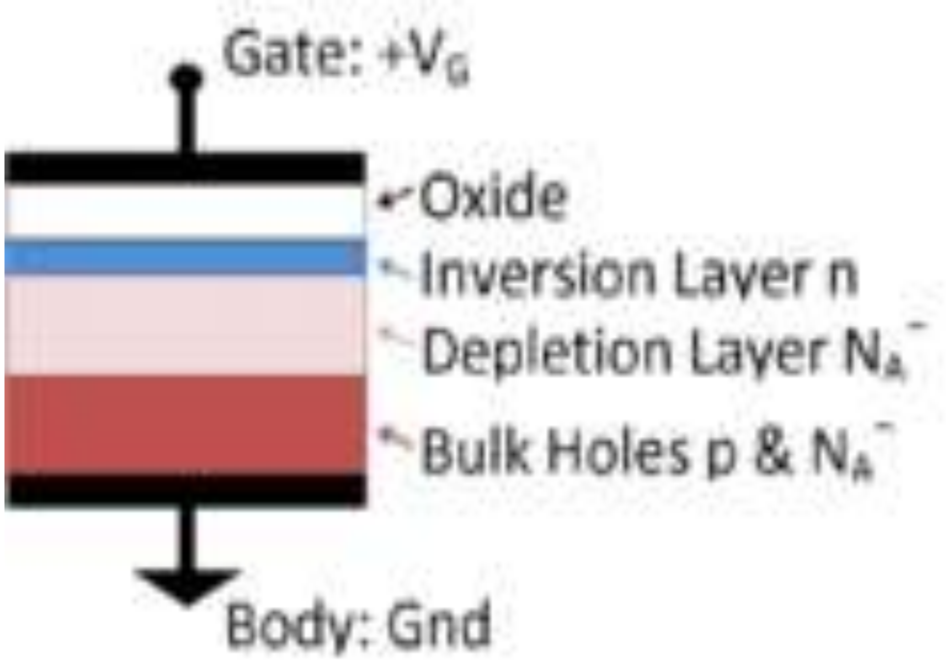
JFET

MOSFET enh

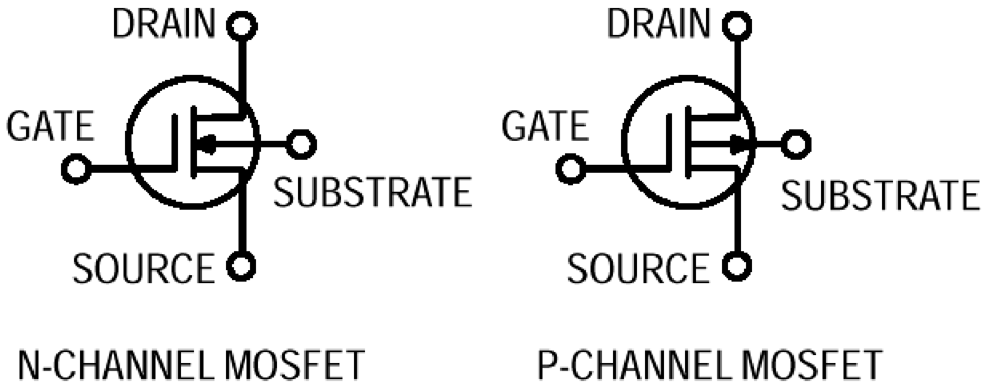
MOSFET dep

MOSFET operation

- **Metal–oxide–semiconductor structure**



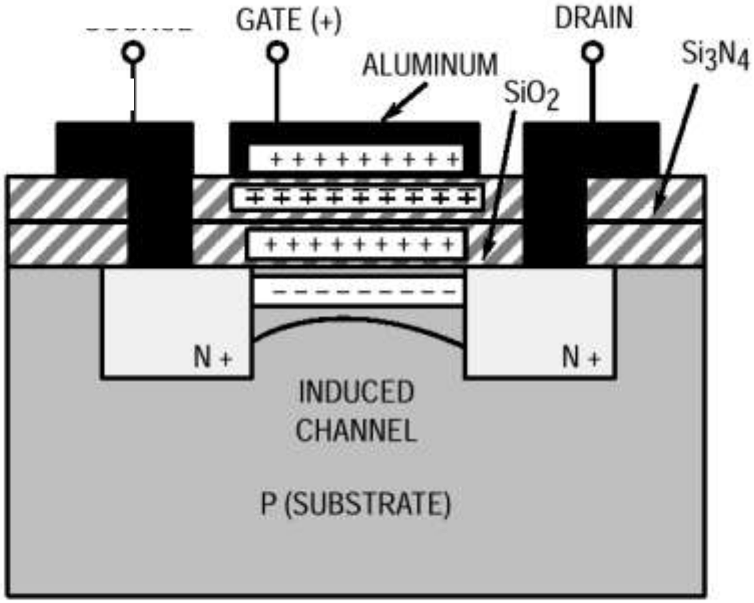
Metal-Oxide-Semiconductor FET



This device is the reason that there are warning labels on almost all computer hardware - “static-sensitive device; handle with care”. Memory in most cases turn out to be MOSFET switches, as is most of the circuitry on the CPU (incidentally the change in operating voltage for the CPU was a result of changing from BJTs to MOSFETs).

As with the JFET there is an additional layer (literally the wafer that it was grown on) that is normally not an external contact - it is internally connected to the source.

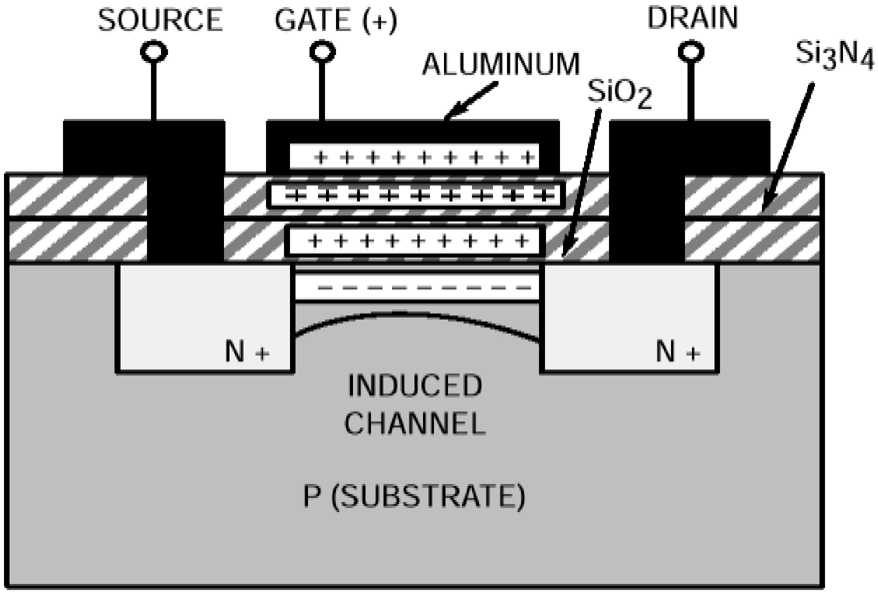
Metal-Oxide-Semiconductor FET



We are only going to talk about the “enhancement” mode, which as the nice feature that as you apply a more and more positive control voltage V_{GS} the current increases. There is also a threshold voltage V_T.

How does it work? There is no conduction between the source and drain normally (VGS = 0) because regardless of what voltage VDS you apply there is a reverse biased PN junction. Even apply a voltage VGS does not appear from the structure to have an obvious effect since it is not even attached - there is a thin SiO2 insulating layer in between! This gate oxide incidentally is very important - it is one of the current limitations on how fast computers run!

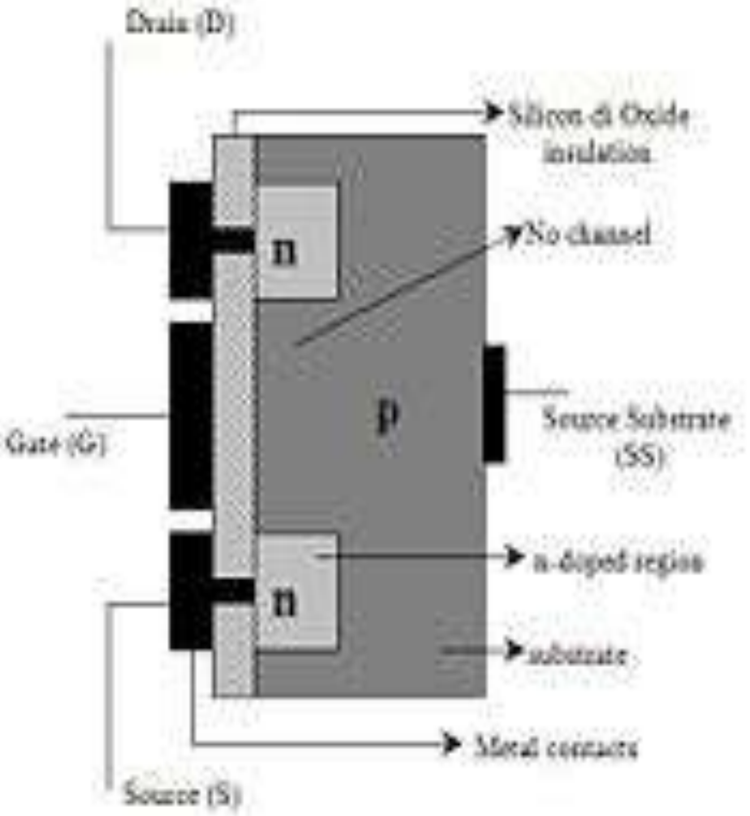
Metal-Oxide-Semiconductor FET(2)



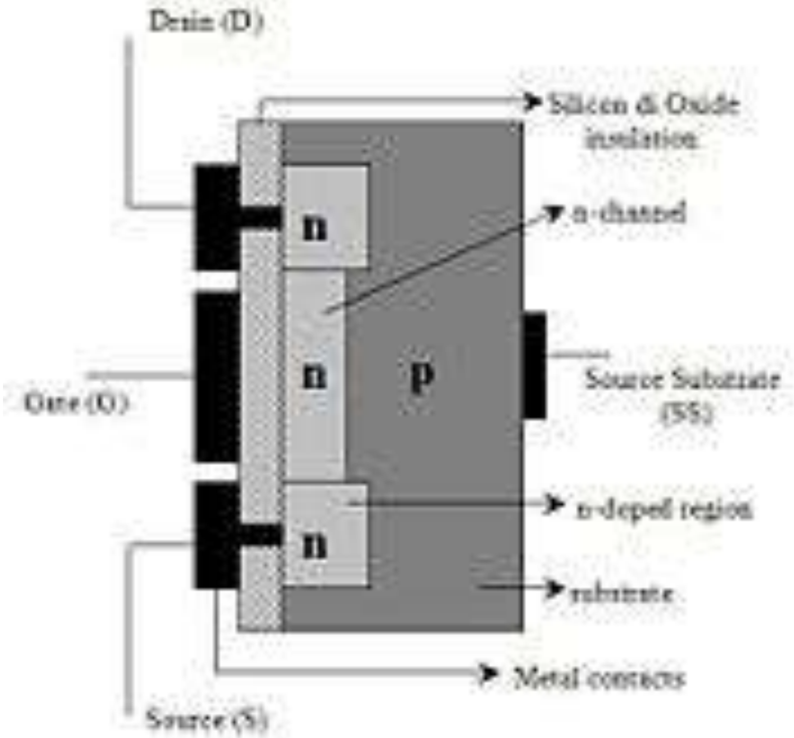
However when you apply a positive voltage the oxide behaves like a capacitor - since positive charge builds up on one side, there must be an equal and opposite charge on the other side.

- This charge must come from the substrate. Since it is P-type there are not many electrons but those that are present are all sucked up to the gate oxide. This creates a region that is very thin, but very rich in electrons, converting P-type to N-type locally. This "channel" is enhanced by applying higher positive biases.
- While there are many applications for MOSFETs (remember they are just like JFETs with the threshold voltage shifted higher) The dominant application is a switch. Most of digital electronics is based on low power switches and most DC power supplies are based on high power switches.

MOSFET structure and channel formation



Cross section of an NMOS without channel formed: OFF state



Cross section of an NMOS with channel formed: ON state

Modes of operation

- For an **enhancement-mode, n-channel MOSFET** the three operational modes are:
- Cut-off or Sub-threshold or Weak Inversion Mode
- **When $V_{GS} < V_{th}$:**
- where V_{th} is the threshold voltage of the device.
- According to the basic threshold model, the transistor is turned off, and there is no conduction between drain and source.

- where I_{D0} = current at $V_{GS} = V_{th}$ and the slope factor n is given by

$$n = 1 + C_D / C_{OX},$$

- with C_D = capacitance of the depletion layer and C_{OX} = capacitance of the oxide layer. In a long-channel device, there is no drain voltage dependence of the current once $V_{DS} >> V_T$, but as channel length is reduced drain-induced barrier lowering

LECTURE 5:

- TOPIC TO BE COVERED :

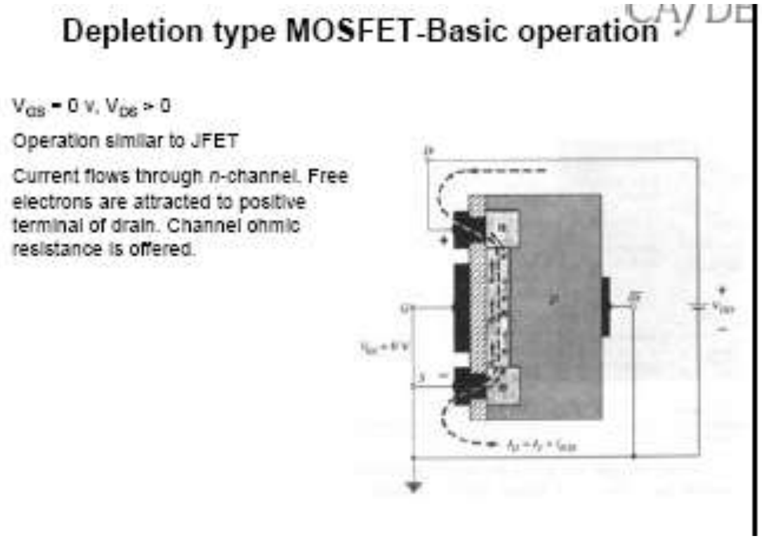
➢ *Depletion-mode MOSFET*

➢ Enhancement type MOSFET

Depletion-mode MOSFET

With an appropriate voltage applied between source and drain, current will flow through the channel, as a semiconductor resistance. However, if we now apply a negative voltage to the gate, as shown to the right, it will amount to a small negative static charge on the gate. This negative voltage will repel electrons, with their negative charge, away from the gate. But free electrons are the majority current carriers in the n-type silicon channel. By repelling them away from the gate region, the applied gate voltage creates a depletion region around the gate area, thus restricting the usable width of the channel just as the pn junction did.

Because this type of FET operates by creating a depletion region within an existing channel, it is called a *depletion-mode MOSFET*.

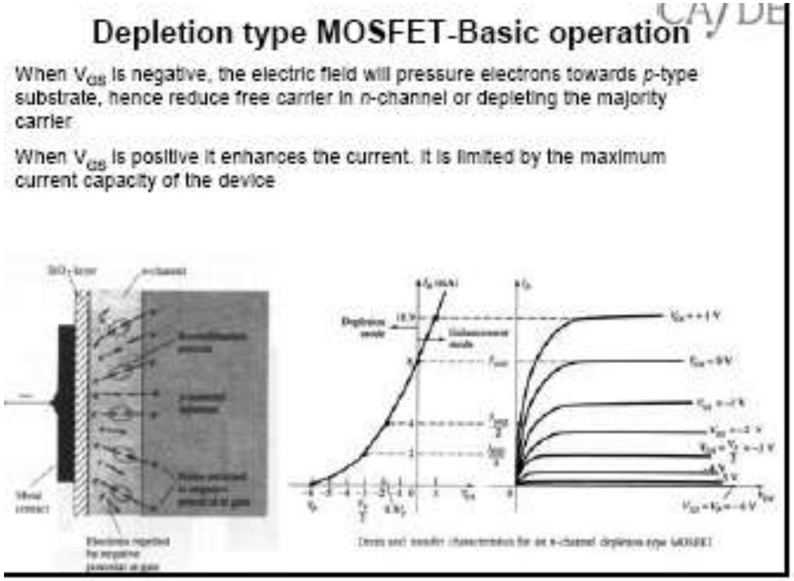


Depletion type MOSFET-Basic operation

$V_{GS} = 0$ V, $V_{DS} > 0$

Operation similar to JFET

Current flows through *n*-channel. Free electrons are attracted to positive terminal of drain. Channel ohmic resistance is offered.

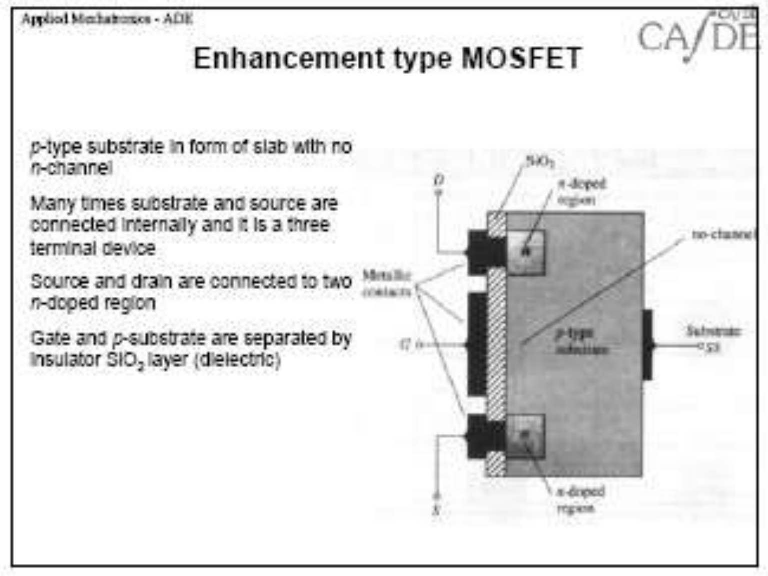


Depletion type MOSFET-Basic operation

When V_{GS} is negative, the electric field will pressure electrons towards *p*-type substrate, hence reduce free carrier in *n*-channel or depleting the majority carrier

When V_{GS} is positive it enhances the current. It is limited by the maximum current capacity of the device

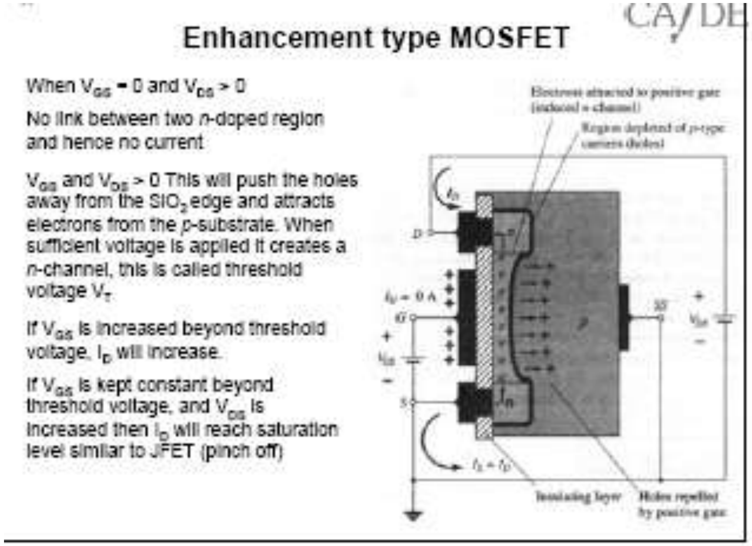
Enhancement type MOSFET :



Applied Mechatronics - ADE

Enhancement type MOSFET

- *p*-type substrate in form of slab with no *n*-channel
- Many times substrate and source are connected internally and it is a three terminal device
- Source and drain are connected to two *n*-doped region
- Gate and *p*-substrate are separated by insulator SiO_2 layer (dielectric)



Enhancement type MOSFET

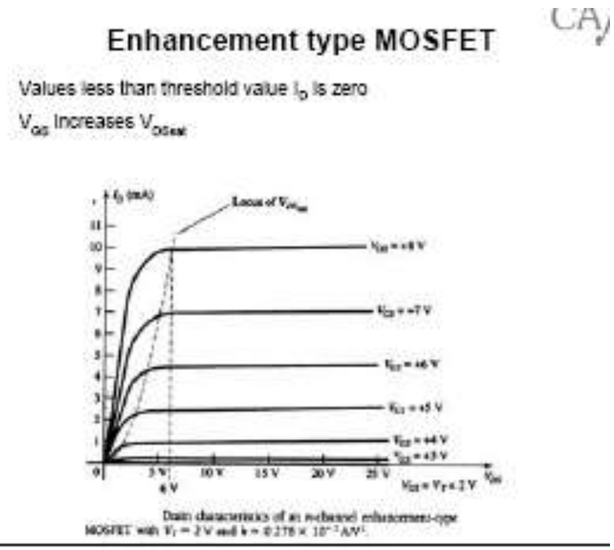
When $V_{GS} = 0$ and $V_{DS} > 0$

No link between two *n*-doped region and hence no current

V_{GS} and $V_{DS} > 0$ This will push the holes away from the SiO_2 edge and attracts electrons from the *p*-substrate. When sufficient voltage is applied it creates a *n*-channel, this is called threshold voltage V_T

If V_{GS} is increased beyond threshold voltage, I_D will increase.

If V_{GS} is kept constant beyond threshold voltage, and V_{DS} is increased then I_D will reach saturation level similar to JFET (pinch off)



Enhancement type MOSFET

Values less than threshold value I_D is zero

V_{GS} Increases V_{DSsat}

Drain characteristics of an n-channel enhancement-type MOSFET with $V_T = 2$ V and $k = 0.278 \times 10^{-3}$ A/V^2.

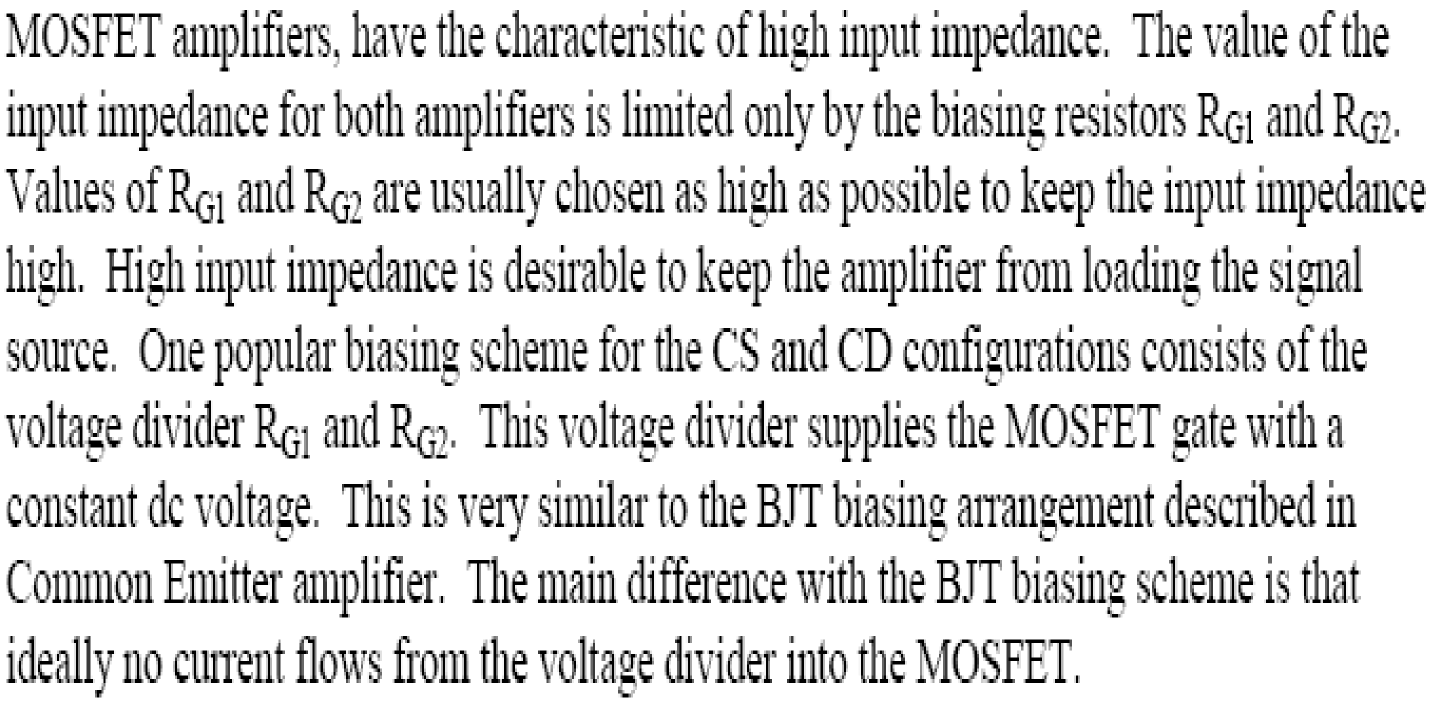
Lecture 7 :

- Topics to be covered:

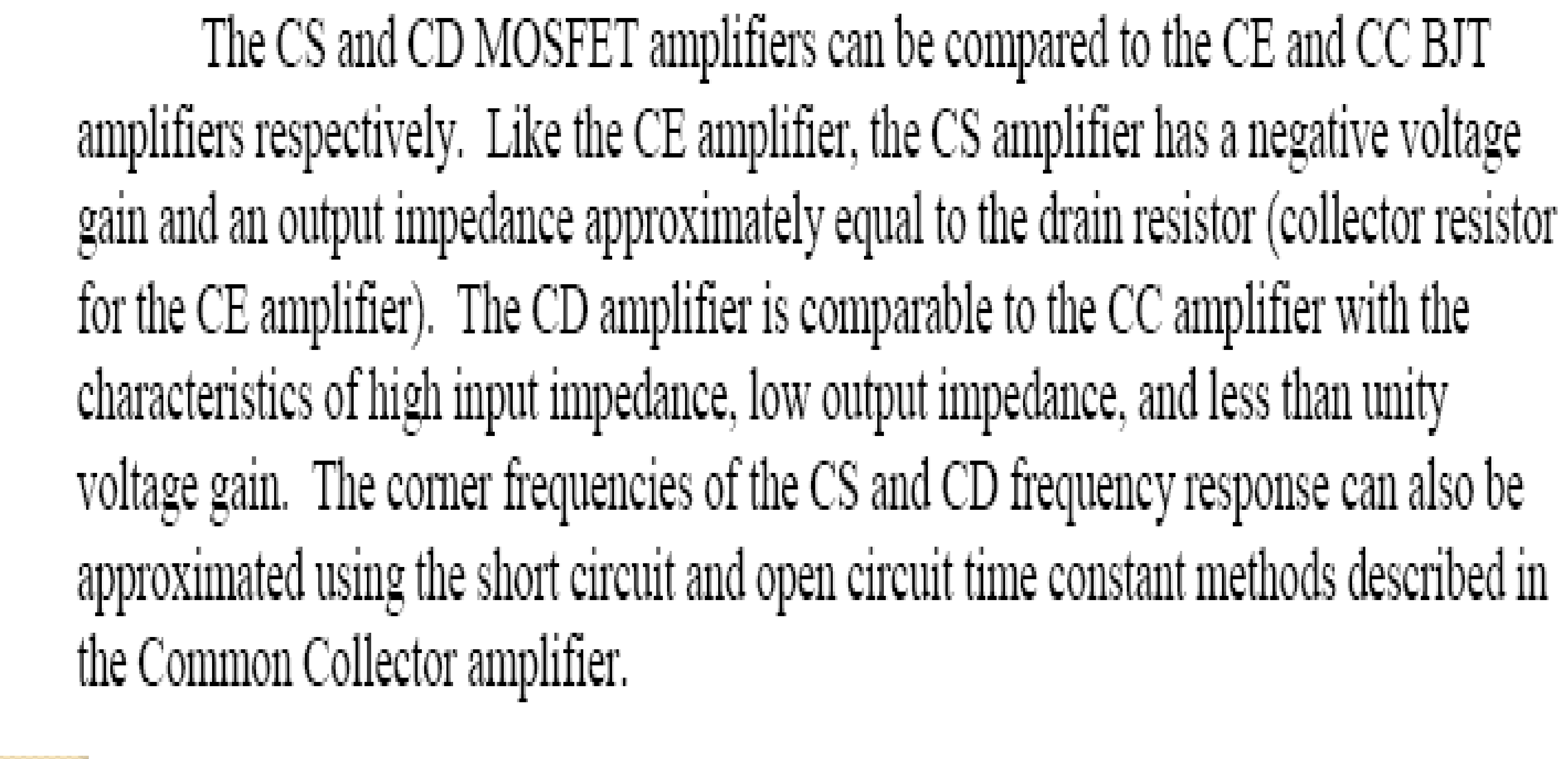
➢ CS Amplifier

➢ CD Amplifier

CS & CD Amplifier :



MOSFET amplifiers, have the characteristic of high input impedance. The value of the input impedance for both amplifiers is limited only by the biasing resistors R_{G1} and R_{G2}. Values of R_{G1} and R_{G2} are usually chosen as high as possible to keep the input impedance high. High input impedance is desirable to keep the amplifier from loading the signal source. One popular biasing scheme for the CS and CD configurations consists of the voltage divider R_{G1} and R_{G2}. This voltage divider supplies the MOSFET gate with a constant dc voltage. This is very similar to the BJT biasing arrangement described in Common Emitter amplifier. The main difference with the BJT biasing scheme is that ideally no current flows from the voltage divider into the MOSFET.



The CS and CD MOSFET amplifiers can be compared to the CE and CC BJT amplifiers respectively. Like the CE amplifier, the CS amplifier has a negative voltage gain and an output impedance approximately equal to the drain resistor (collector resistor for the CE amplifier). The CD amplifier is comparable to the CC amplifier with the characteristics of high input impedance, low output impedance, and less than unity voltage gain. The corner frequencies of the CS and CD frequency response can also be approximated using the short circuit and open circuit time constant methods described in the Common Collector amplifier.

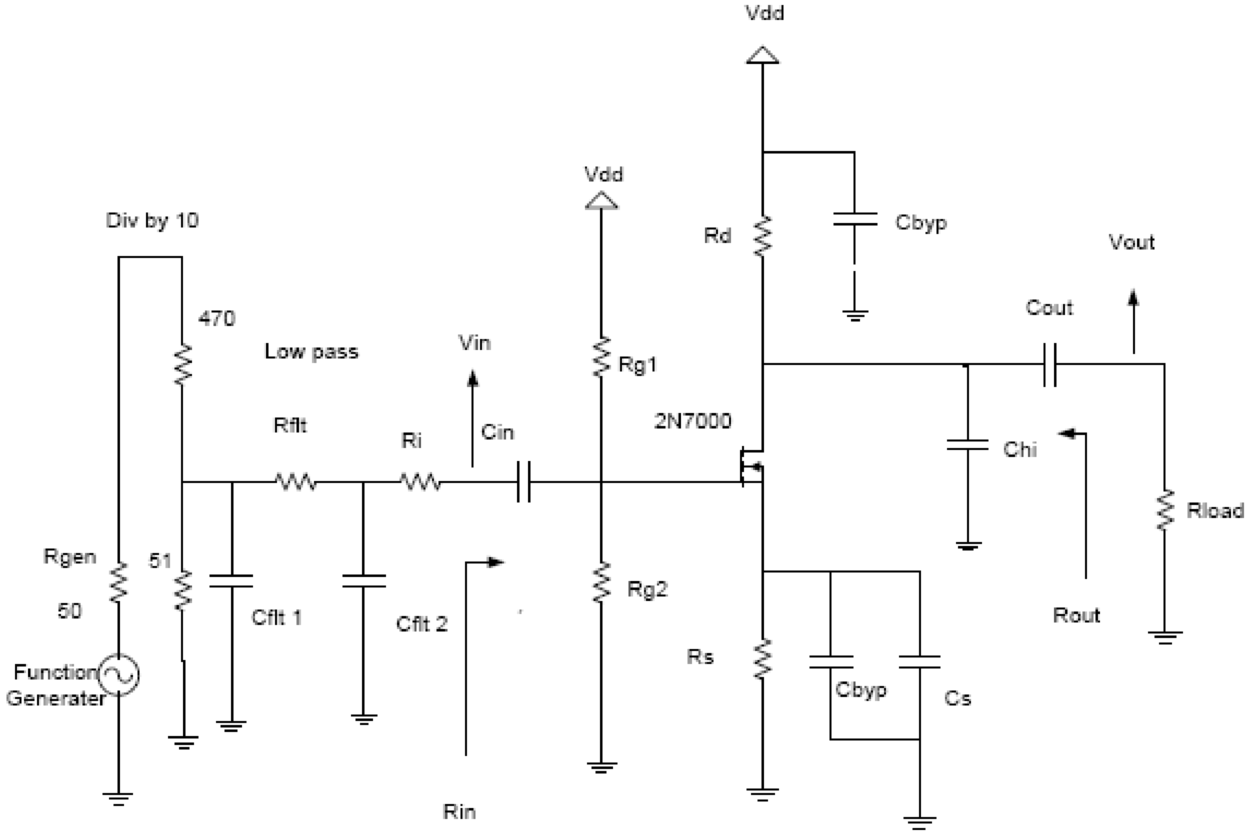


Figure 1: Common Source MOSFET Amplifier

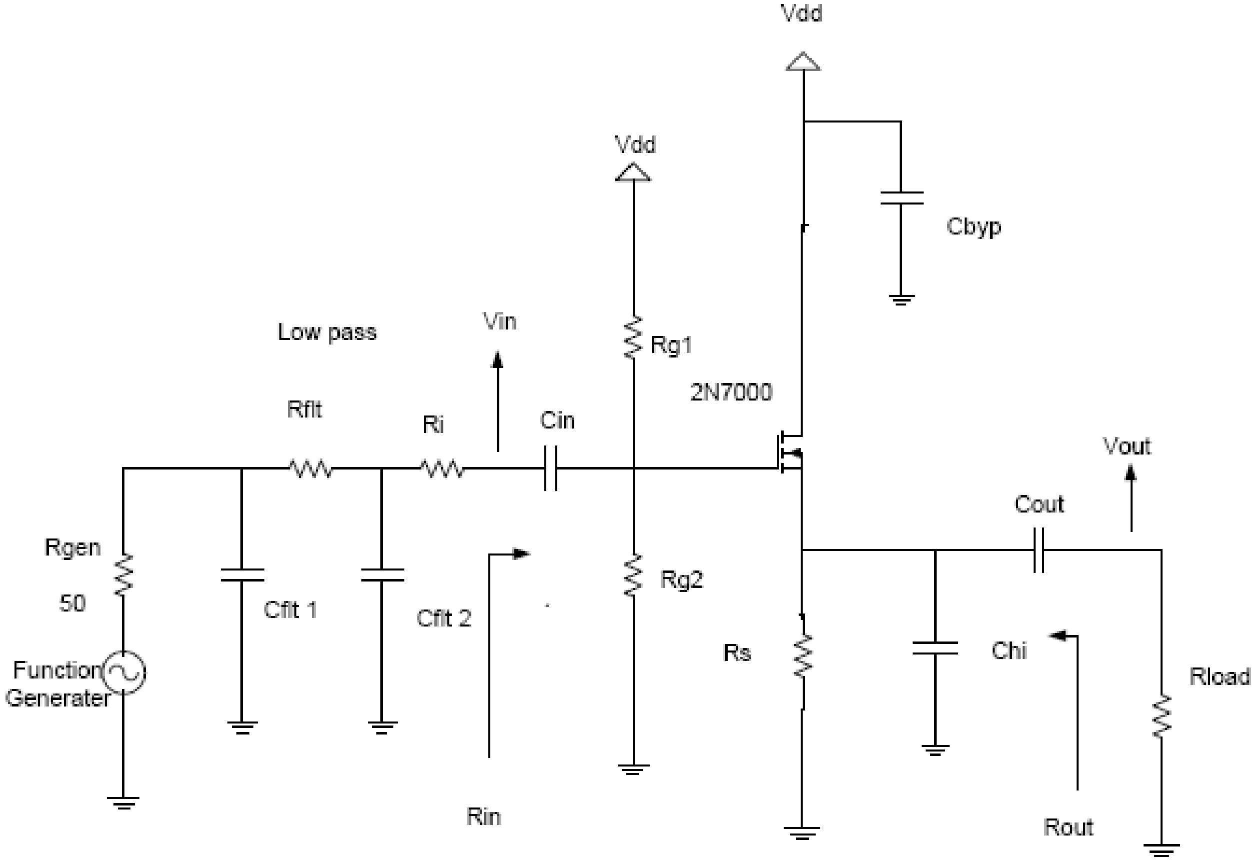


Figure 2: Common Drain MOSFET Amplifier

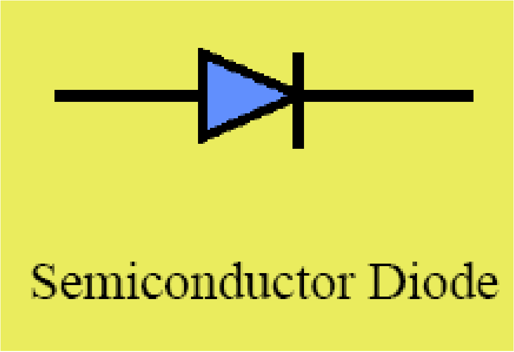
Problems :

Problems :

Problems :

Lecture-10

Basic Electronics:Unit-0



Topics to be covered:

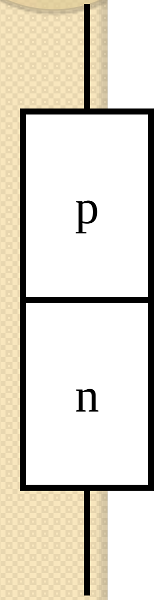
Diode -introduction.

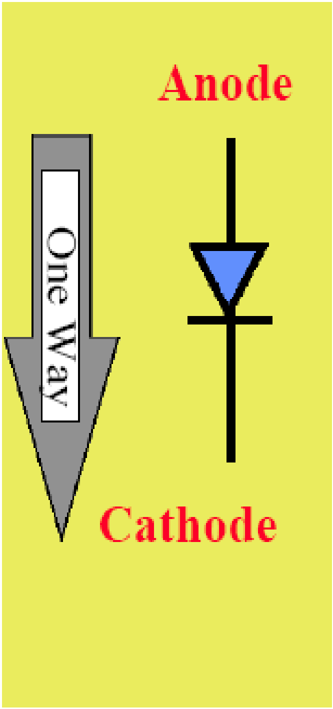
Open circuited p-n junction.

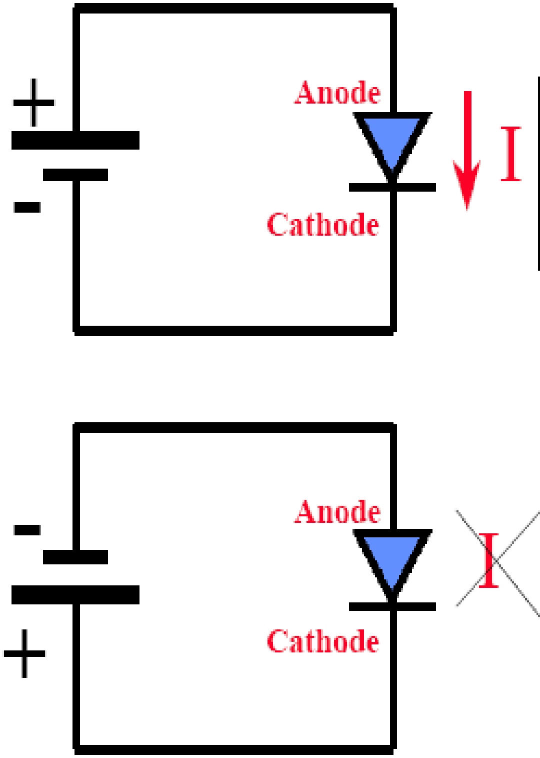
Why diodes?

- R, C, L are linear circuit elements.
- Many signal processing functions need nonlinear elements.
- Diode is the most fundamental nonlinear circuit element.
- Basic function: to allow current to flow only in one direction
- Diode $\longrightarrow$ Di + Electrode

Diode symbol & operation:



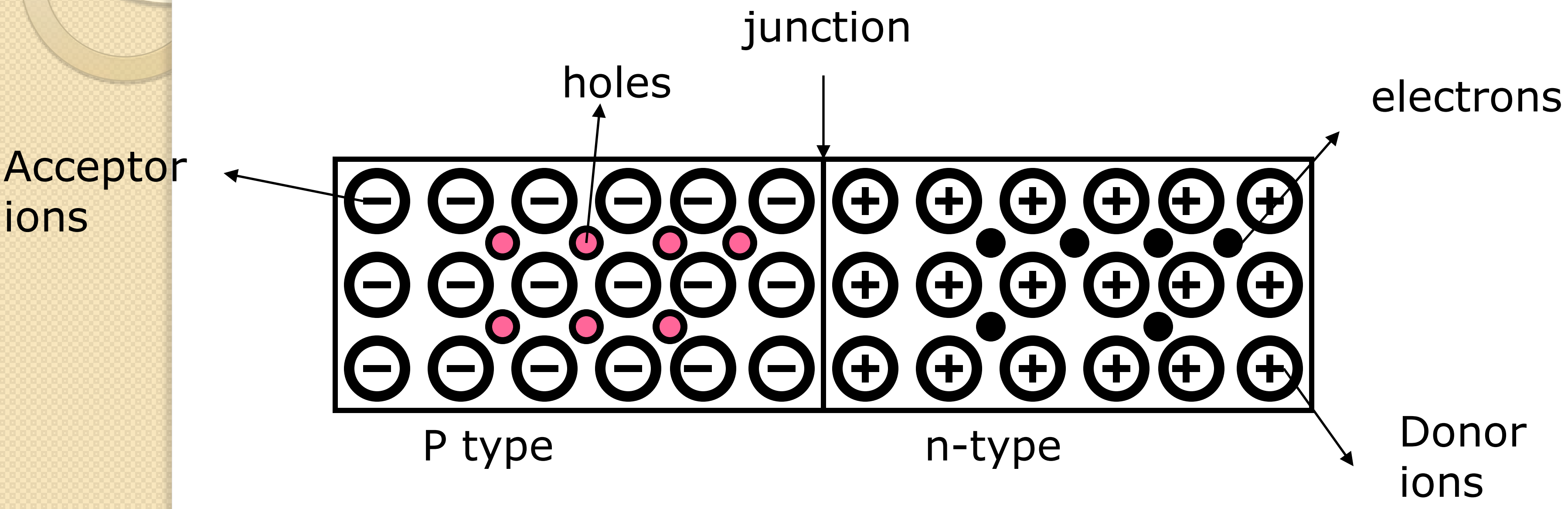




FORWARD BIASED

REVERSE BIASED

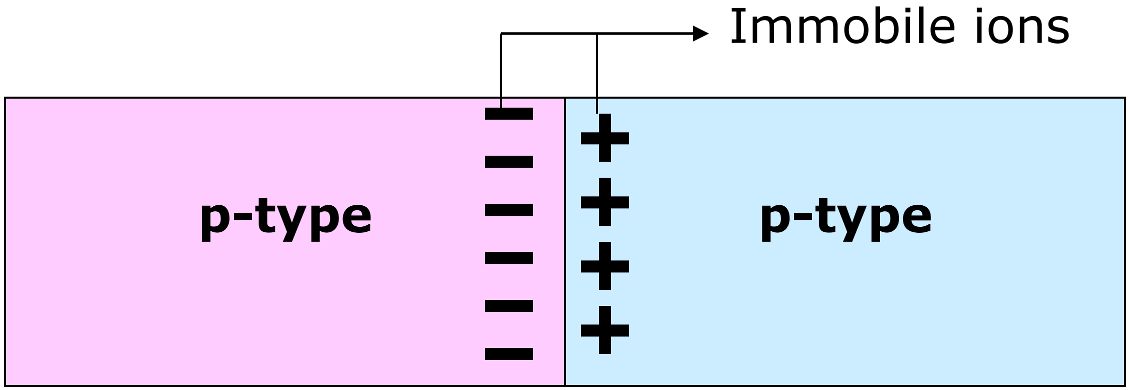
Open circuited p-n junction (formation of depletion region):



- Being free particles, **electrons** start diffusing from n-type material into p-material.
- Being free particles, **holes,** too, start diffusing from p-type material into n-material.
- However, every electrons transfers a negative charge (-q) onto the p-side and also leaves an uncompensated (+q) charge of the donor on the n-side. Every hole creates one positive charge (q) on the n-side and (-q) on the p-side.

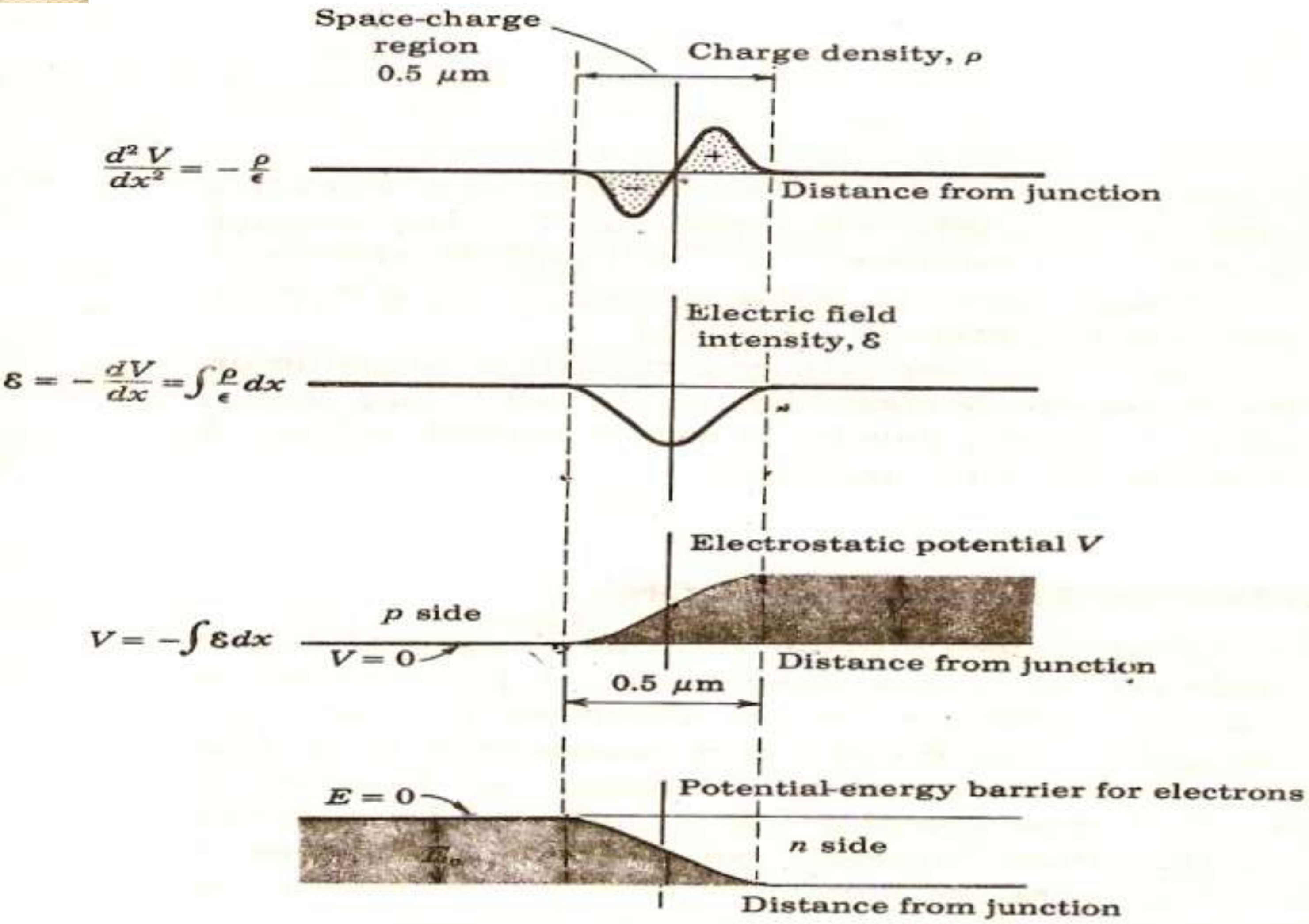
Formation of depletion region:

- Negative charge stops electrons from further diffusion.
- Positive charge stops holes from further diffusion.
- The diffusion forms a dipole charge layer at the p-n junction interface.
- **There is a "built-in" VOLTAGE at the p-n junction interface that prevents penetration of electrons into the p-side and holes into the n-side.**



Defining depletion region:

Thus at eqilibrium there exists a layer of –ve charges in p region & layer of +ve charges in n region near the junction which do not contain any free electron or hole & consist only of immobile ions . This region is called depletion region or space charge region. Its width is generally 0.5 to 1 micron.



Plots of charge density, electric field intensity & potential energy barriers at the junction

Diode applications:

- Rectifiers.
- Clippers.
- Clampers.

………… To be studied later.

Expected questions:

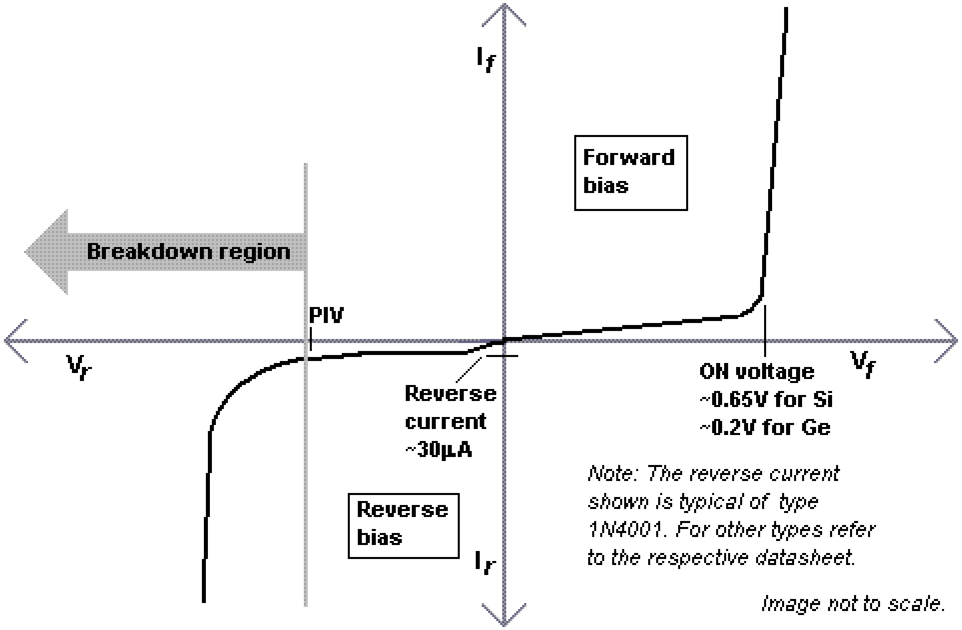
1) Define diode. Draw its symbol & explain its operation.
2) Define depletion region. Explain how it is formed.
3) Draw & explain the waveforms of charge density,Electric field intensity & potential energy barriers of n & p side.

LECTURE 12 :

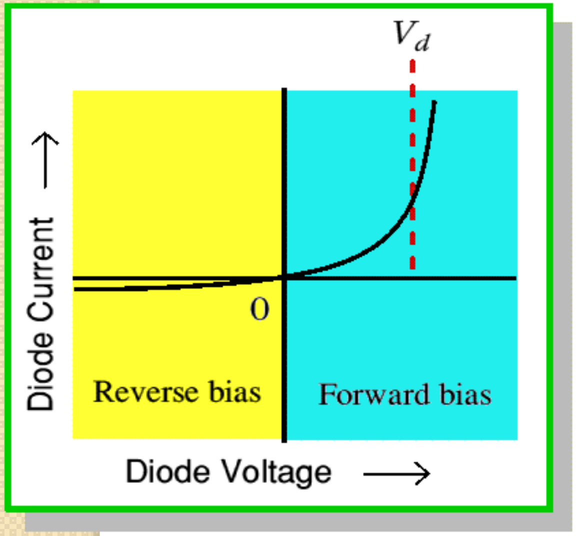
- TOPIC TO BE COVERED :

➢ **Voltage-current characteristics:**

Voltage-current characteristics:



I-V characteristics of P-N diode



Observation :-

* Cut-in voltage for Si & Ge diodes are 0.6 and 0.2v respectevely.

* Breakdown voltage of silicon diode is higher that that of the Ge diode. So SI. Diodes can withstand to a higher reverse voltage.

* The reverse saturation current Io for a Ge diode is few μA at room tempreture.

Temperature dependency of reverse saturation current.

- The *Shockley ideal diode equation* or the *diode law* (named after transistor co-inventor William Bradford Shockley, not to be confused with tetrode inventor Walter H. Schottky) is the I–V characteristic of an ideal diode in either forward or reverse bias (or no bias). The equation is:
- Where
- *I* is $I = I_S\left(e^{V_D/(nV_T)} - 1\right),$

- For even rather small *forward bias* voltages the exponential is very large because the thermal voltage is very small, so the subtracted ‘1’ in the diode equation is negligible and the forward diode current is often approximated as

$$I = I_S e^{V_D/(nV_T)}$$

Lecture 13:

- Topic to be covered :
- **Diode Resistance**
- **The piecewise Linear VI characteristic of a pn diode.**

Diode Resistance

Using the Shockley equation, the small-signal diode resistance *rD* of the diode can be derived about some operating point (Q-point) where the DC bias current is *IQ* and the Q-point applied voltage is *VQ*. To begin, the diode **small-signal conductance** is found, *gD*, that is, the change in current in the diode caused by a small change in voltage across the diode, divided by this voltage change, namely:

$$g_D = \left.\frac{dI}{dV}\right|_Q = \frac{I_0}{V_T} e^{V_Q/V_T} \approx \frac{I_Q}{V_T}$$

- The latter approximation assumes that the bias current *IQ* is large enough so that the factor of 1 in the parentheses of the Shockley diode equation can be ignored. This approximation is accurate even at rather small voltages, because the thermal voltage *VT* ≈ 26 mV at 300K, so *VQ*/*VT* tends to be large, meaning that the exponential is very larg

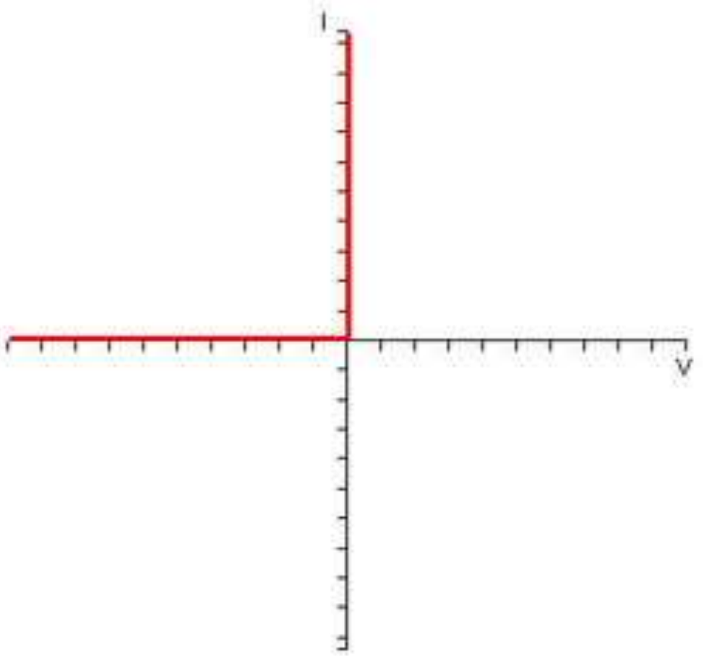
- Noting that the small-signal resistance *rD* is the reciprocal of the small-signal conductance just found, the diode resistance is independent of the ac current, but depends on the dc current, and is given as:

$$r_D = \frac{V_T}{I_Q}$$

The piecewise Linear VI characteristic of a pn diode.

- Firstly, let us consider a mathematically idealized diode. In such an ideal diode, if the diode is reverse biased, the current flowing through it zero. This ideal diode starts conducting at 0 V and for any positive voltage an infinite current flows and the diode acts like a short circuit. The I-V characteristics of an ideal diode are shown below:

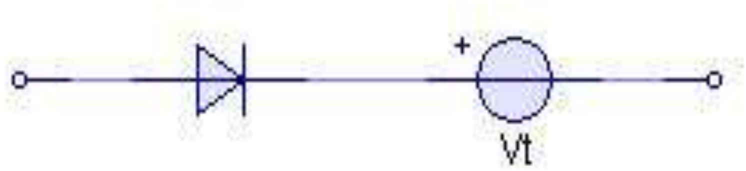
The piecewise Linear VI characteristic of a pn diode.



I-V characteristic of an ideal diode.

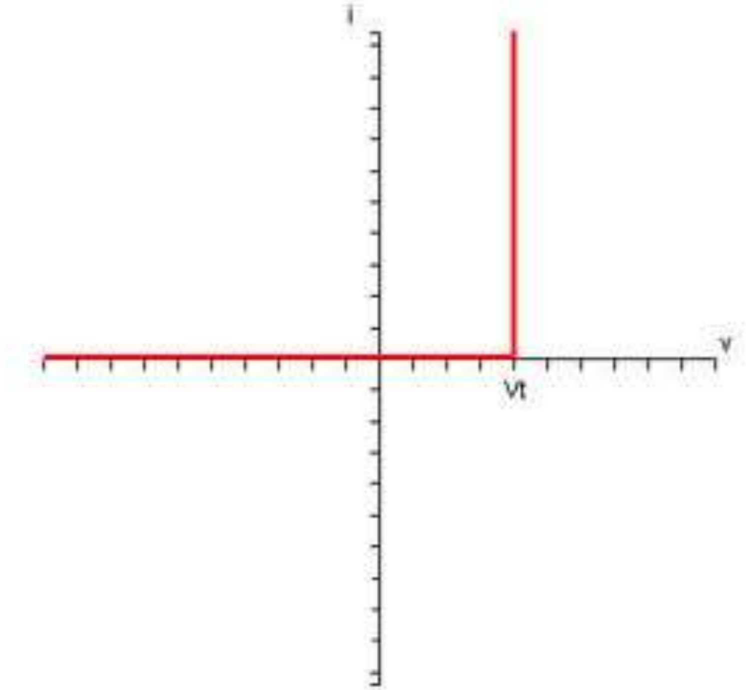
- **Ideal diode in series with voltage source**

  Now let us consider the case when we add a voltage source in series with the diode in the form shown below:



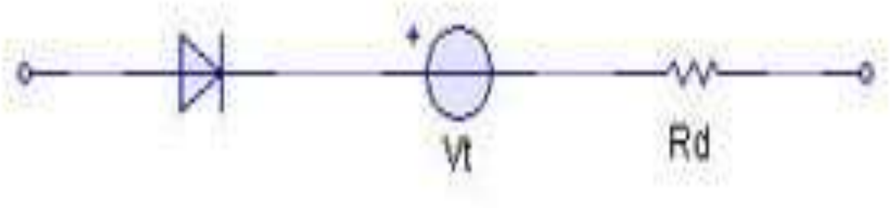
Ideal diode with a series voltage source.

- . In order to get the diode to conduct, the voltage at the anode will need to be taken to *Vt*. This circuit approximates the cut-in voltage present in real diodes. The combined I-V characteristic of this circuit is shown below:



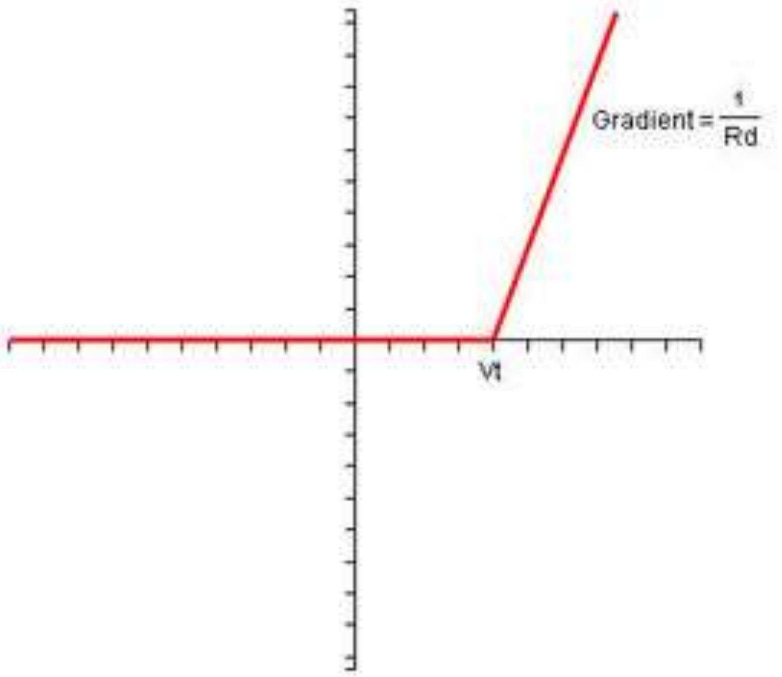
I-V characteristic of and ideal diode with a series voltage source.

- **Diode with voltage source and current-limiting resistor**
- The last thing needed is a resistor to limit the current, as shown below:



Ideal diode with a series voltage source and resistor.

The *I-V* characteristic of the final circuit looks like this:



I-V characteristic of and ideal diode with a series voltage source and resistor.

Capacitance

- The charge in the diode carrying current I_Q is known to be

$$Q = I_Q \tau_F + Q_J$$

- where τ_F is the forward transit time of charge carriers:[2] The first term in the charge is the charge in transit across the diode when the current I_Q flows. The second term is the charge stored in the junction itself when it is viewed as a simple capacitor; that is, as a pair of electrodes with opposite charges on them. It is the charge stored on the diode by virtue of simply having a voltage across it, regardless of any current it conducts.
- In a similar fashion as before, the diode capacitance is the change in diode charge with diode voltage:

$$C_D = \frac{dQ}{dV_Q} = \frac{dI_Q}{dV_Q}\tau_F + \frac{dQ_J}{dV_Q} \approx \frac{I_Q}{V_T}\tau_F + C_J$$

where

$$C_J = \frac{dQ_J}{dV_Q}$$

is the junction capacitance and the first term is called the diffusion capacitance, because it is related to the current diffusing through the junction.

Diffusion capacitance

- **Diffusion** capacitance is the capacitance due to transport of charge carriers between two terminals of a device, for example, the diffusion of carriers from anode to cathode in forward bias mode of a diode or from emitter to base (forward biased junction in active region) for a transistor. In a semiconductor device with a current flowing through it (for example, an ongoing transport of charge by diffusion) at a particular moment there is necessarily some charge in the process of transit through the device. If the applied voltage changes to a different value and the current changes to a different value, a different amount of charge will be in transit in the new circumstances.

- The change in the amount of transiting charge divided by the change in the voltage causing it is the diffusion capacitance. The adjective "diffusion" is used because the original use of this term was for junction diodes, where the charge transport was via the diffusion mechanism.

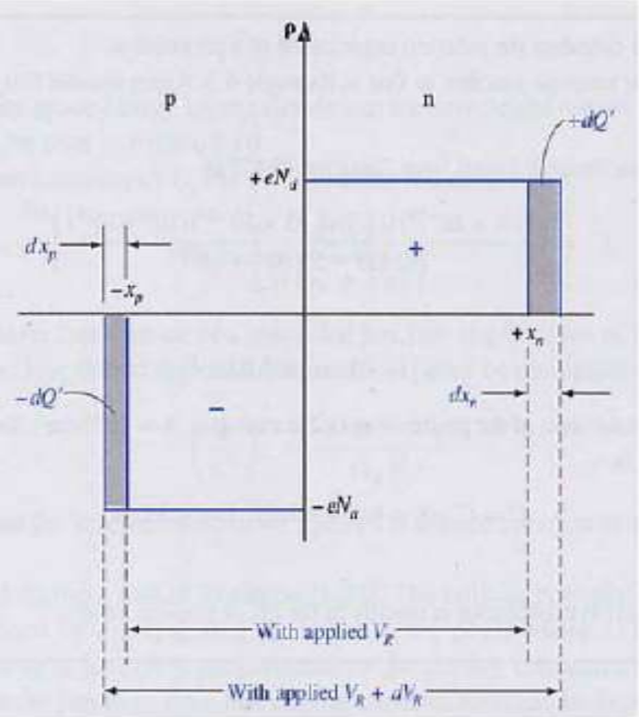
the amount of charge in transit through the device at this particular moment, denoted Q, is given by

$Q = I(V)\tau F$.

Consequently, the corresponding diffusion apacitance:*Cdiff*.is

$$C_{diff} = \frac{dQ}{dV} = \frac{dI(V)}{dV}\tau_F$$

Depletion Capacitance



D.A. Neaman, *Semiconductor Physics & Devices*, 2nd Ed., Irwin

Per unit area

$$C_j = \frac{dQ}{dV} = \frac{qN_D dx_n}{dV} = \frac{qN_A dx_p}{dV} = qN_D \frac{dx_n}{dV}$$

$$x_n = \left[\frac{2\varepsilon_s (V_{bi} - V)}{q}\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A + N_D}\right)\right]^{1/2}$$

$$C_j = \left[\frac{q\varepsilon_s N_A N_D}{2(V_{bi} - V)(N_A + N_D)}\right]^{1/2} = \frac{\varepsilon_s}{W}$$

Similar to a parallel-plate capacitor

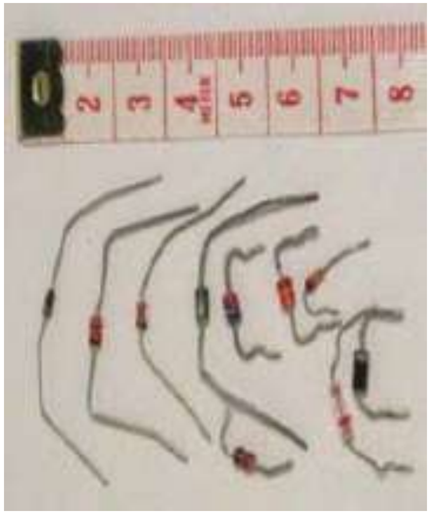
Reverse bias $V = -V_R$

$$C_j = \left[\frac{q\varepsilon_s N_A N_D}{2(V_{bi} + V_R)(N_A + N_D)}\right]^{1/2}$$

PN-junction diodes: Applications

- Diode applications:
  - Rectifiers
  - Switching diodes
  - Zener diodes
  - Varactor diodes

- Photodiodes
  - pn junction photodiodes
  - p-i-n and avalanche photodiodes



- Solar Cells
- Light Emitting Diodes
- Lasers

PN-junction diodes: Applications

- **Solid state lighting, photovoltaic,**
- **photo detection, radio demodulation**
- **over-voltage protection, Logic gates**
- **temperature measurement, etc.**

Lecture 16

- Topic to be covered:

➢ Avalanche & Zener Breakdown

Avalanche & Zener Breakdown :

Avalanche breakdown can occur within insulating or semiconducting solids, liquids, or gases when the electric field in the material is great enough to accelerate free electrons to the point that, when they strike atoms in the material, they can knock other electrons free: the number of free electrons is thus increased rapidly as newly generated particles become part of the process.

- This phenomenon is usefully employed in special purpose semiconductor devices such as the avalanche diode, the avalanche photodiode and the avalanche transistor, as well as in some gas filled tubes

The avalanche process

- Avalanche breakdown is a current multiplication process that occurs only in strong electric fields, which can be caused either by the presence of very high voltages, such as in electrical transmission systems, or by more moderate voltages which occur over very short distances, such as within semiconductor devices.

- As avalanche breakdown begins, free electrons are accelerated by the electric field to very high speeds. As these high-speed electrons move through the material they inevitably strike atoms. If their velocity is not sufficient for avalanche breakdown (because the electric field is not strong enough) they are absorbed by the atoms and the process halts. However, if their velocity *is* high enough, when they strike an atom, they knock an electron free from it, ionizing it

Applications

- In avalanche transistors and avalanche photodiodes, this effect is used to multiply normally tiny currents, thus increasing the gain of the devices: in avalanche photodiodes, current gains of over a million can be achieved
- Also, the phenomenon is very fast, meaning that avalanche current quickly follows avalanche voltage variations or starting charge (number of free electrons available to start the process) variations, and this gives to avalanche transistors and avalanche photodiodes the capability of working in the microwave frequency range and in pulse circuits .

Lecture-02
Basic Electronics:Unit-01

Topics to be covered:

- ✓Commonly used semiconductors.
- ✓Electronic configuration of Ge & Si.
- ✓The energy band theory of crystals.
- ✓The eV unit of energy.

Commonly used semiconductors:

The two most commonly used semiconductors are:

- Germanium.
- Silicon.

Why?

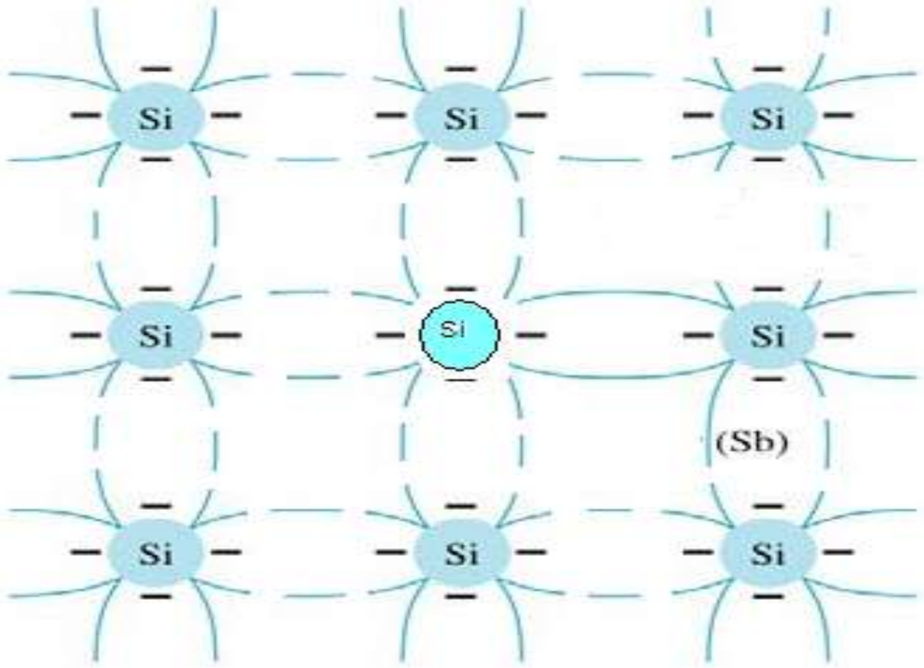
Electronic configuration of Ge & Si:

- The atomic number if Si is 14 & Ge is 32, thus has 4 valence electrons, so that atom is tetravalent.
- Si = $1s^2 2s^2 2p^6 3s^2 3p^2$.
- Ge = $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$.

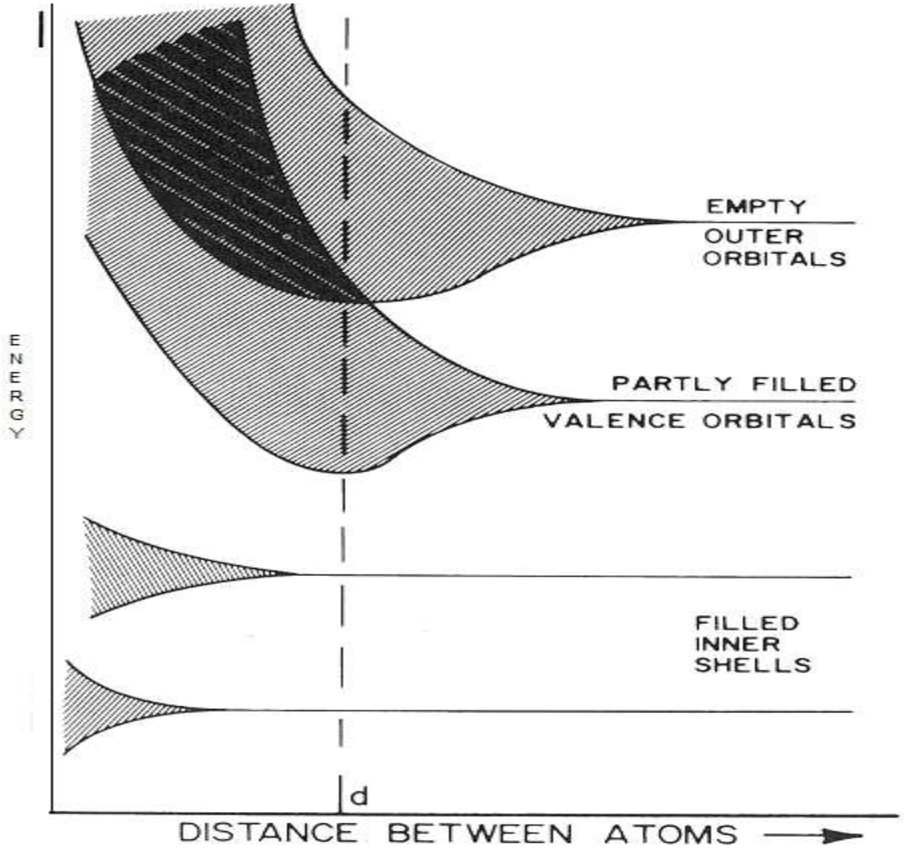
Refer to the crystal structure of silicon in next slide:

- Each valence electron of germanium/silicon is shared by one of its four nearest neighbours.
- A covalent bond is represented by dashed lines.
- Each valence electron is thus tightly bounded to nucleus & hence inspite of availability of four valence electrons the crystal has low conductivity.

Crystal structure of silicon:



Energy band theory of crystals:



The eV unit of energy:

- The unit of work or energy, called electron volt (eV) is defined as follows

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{Joules.}$$

- The name electron volt arises from the fact that if an electrons falls through a potential of one volt, its K.E will increase by decrease in P.E or by

$$qV = (1.6 \times 10^{-19} C)(1V) = 1.6 \times 10^{-19}\ J = 1eV$$

Expected questions:

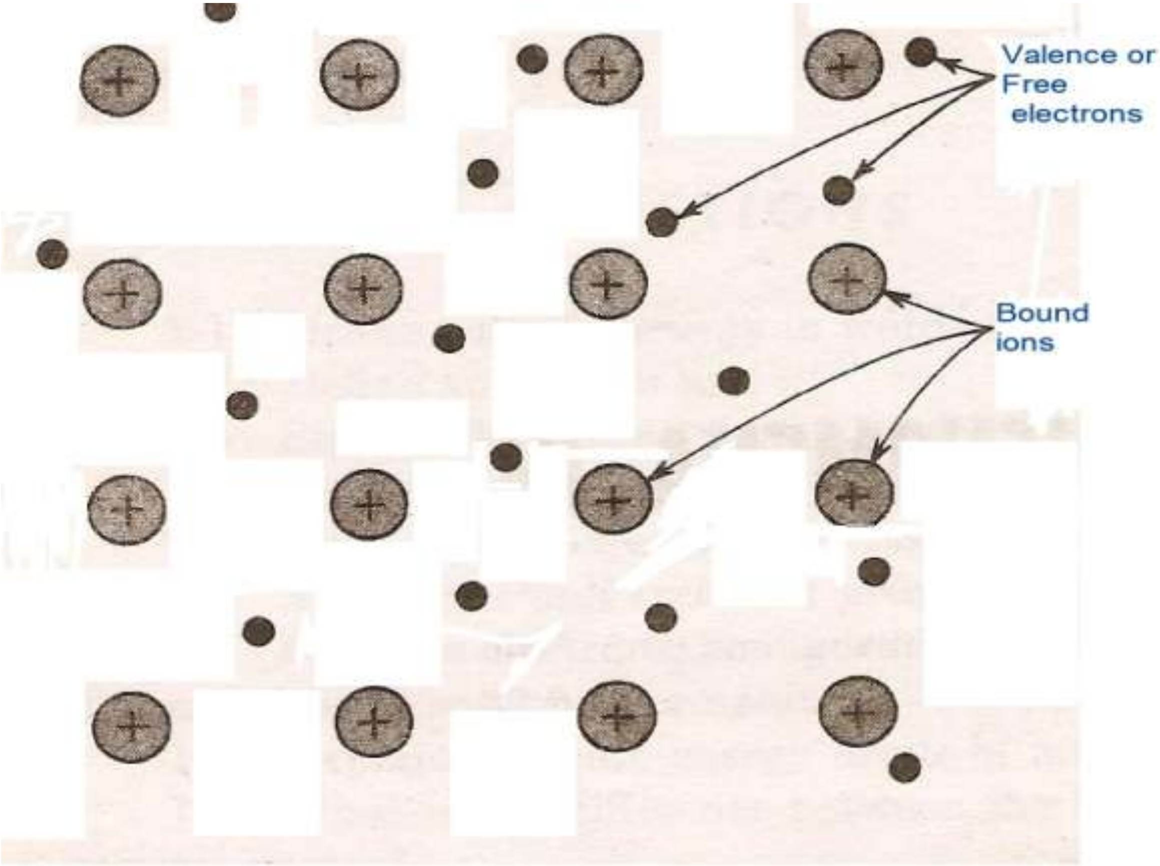
1. Why si & ge are most widely used semiconductors ?
2. Explain why a semiconductors behave like insulators at 0 degree kelvin ?
3. Define an electron volt.
4. Explain the effect of temperature on conductivity of insulator, s/c & metal.

Lecture-03
Basic Electronics:Unit-01

Topics to be covered:

- ✓Electron gas description of metal.
- ✓Mean free path.
- ✓Drift velocity.
- ✓Mobility.
- ✓Current density.
- ✓Conductivity.

Electron gas description of metal:



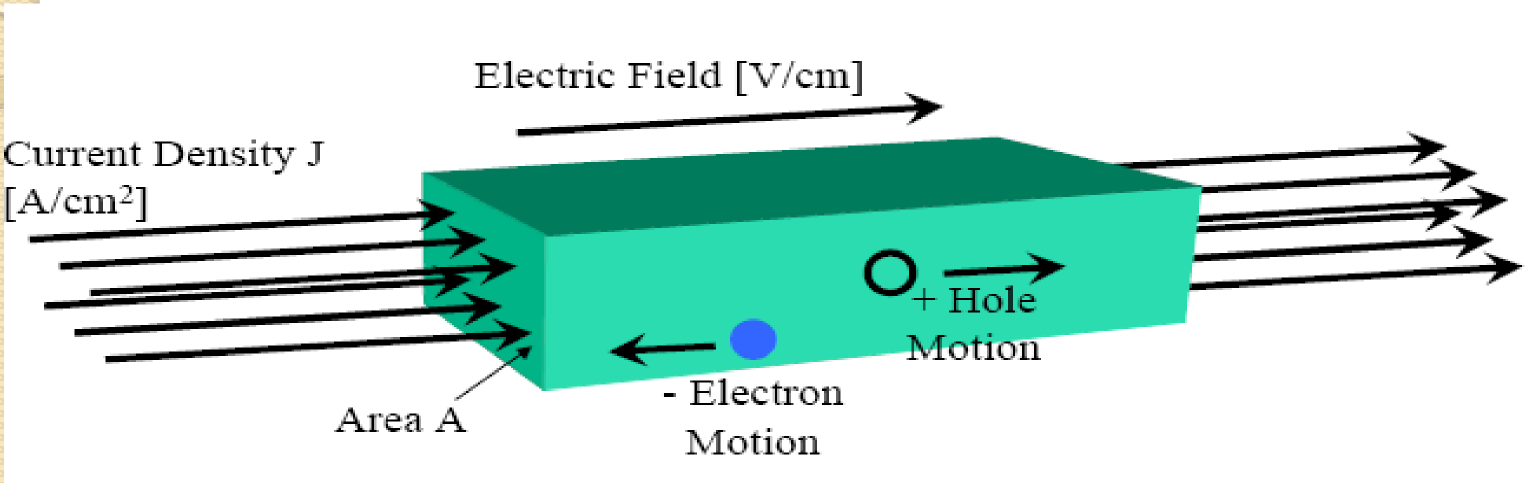
Mean free path:

Refer the fig in last slide:

- Ions are almost stationary.
- Electrons are in continuous motion.
- Thus electrons collide with this ions & their direction changes on each collision.

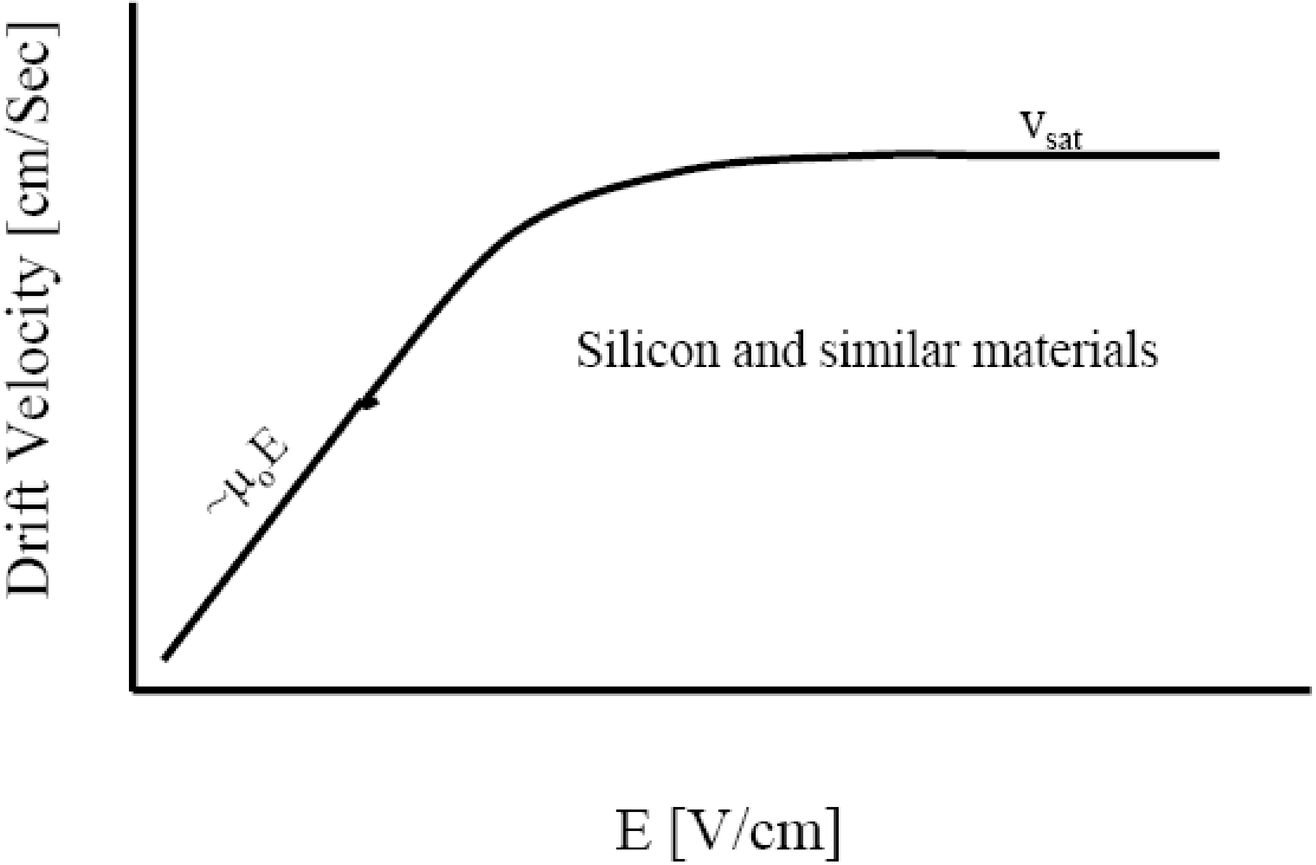
The average distance between each collision is called mean free path.

Drift velocity:



- Holes move in the direction of the electric field (from + to -).
- Electrons move in the opposite direction of the electric field (from - to +).
- Average net motion is described by the drift velocity, v_d with units cm/second.
- Net motion of charged particles gives rise to a current called as drift current
- Thus V_d proportional to applied E.

Drift velocity versus E:



Mobility:

In physics, **electron mobility** (or simply, **mobility**), is a quantity relating the drift velocity of electrons(V_d) to the applied electric field(E) across a material, according to the formula:

$$V_d = \mu E$$

Here μ is the he semiconductor and measures the ease with which carriers can move through the crystal. $[\mu] = cm^2/V\text{-}Second.$

Current density:

J is current per unit area:

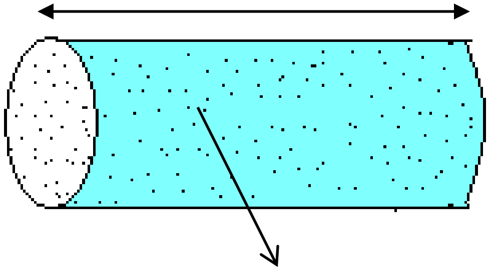
$J = I/A$ ------ (1)

Let the time taken by electrons to travel distance L m is T sec.

Thus I = Total charge/sec   A=area

$= Nq / T = Nqv/L.$

v = drift speed in m/s.



Finally from (1):

$J = Nqv/LA$ ------ (2)

Also the electron concentration n is defined as

n = electrons per volume i.e (e^{-s}/m^3)

$= N/LA$

Thus from (2)

$$\boxed{J = nqv = \rho v}$$

Here $\rho = nq$ is called charge density in Coulombs/m^3

Conductivity:

- Conductivity is defined as ability of a conductor to conduct.
- Current density
- Where

$$J = nqv = nq\mu E = \sigma E \qquad \text{-----(1)}$$

$$\sigma = nq\mu \qquad \text{-----(2)}$$

is called co the metal in (ohm-meter)$^{-1}$.

- From eq^{n} (1) it is clear that conduction current is proportional to applied voltage as stated by Ohm's Law.

Expected questions:

- In a certain wire charge moves past a point in 0.5 second. Find the current in amperes. (Answer: 8 amp).
- Give the electron gas description of metal.
- Define mobility & conductivity & give their dimensions.
- Define mean free path.

Lecture-05 Basic Electronics:Unit-01

Topics to be covered:

✓Electrons & holes (Review).
✓Contribution of hole in conductivity.
✓Intrinsic semiconductors.
✓Extrinsic semiconductors.
✓Doping & dopants (Impurities).
✓Donors (pentavalent impurities).
✓Acceptors (Trivalent impurities).
✓Mass action law.

Electrons & holes in pure s/c:

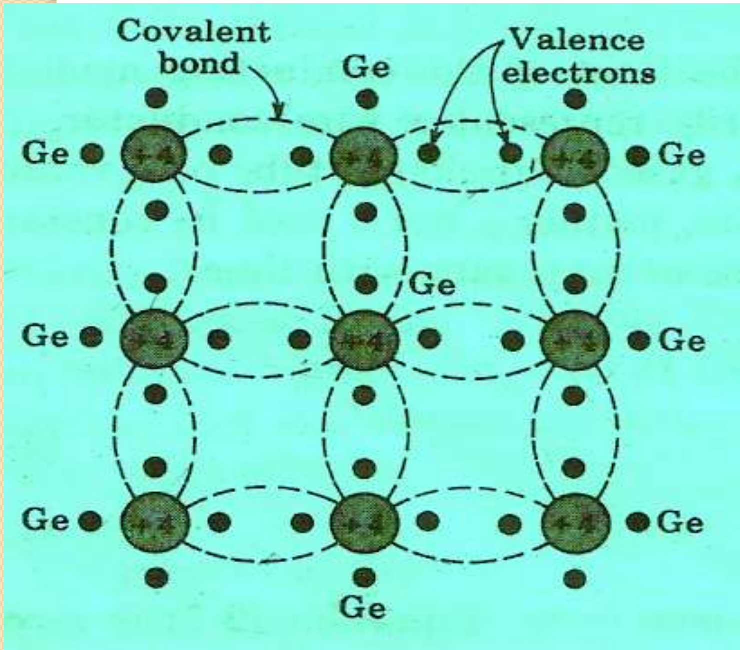
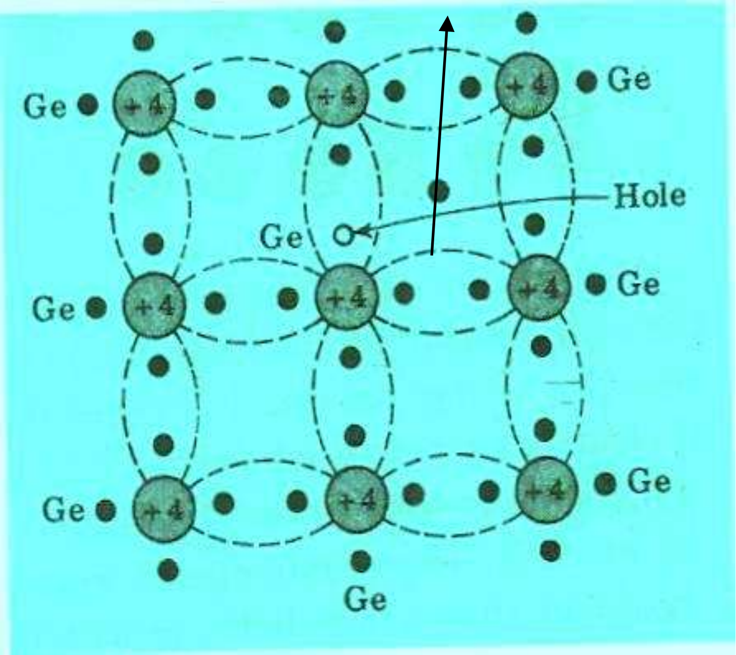


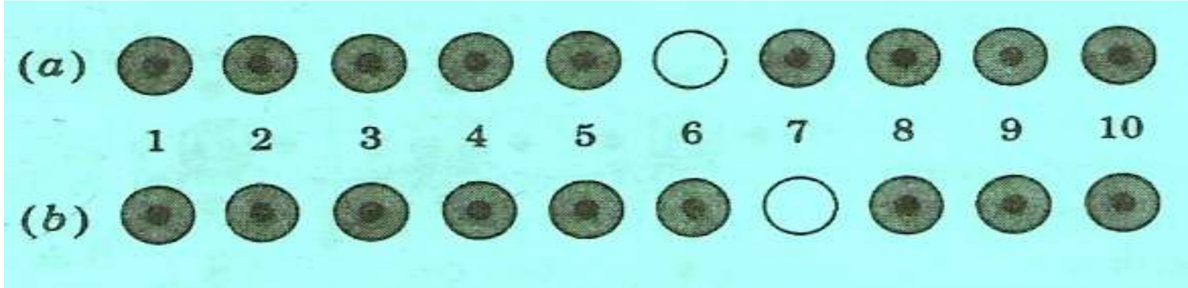
Fig:Crystal structure of Ge



Free electron

Fig: Crystal structure of Ge with broken covalent bond

Contribution of hole to conductivity:



- Any broken bond (hole) makes easier for a valence electron to leave its covalent bond & fill this hole.
- The vacant hole can be further occupied by some other electron.
- Thus the hole moves in a direction opposite to that of electron.

Intrinsic & Extrinsic semiconductors:

- Intrinsic or pure semiconductor:

$$\boxed{n = p = n_i}$$

n_i = intrinsic concentration.

- Extrinsic semiconductors:

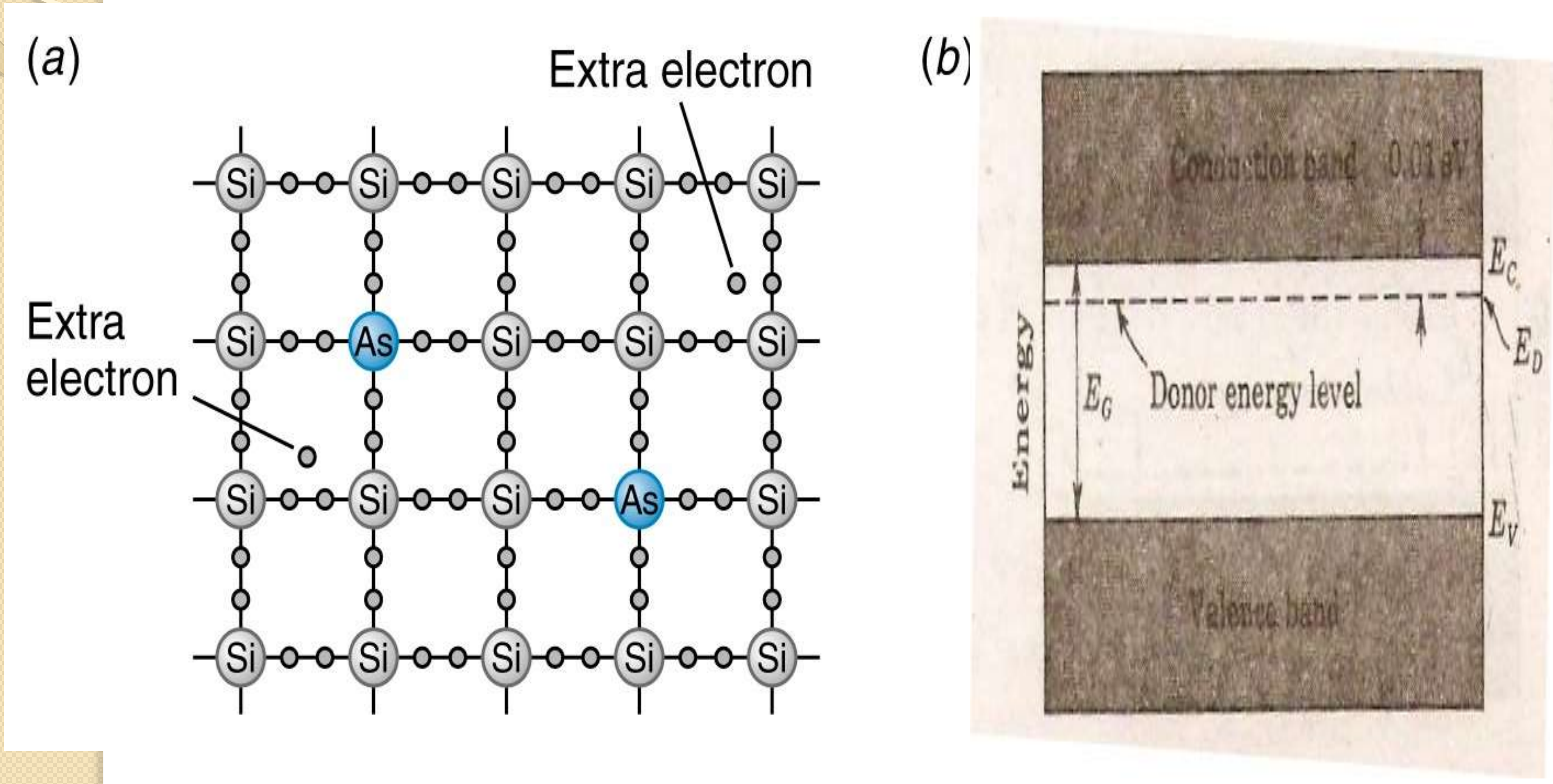
$$\boxed{n \neq p}$$

- Extrinsic s/c are further classified as n-type & p-type semiconductor (depending upon doping).

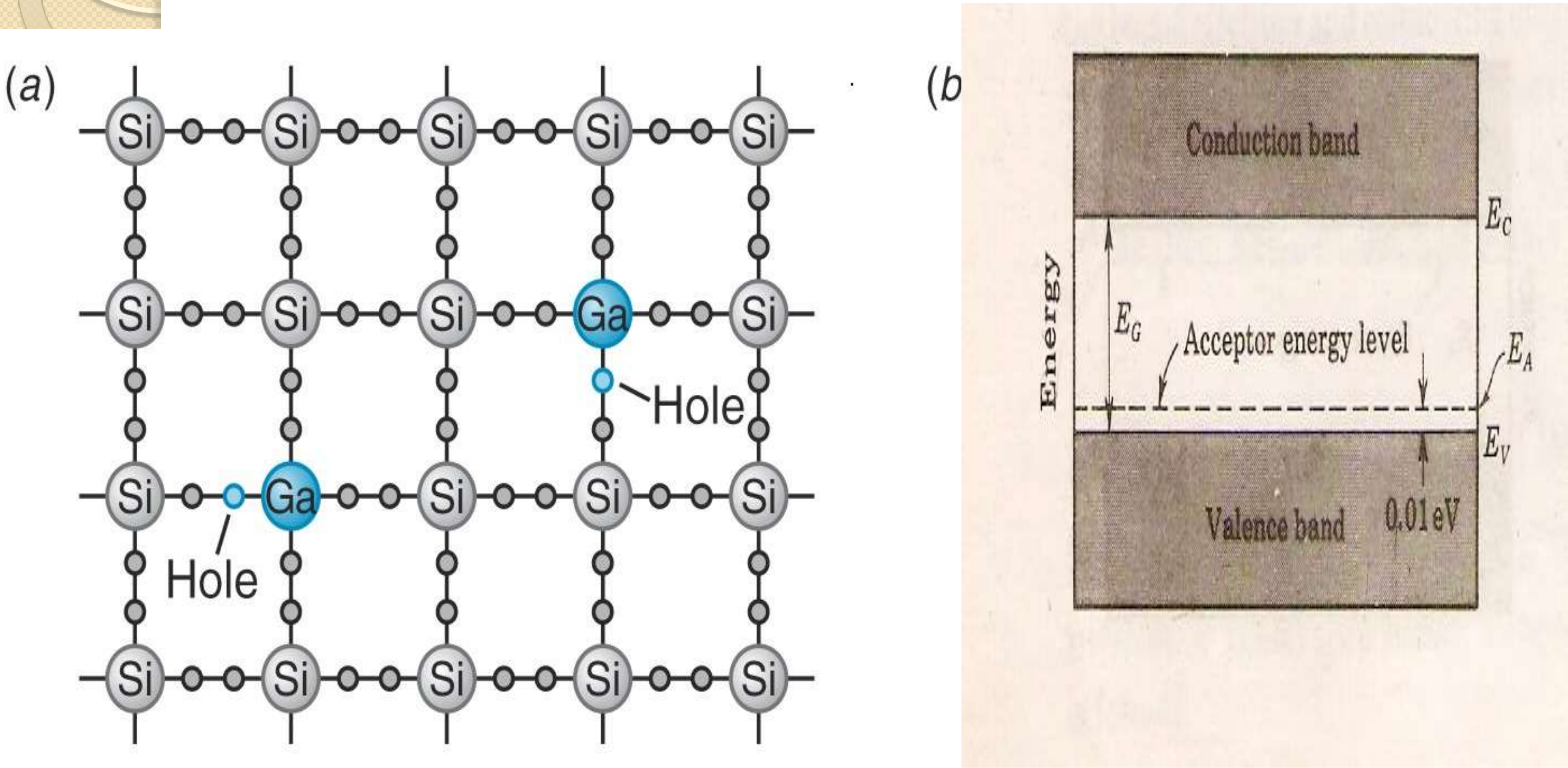
Doping:

- The doping is the process of adding impurity atoms to intrinsic silicon or germanium to improve the conductivity of the semiconductor.
- Increase the conductivity of a semiconductor by adding a small amount of another material called a dopant (instead of heating it!)
- By substituting a semiconductor atom with a special impurity atom (Column V or Column III element), a conduction electron or hole is created.
- Column V – Pentavalent impurity - as they have five valence electrons they create a conduction electron & are called Donors or Donor impurities (antimony, phosphorous & arsenic).
- Column III – Trivalent impurity as - they have three valence electrons they create a conduction hole & are called Acceptors or Acceptor impurities (boron, gallium & indium).

Donor impurities (Pentavalent atoms):



Acceptor impurities (Trivalent atoms):



P-type & n-type semiconductors:

- **p-type semiconductor is created by adding trivalent atoms to an intrinsic semiconductor.**

  Majority carriers: Holes.

  Minority Carriers: Electrons.

- **n-type semiconductor is created by adding pentavalent atoms to an intrinsic semiconductor.**

  Majority carriers: Holes.

  Minority Carriers: Electrons.

- **Commonly used trivalent impurities:**

  Aluminum (Al) **Gallium (Ga)**

  Boron (B) **Indium (In)**

- **Commonly used pentavalent impurities:**

  Phosphorus (P) **Arsenic (As)**

  Antimony (Sb) **Bismuth (Bi)**

Mass action law:

Statement: Under thermal equilibrium, the product of free –ve & +ve concentrations is constant independent of amount of donor & acceptor impurity doping i.e

$$\boxed{n.P = n_i^2}$$

n_i= intrinsic concentration.

Expected questions:

1. Define a electron & hole in a semiconductors.
2. Explain how holes contributes to the process of conductivity ?
3. Define intrinsic concentration of holes. What is the relationship between this density of & intrinsic concentration of electrons ? What do these equal at 0 degree kelvin.
4. Write shortnotes on donor & accptor impurities.
5. State mass action law.

Lecture-06
Basic Electronics:Unit-01

Topics to be covered:

- ✓Charge densities in s/c
- ✓Electrical properties of Ge & Si:
  1. Conductivity .
  2. Intrinsic concentration.
  3. The energy gap.
  4. Mobility.

Charge density in semiconductor:

N_D: ionized donor concentration (cm^{-3})
N_A: ionized acceptor concentration (cm^{-3})

Charge neutrality condition: $N_D + p = N_A + n$

At thermal equilibrium, $np = n_i^2$ ("Law of Mass Action")

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Note: Carrier concentrations depend on *net* dopant concentration (N_D - N_A) !

N-type material:

- In an n-type material the free electron concentration is approximately equal to the density of donor atoms i.e

$$n_n = N_D.$$

- Thus c of holes in n-type s/c using mass action law is:

$$p_n = n_i^2 / N_D.$$

P-type material:

- In an p-type material the free hole concentration is approximately equal to the density of acceptor atoms i.e

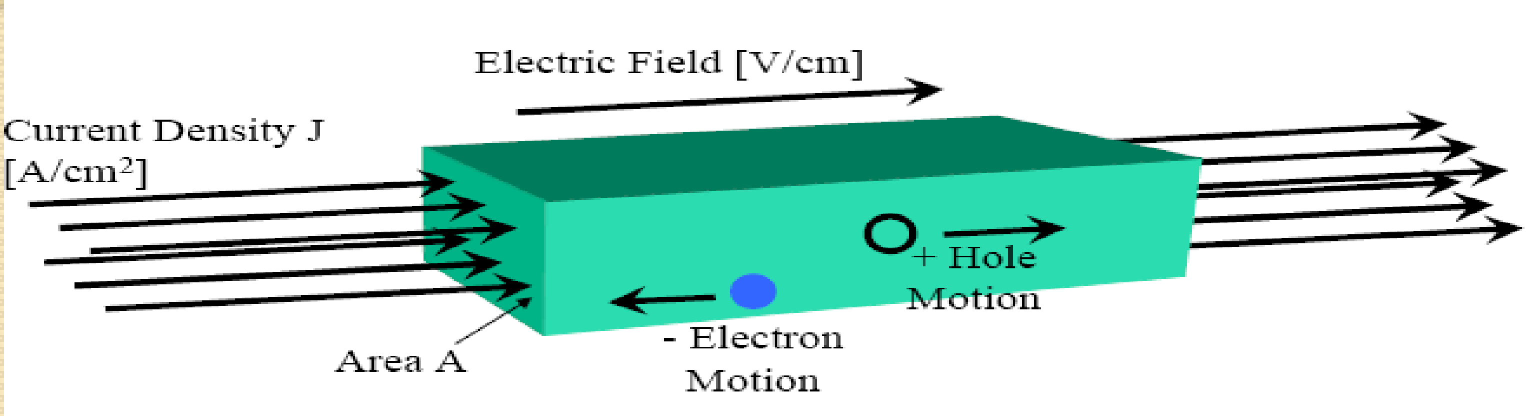
$$p_p = N_A$$

- Thus conce electrons in p-type s/c using mass action law:

$$n_p = n_i^2/N_A$$

Electrical properties of si & ge:

1. Conductivity:



On application of electric field E the electrons & holes move in opposite directions but since they are of opposite sign the net current is in same direction.

Hence J is given by:

$$J = (n\mu_n + p\mu_p)\, qE$$
$$= \sigma E.$$

where $\sigma = (n\mu_n + p\mu_p)\, q$ is the conductivity.

Electrical properties of si & ge:

2. Intrinsic concentration: With increase in temperature the density of hole-electron pair increases & thus conductivity increases. It has been found that n_i varies with temperature T as

$$n_i^2 = A_o T^3 e^{(-EGo / kT)}$$

Where

- E_{Go} is the energy gap at 0 degree kelvin.
- K is Boltzman constant in eV/K & A_0 is constant.

Electrical properties of si & ge:

3. The Energy Gap: The forbidden energy gap depends on temperature. Experimentally it is found that

- $E_G = 1.21 - 3.60 \times 10^{-4} T$ for silicon.

  At room temperature $E_G = 1.1$ eV.

- $E_G = 0.785 - 2.23 \times 10^{-4} T$ for germanium.

  At room temperature $E_G = 0.72$ eV.

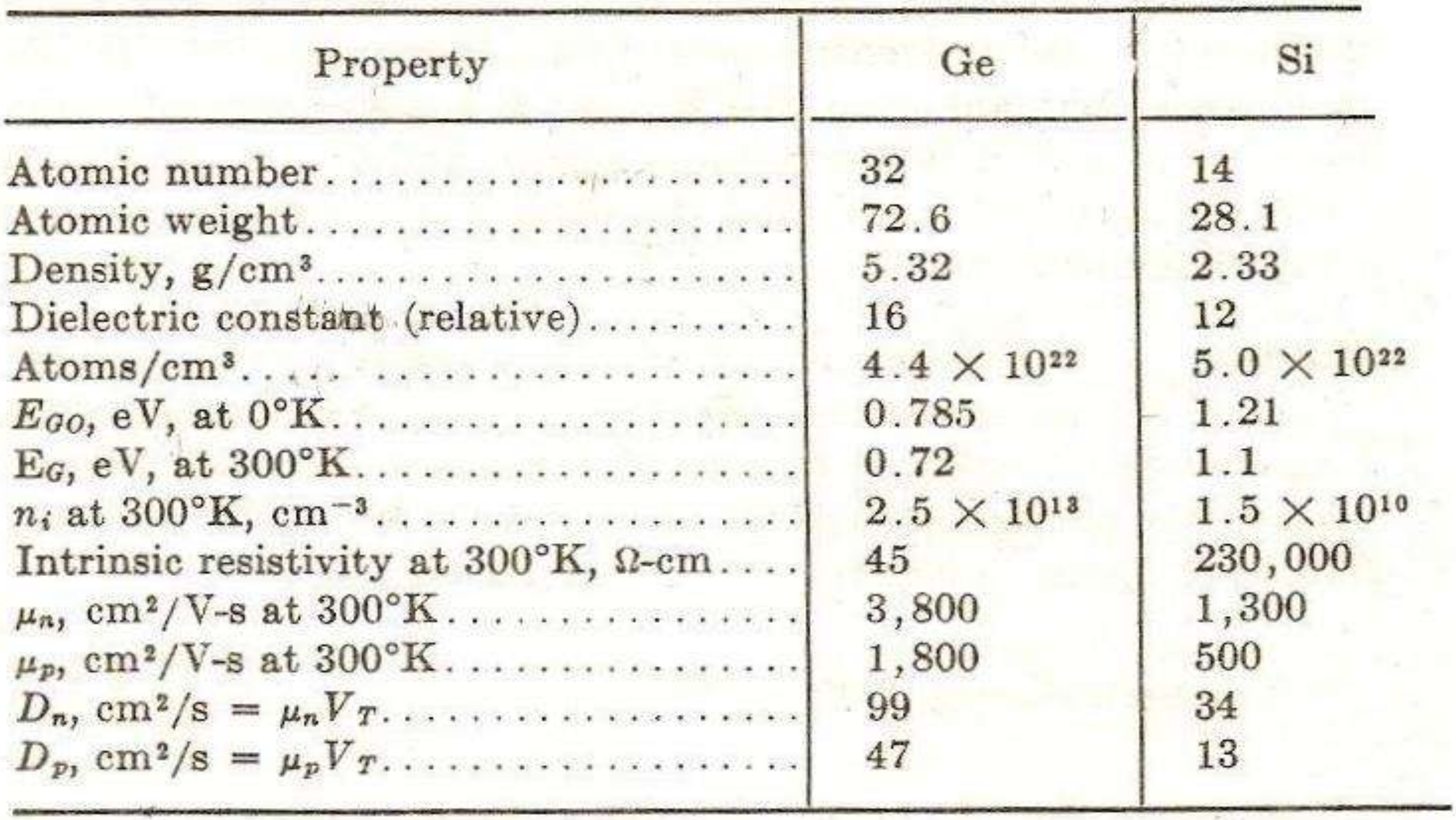
Electrical properties of si & ge:

4. Mobility: For temperature range 100 t0 400 degree K:

$$\mu \propto T^{-m}$$

- For silicon m = 2.5 (2.7) for electrons (holes).
- For germanium m= 1.66 (2.33) for electrons (holes).

properties of silicon & germanium.



Property	Ge	Si
Atomic number	32	14
Atomic weight	72.6	28.1
Density, g/cm^3	5.32	2.33
Dielectric constant (relative)	16	12
Atoms/cm^3	4.4×10^{22}	5.0×10^{22}
E_{GO}, eV, at 0°K	0.785	1.21
E_G, eV, at 300°K	0.72	1.1
n_i at 300°K, cm^{-3}	2.5×10^{13}	1.5×10^{10}
Intrinsic resistivity at 300°K, Ω-cm	45	230,000
μ_n, cm^2/V-s at 300°K	3,800	1,300
μ_p, cm^2/V-s at 300°K	1,800	500
D_n, cm^2/s $= \mu_n V_T$	99	34
D_p, cm^2/s $= \mu_p V_T$	47	13

Expected questions:

1. A semiconductor is doped with donor & acceptor concentration N_D & N_A respectively. Write the equations to determine n & p.
2. Explain the electrical properties of silicon & germanium.

Lecture-07
Basic Electronics:Unit-01

Topics to be covered:

✓Factors on which conductivity depends.

✓Conductivity modulation.
  - Thermistors.
  - Photoconductors.

✓Generation of charge carriers.

✓Recombination of charge carriers.

Conductivity depends on:

- Conductivity is given by the equation:

  $$\sigma = (n\mu_n + p\mu_p)\, q$$

- Conductivity of a s/c is proportional to the concentration of free carriers ‘n’ & ‘p’.

- Conductivity can thus be increased by varying ‘n’ or ‘p’ (conductivity modulation).

Conductivity modulation:

1. Thermistors:

- The conductivity of a ge(si) increases approximately 6(8) percent per degree rise in temperature.
- This feature can be limitation or advantage depending upon application.
- Due to this property of s/c , it is also called (or used) as thermistors.

Conductivity modulation:

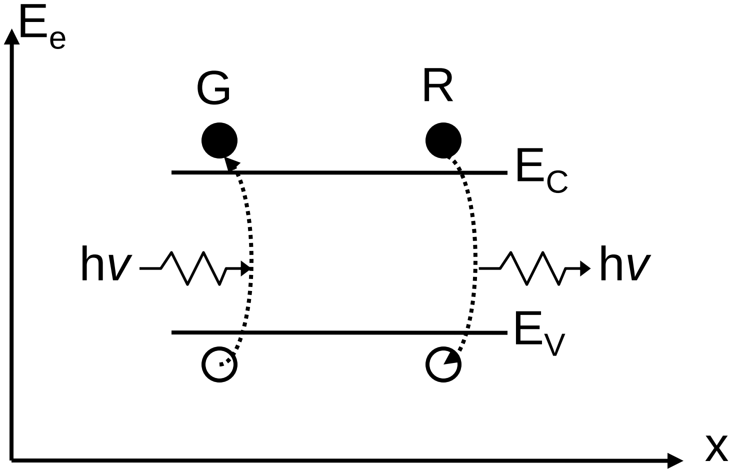
2. Photoconductors:

- ✓ Illuminating the s/c supplies radiant energy to the s/c & thus few covalent bonds are broken resulting in generation of new electron hole pairs.
- ✓ Conductivity increases or the resistance decreases.
- ✓ Are called photoresistors or photoconductors.

Generation & recombination:

- **Generation (G)**:
  How e^- and h^+ are produced or created.

- **Recombination (R)**: How e^- and h^+ are destroyed or removed



Mean life time of charge carrier:

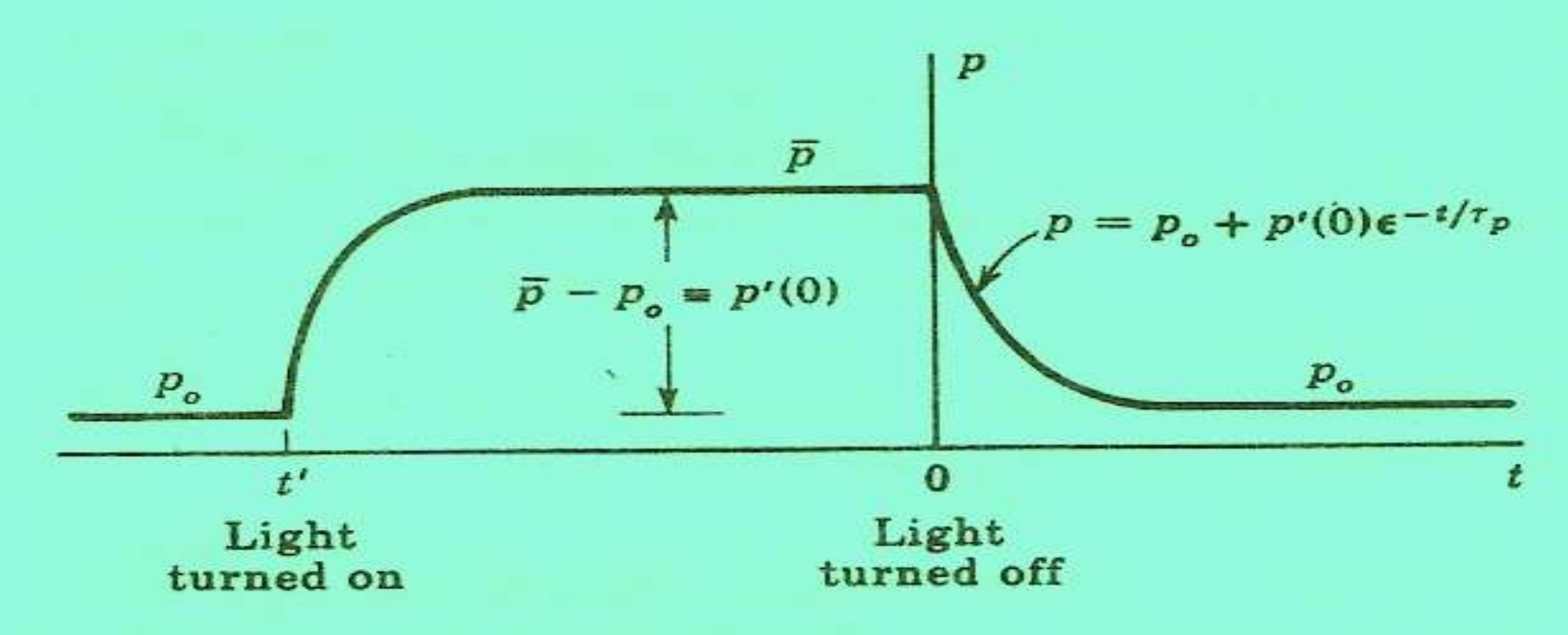
- In pure s/c concentration of electrons is equal to concentration of holes. Due to increase in temperature some new electron-hole pairs are generated. This process is called generation of charge carriers.

- Recombination is a process in where a electron moves from conduction band to valence band & get combined with holes.

- On an average a e^- or a hole exists for T_p or T_n seconds. This time is called mean life time of carrier.

Related derivation:

Consider a bar of n-type silicon containing thermal equilibrium concentration p_o & n_o. The process is illustrated below:



Derivation contd…….

1. At t = t’ the specimen is illuminated & new e^{-} - hole pairs are generated.
2. Since electron-hole pairs are generated thus excess concentration of charge carriers is same.
3. Percentage increase in majority carrier concentration is very less & hence only minority carrier concentration is considered.
4. At t=0, the radiation is removed. It can be shown that hole (minority) concentration decreases exponentially to zero for t > 0 i.e

$$p = p_o + p'(0)\epsilon^{-t/\tau_p}$$

Expected questions:

- Define conductivity modulation.
- Given a intrinsic semiconductor specimen, state two physical process to increase the conductivity.
- Define mean life time of carrier.
- Explain physically the meaning of the following statement: An electron & hole recombine & disappear.
- Radiation falls on a s/c specimen which is uniformily illuminated & a steady state is reached. At t=0, the light is turned off:

  a) Sketch the minority carrier concentration as a function of time for t ≥0.

  b) Define all symbols in the equation describing your sketch.

Lecture-08
Basic Electronics:Unit-01

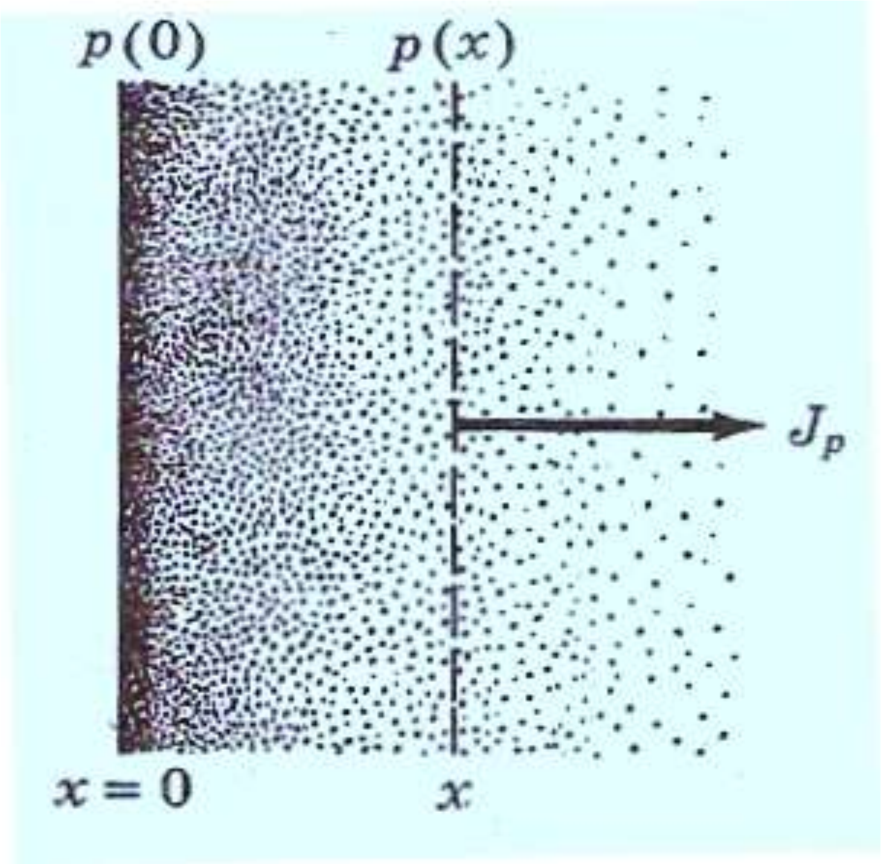
Topics to be covered:

- ✓Diffusion.
- ✓Diffusion current.
- ✓Einstein relationship.
- ✓Equations of total current.

Diffusion:

Current Flow:

- Drift: charged particle motion in response to an electric field.
- Diffusion:Particles tend to spread out or redistribute from areas of high concentration to areas of lower concentration.



Diffusion current:

- In semiconductors, “flow of carriers” from one region of higher concentration to lower concentration results in a “diffusion current”.

- Thus diffusion hole current density

$$J_p \quad -dp/dx$$

$$\propto J_p = -qD_p \, dp/dx \text{ amp/m}^2$$

Where D_p(m^2/sec) is the diffusion constant for holes.Negative sign shows that p decreases with increasing x as shown in figure(slide 2).

- The diffusion electron current density

$$J_n = qD_n \, dn/dx \text{ amp/m}^2$$

Einstein relationship

- According to the Einstein's relation for a s/c, the ratio of diffusion constant (D_P,D_n)to the mobility (μ_P, μ_n) of the charge carriers is constant and equal to volt equivalent of the temperature (V_T).

- $$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

where,

D_p= Diffusion constant for holes in m^2/sec,
D_n= Diffusion constant for electrons in m^2/sec,
μ_p= Holes mobility in m^2/sec,
μ_n = Electrons mobility in m^2/sec,
V_T = Volt equivent of temperature.

Equations of total current

- The total current is the sum of drift current and diffusion current. Thus, for a P- type s/c the total current per unit area,

$$Jp = q.\mu_p.p.E+(-q.Dp.dp/dx)$$
$$= q.\mu_p.p.E-q.Dp.dp/dx$$

- Similarly, for an N-type s/c

$$Jn = q.\ \mu_n.\ n.\ E+(\ -q\ .Dn.dn/dx)$$

$$= q.\ \mu_n.\ n.\ E-q\ .Dn.\ dn/dx$$