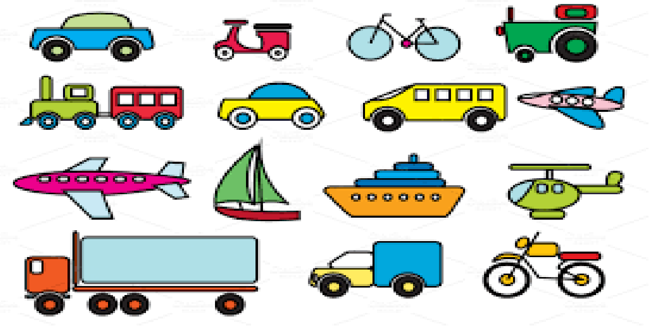
EC203 - Electronic Devices and Circuits-I

Dr. Pavankumar Bikki

COURSE OBJECTIVES

- Study and analyze the behavior of PN junction diodes.
- Characterize the current flow of a bipolar transistor in CB,CE and CC configurations
- Bias the transistors and FETs for amplifier applications.
- Realize simple amplifier circuits using BJT and FET.
- Analyse RC circuits for low pass and high pass filtering
- Understand the Negative Resistance behavior of semiconductor devices

WHY WE NEED TO STUDY?



SEMICONDUCTOR DIODES

- Band structure of pn junction, current components,
- Quantitative theory of pn diode,
- Volt-ampere characteristics and its temperature dependence,
- Narrow-base diode,
- Transition and diffusion capacitance of p-n junction diodes,
- Breakdown of junctions on reverse bias,
- Zener and Avalanche breakdowns.

Electronic Devices and Circuits

Electronic device are widely used in almost all the industries for quality control and automation.

For example:

- Bio-medical applications
- Communication
- Computer's
- Aerospace etc.

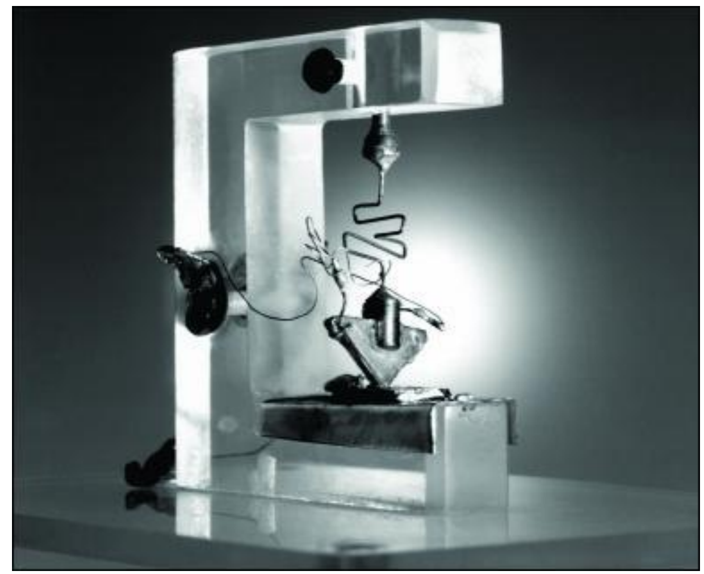
Electronic Devices and **Circuits**

- **Circuits:** Consisting an active and passive elements.
- **Active Elements:** BJT, MOSFET, Op-amp etc.
- **Passive Elements:** Resistor, capacitor and inductors

The Start of the Modern Electronics Era

It can be said that the invention of the transistor and the subsequent development of the microelectronics have done more to shape the modern era than any other invention.

Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.



The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world

Electronics Milestones

1874 Braun invents the solid-state rectifier

1906 DeForest invents triode vacuum tube.

1907-1927 First radio circuits developed from diodes and triodes.

1925 Lilienfeld field-effect device patent filed.

1947 Bardeen and Brattain at Bell Laboratories invent bipolar transistors.

1952 Commercial bipolar transistor production at Texas Instruments.

1956 Bardeen, Brattain, and Shockley receive Nobel prize.

1961 First commercial IC from Fairchild Semiconductor

1968 First commercial IC op-amp

1970 One transistor DRAM cell invented by Dennard at IBM.

1971 4004 Intel microprocessor introduced.

1978 First commercial 1-kilobit memory.

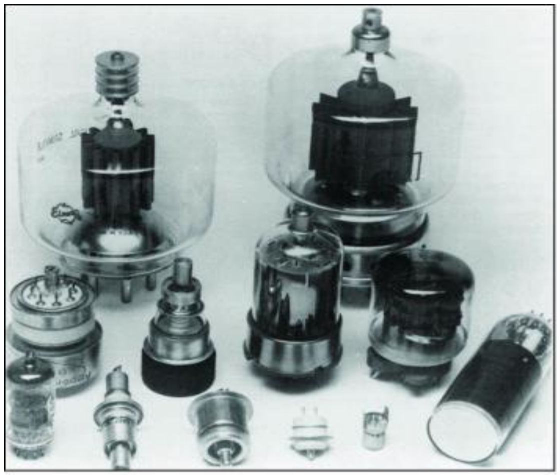
1974 8080 microprocessor introduced.

1984 Megabit memory chip introduced.

1995 Gigabite memory chip presented.

Evolution of Electronic Devices

Vacuum Tubes



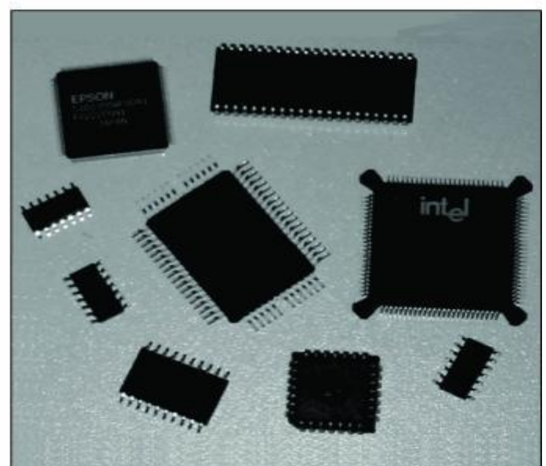
(a)

(b)

Discrete Transistors

SSI and MSI Integrated Circuits

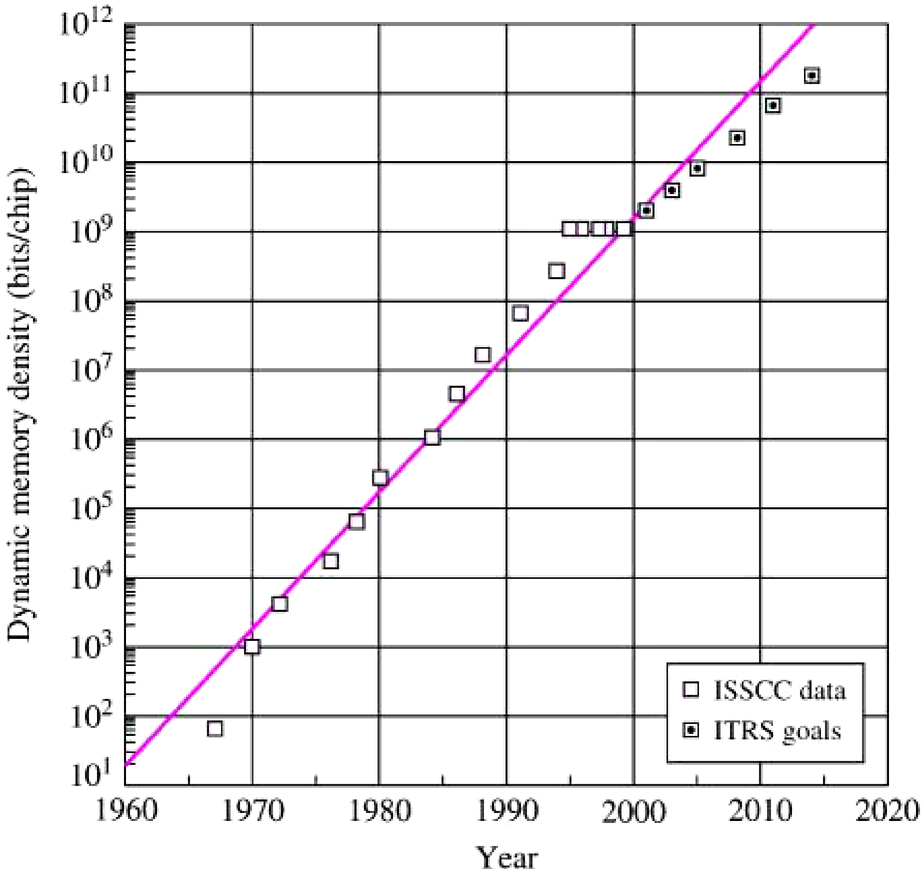
(c)



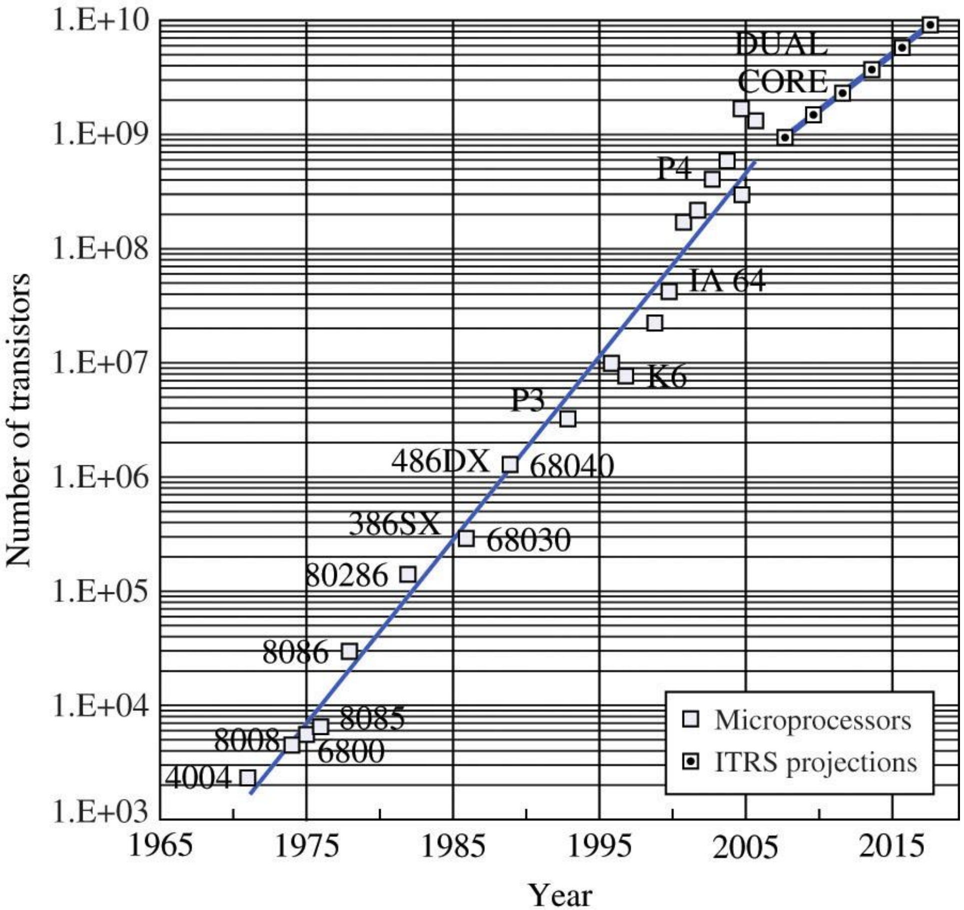
(d)

VLSI Circuits

Rapid Increase in Density of Microelectronics

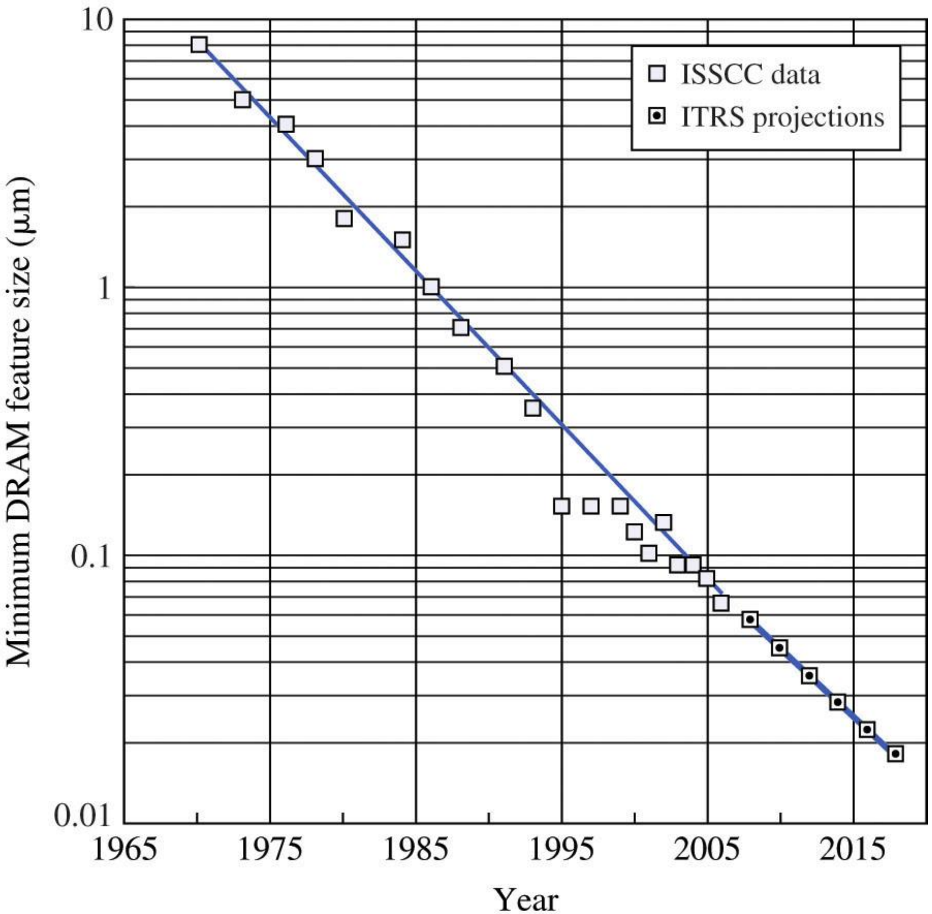


Memory chip density versus time.



Microprocessor complexity versus time.

Device Feature Size

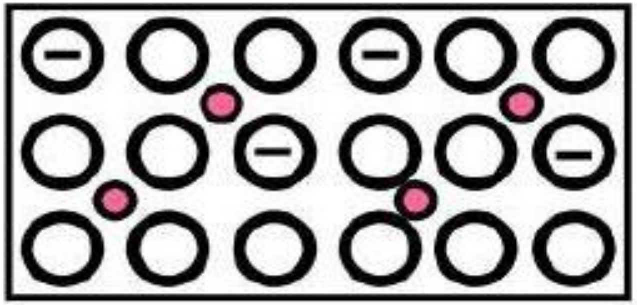


- Feature size reductions enabled by process innovations.
- Smaller features lead to more transistors per unit area and therefore higher density.
- SSI – small scale integration (< 10^2)
- MSI – medium SI (10^{2}- 10^3)
- LSI – large SI (10^{3}- 10^4)
- VLSI – very large SI (10^{4}- 10^9)
- ULSI & GSI– ultra large SI & giga-scale integration (> 10^9)

Introduction

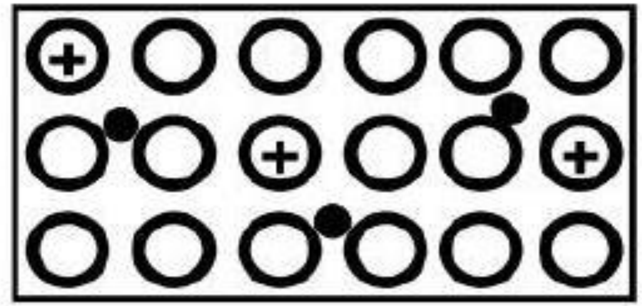
- So far we learned the basics of semiconductor physics, concluding in the **Minority Carrier Diffusion Equation**
- We now encounter our simplest **electronic device**, a diode
- Understanding the principle requires the ability to draw band-diagrams
- Making this quantitative requires ability to solve MCDE (only exponentials!)
- Here we only do the equilibrium analysis

P-N Junction Formation



<u>**p-type material**</u>

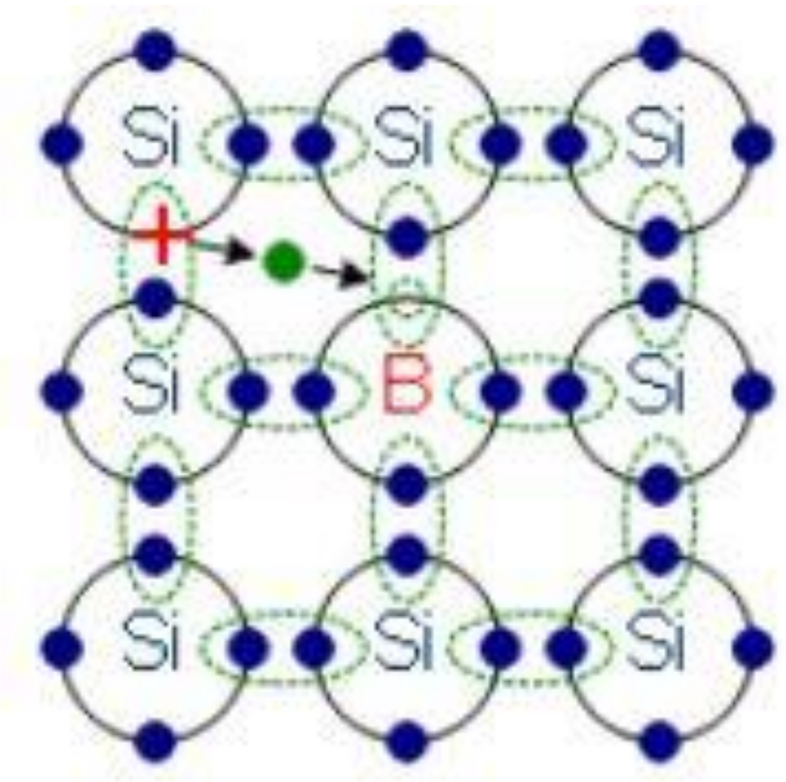
- Semiconductor material doped with **acceptors**.
- Majority carrier are **holes**
- Material has **high hole** concentration
- Concentration of **free electrons** in p-type material is **very low**.
- Contains **NEGATIVELY** charged acceptors (immovable) and **POSITIVELY** charged holes (free)
- Total charge = 0



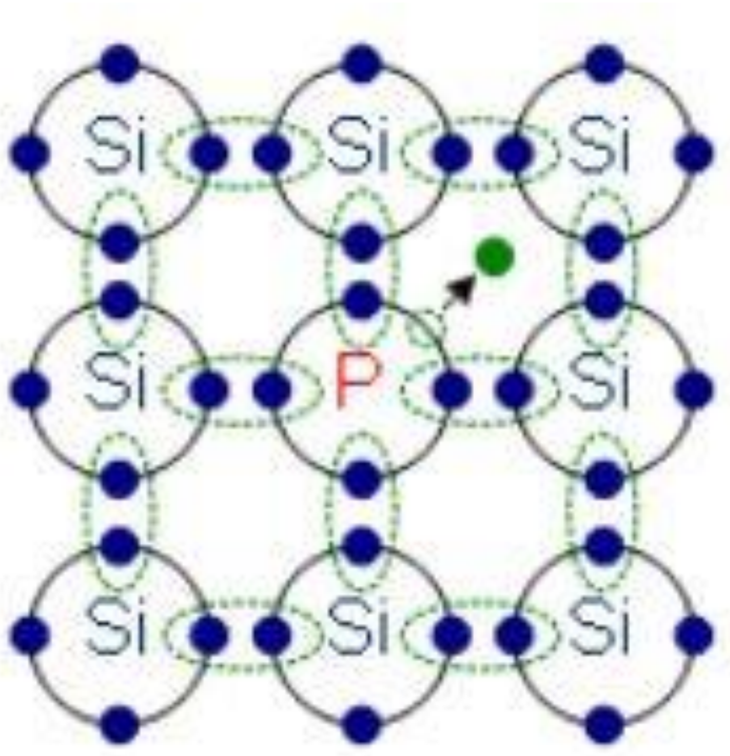
<u>**n-type material**</u>

- Semiconductor material doped with **donors**.
- Majority carrier are **electron**
- Material has high concentration of **free electrons**.
- Concentration of **holes** in n-type material is **very low**.
- Contains **POSITIVELY** charged donors (immovable) and **NEGATIVELY** charged free electrons.
- Total charge = 0

Doping



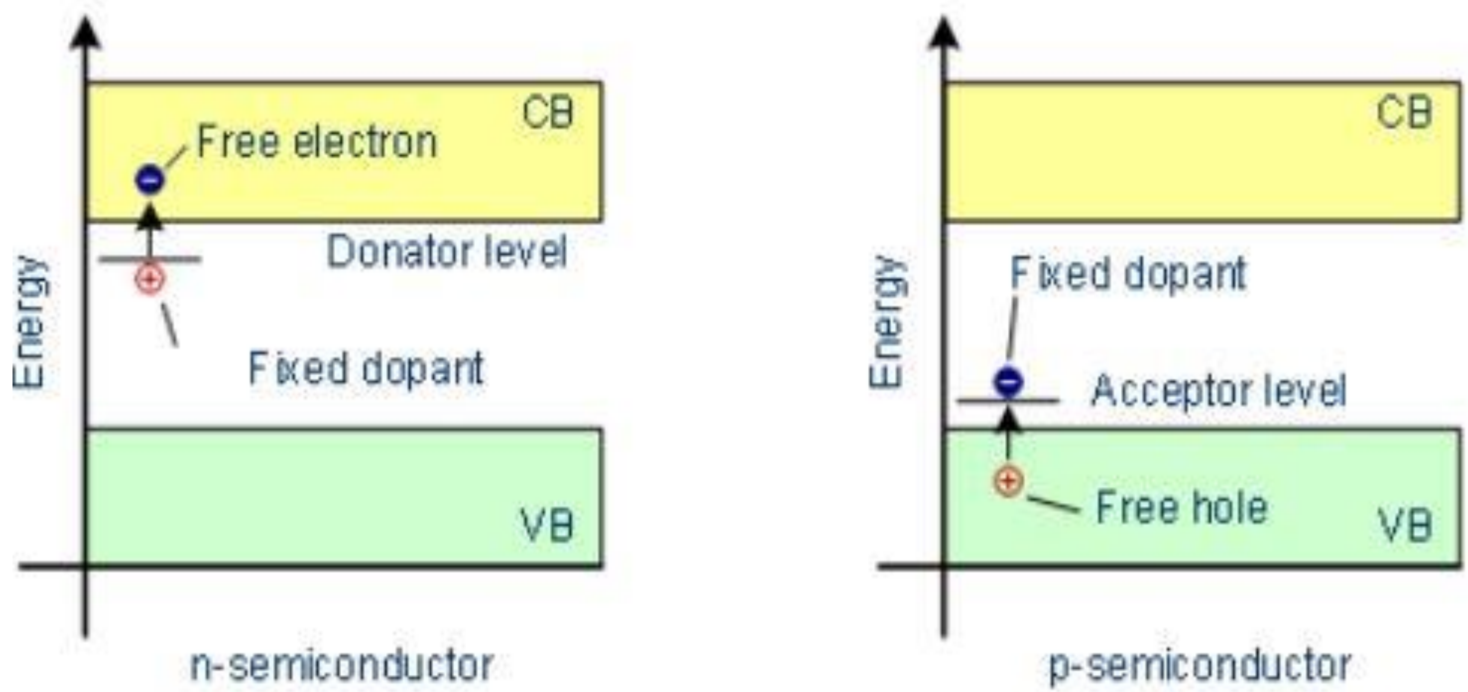
p-doping with boron



n-doping with phosphorus

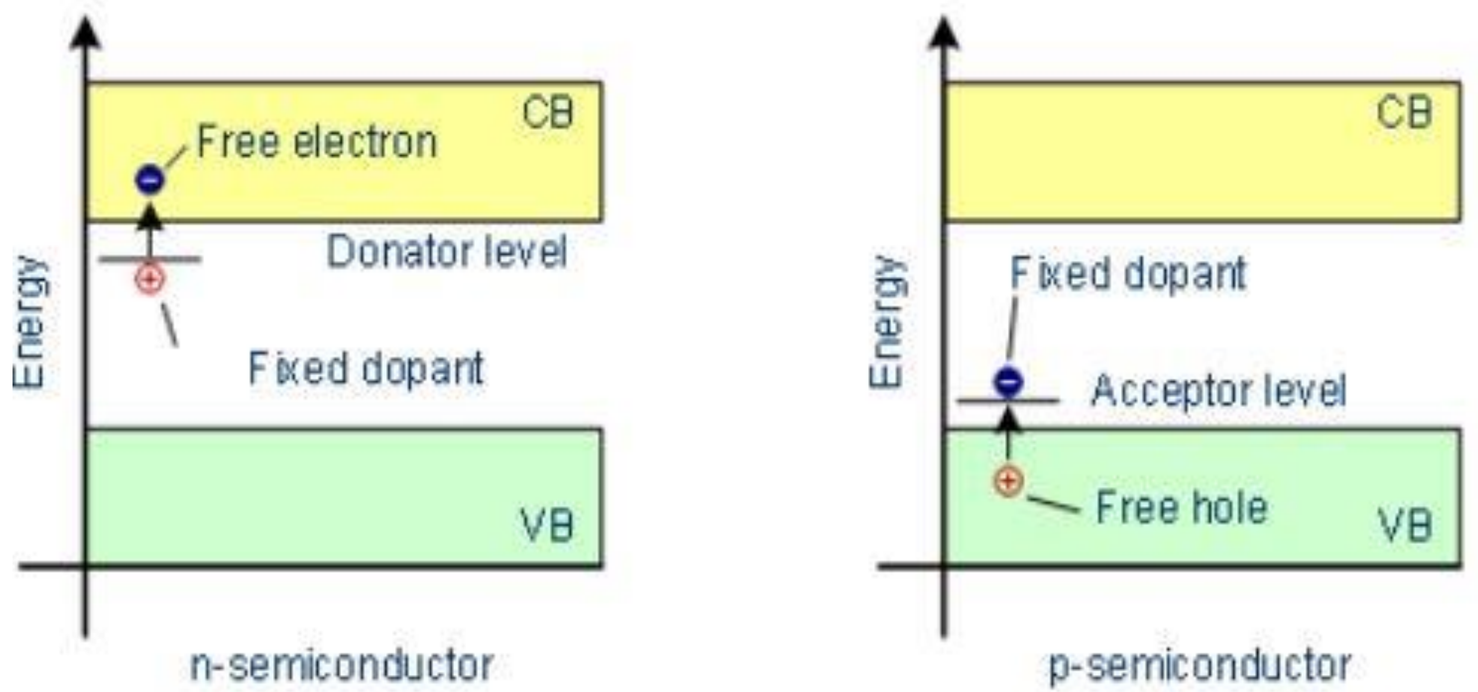
Band model of doped semiconductors

- dopant with five outer electrons, in n-doped semiconductors there is an electron in the crystal which is not bound and therefore can be moved with relatively little energy into the conduction band.
- n-doped semiconductors the donator energy level is close to the conduction band edge, the band gap to overcome is very small.



Band model of doped semiconductors

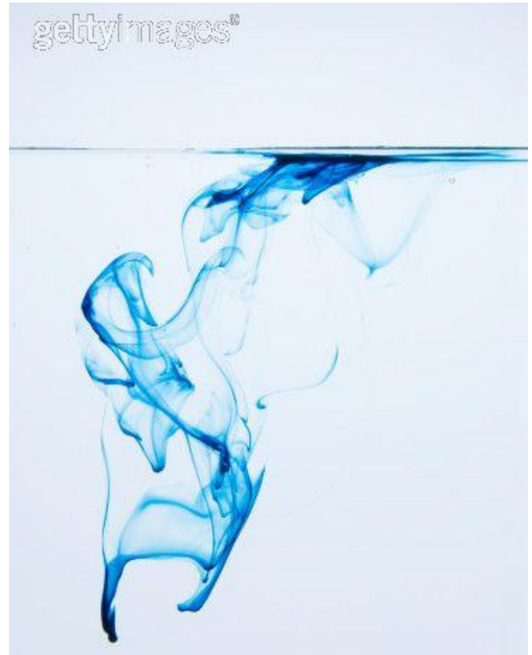
- Analog, through introduction of a 3-valent dopant in a semiconductor, a hole is available, which may be already occupied at low-energy by an electron from the valence band of the silicon.
- For p-doped semiconductors the acceptor energy level is close the valence band.



P-N Junction Formation

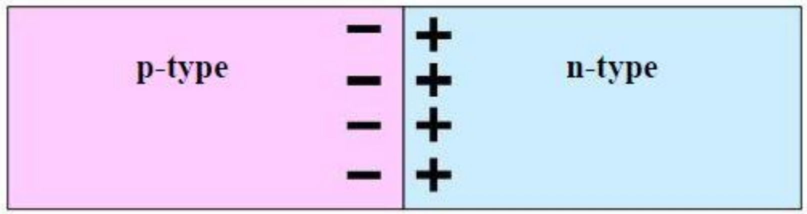
- **What happens if n- and p-type materials are in close contact?**
- Being free particles, **electrons** start diffusing from n-type material into p-material and Being free particles, **holes,** too**,** start diffusing from p-type material into n-material
- eventually all the free electrons and holes had **uniformly distributed** over the entire compound crystal.
- 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) **negative charge** on the p-side

Gradients drive diffusion

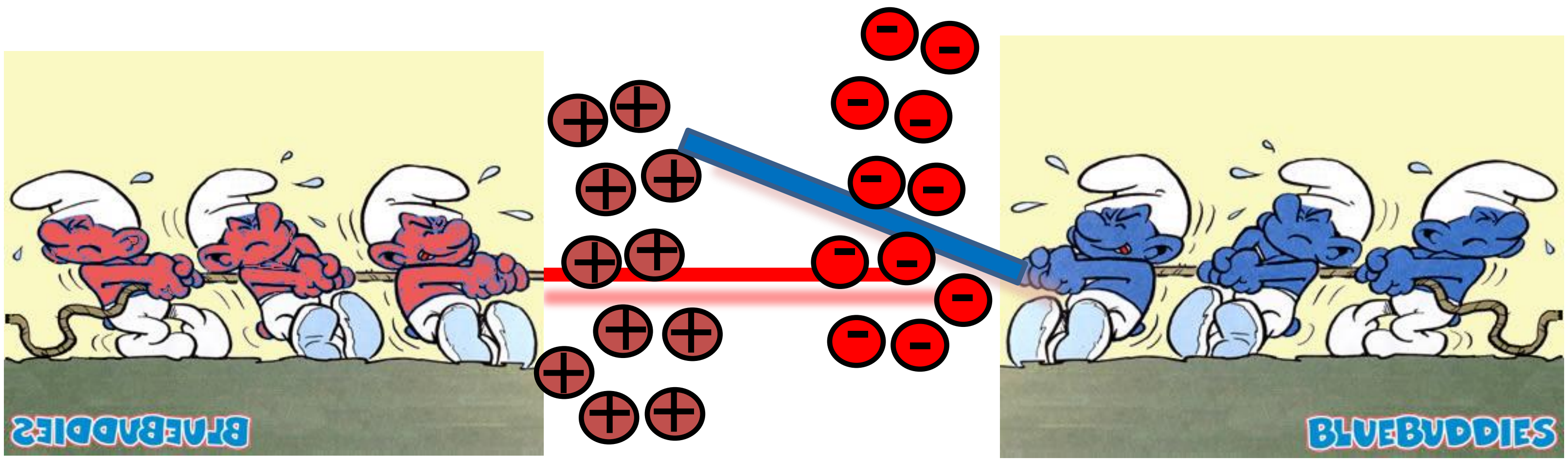


P-N Junction Formation

- **What happens if n- and p-type materials are in close contact?**



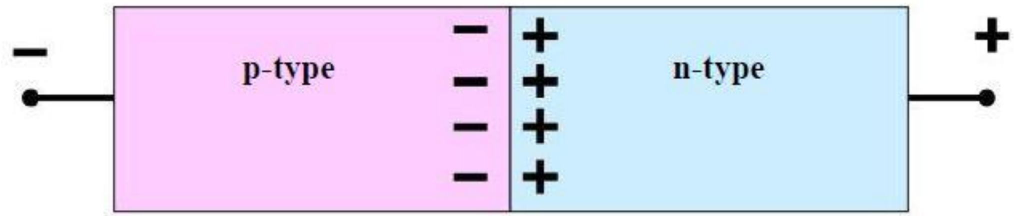
- Electrons and holes remain staying close to the p-n junction because negative and positive charges **attract each other**.
- Negative charge **stops** electrons from further diffusion and Positive charge **stops** holes from further diffusion
- **The diffusion forms a dipole charge layer at the p-n 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.**



But charges can't venture too far from the interface because their Coulomb forces pull them back!

P-N Junction Formation voltage characteristics

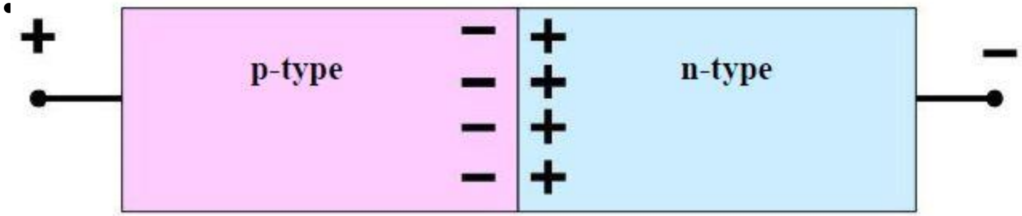
- **What happens when the voltage is applied to a p-n junction?**



- The polarity shown, attracts holes to the left and electrons to the right.
- According to the **current continuity law,** the current can **only** flow if all the charged particles move forming a closed loop
- However, there are very few holes in n-type material and there are very few electrons in the p-type material.
- There are very few carriers available to support the current through the junction plane
- **For the voltage polarity shown, the current is nearly zero**

P-N Junction Formation voltage characteristics

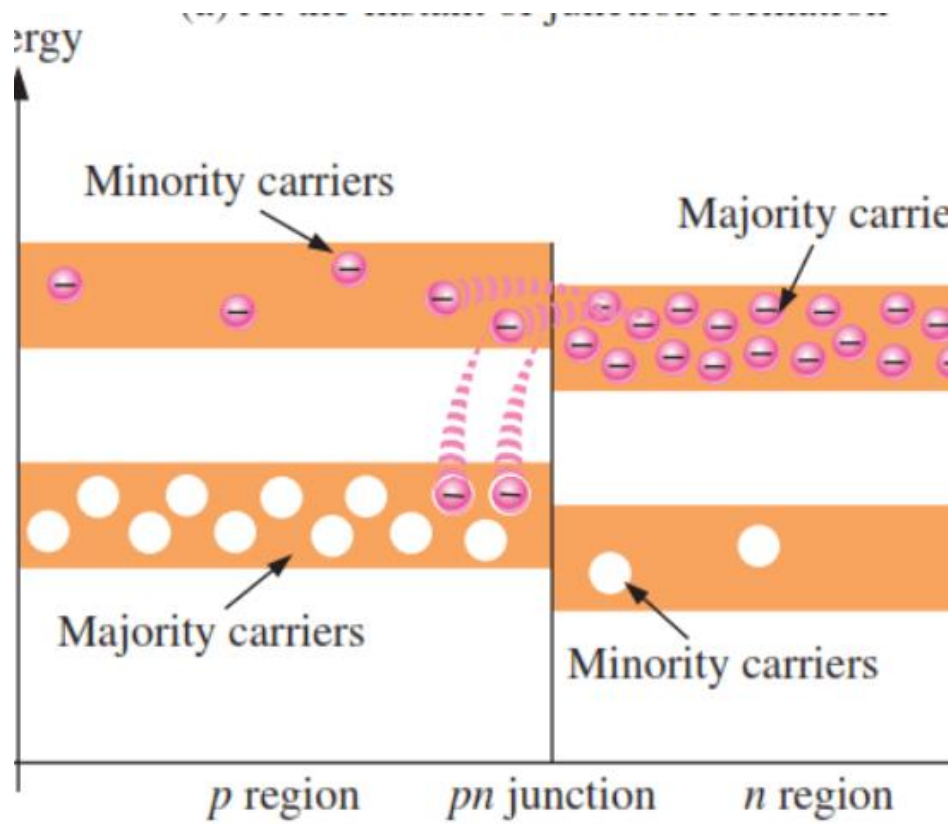
- **What happens if voltage of opposite polarity is applied to a p-n junction?**



- The polarity shown, attracts electrons to the left and holes to the right.
- There are plenty of electrons in the n-type material and plenty of holes in the p-type material.
- There are a lot of carriers available to cross the junction.
- **When the voltage applied is lower than the built-in voltage, the current is still nearly zero.**
- **When the voltage exceeds the built-in voltage, the current can flow through the p-n junction**

Energy Band Diagrams of a PN Junction

- The valence and conduction bands in an n-type material are at slightly lower energy levels than the valence and conduction bands in a p-type material.
- The lower forces in p-type materials mean that the electron orbits are slightly larger and hence have greater energy than the electron orbits in the n-type materials.
- An energy diagram for a pn junction at the instant of formation is shown in Figure. As you can see, the valence and conduction bands in the n region are at lower energy levels than those in the p region, but there is a significant amount of overlapping.



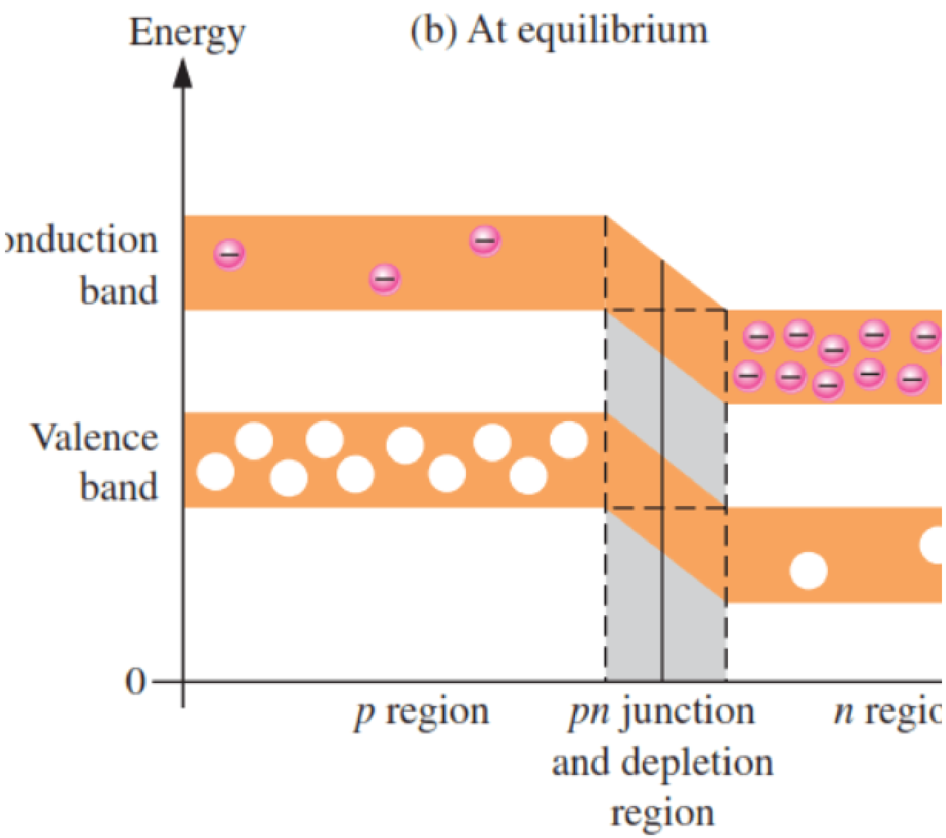
Energy Band Diagrams of a PN Junction

- The free electron In the n region that occupy the upper part of the conduction band in terms of their energy can easily diffuse across the junction (they do not have to gain additional energy) and temporarily become free electrons in the lower part of the p-region conduction band.

- After crossing the junction, the electrons quickly lose energy and fall into the holes in the p-region valence band as indicated in Figure (a)

Energy Band Diagrams of a PN Junction

- As the diffusion continues, the depletion region begins to form and the energy level of the n-region conduction band decreases.
- The decrease in the energy level of the conduction band in the n region is due to the loss of the higher energy electrons that have diffused across the junction to the p region.
- Soon, there are no electrons left in the n-region conduction band with enough energy to get across the junction to the p-region conduction band, as indicated by the alignment of the top of the n-region conduction band and the bottom of the p-region conduction band in Figure (b).



Energy Band Diagrams of a PN Junction

- At this point, the junction is at equilibrium; and the depletion region is complete because diffusion has ceased. There is an energy gradiant across the depletion region which acts as an “energy hill” that an n-region electron must climb to get to the p region
- Notice that as the energy level of the n-region conduction band has shifted downward, the energy level of the valence band has also shifted downward.

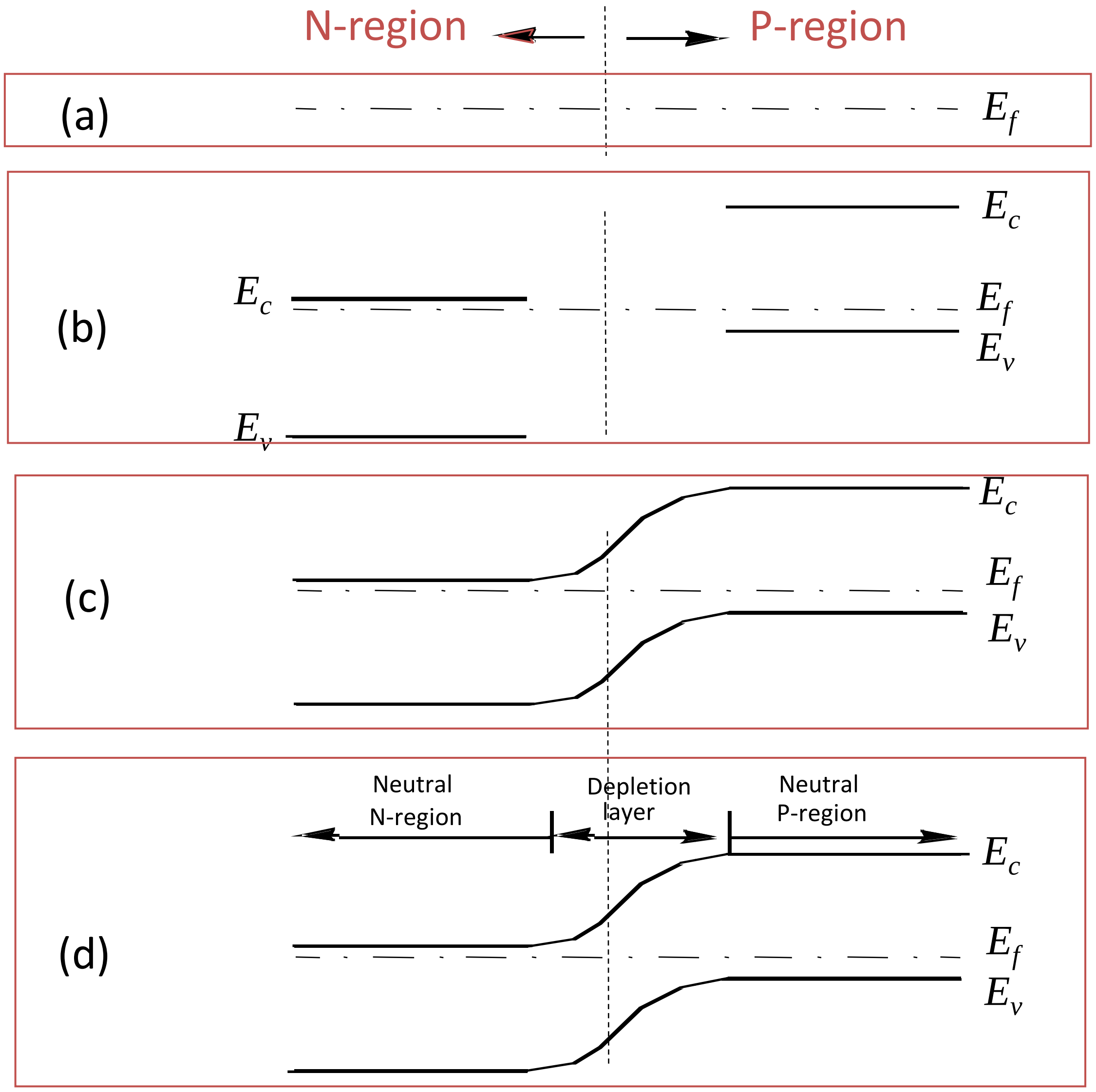
- It still takes the same amount of energy for a valence electron to become a free electron.
- In other words, the energy gap between the valence band and the conduction band remains the same.

Energy Band Diagrams of a PN Junction

- For simplicity, it is usually assumed that the P and N layers are uniformly doped at **acceptor density** $\boldsymbol{N_a}$, and **donor density** $\boldsymbol{N_d}$, respectively.

- This idealized PN junction is known as a **step junction** or an **abrupt junction**.

Energy Band Diagram of a PN Junction



E_f is constant at equilibrium

E_c and E_v are known relative to E_f

E_c and E_v are smooth, the exact shape to be determined.

A depletion layer exists at the PN junction where $n \approx 0$ and $p \approx 0$.

Work Function

- Valence bands and conduction bands are separated by the **band gap (E_g)**. This means the work function is now different from the **ionization energy** *(energy difference between valence bands maximum (VBM) and vacuum level)*.
- In a semiconductor, the Fermi level becomes a somewhat theoretical construct since there are no allowed electronic states within the band gap.
- The Fermi level refers to the point on the energy scale where the probability is just 50%. Even if there are no electrons right at the Fermi level in a semiconductor, the work function can be measured by photoemission spectroscopy(PES).

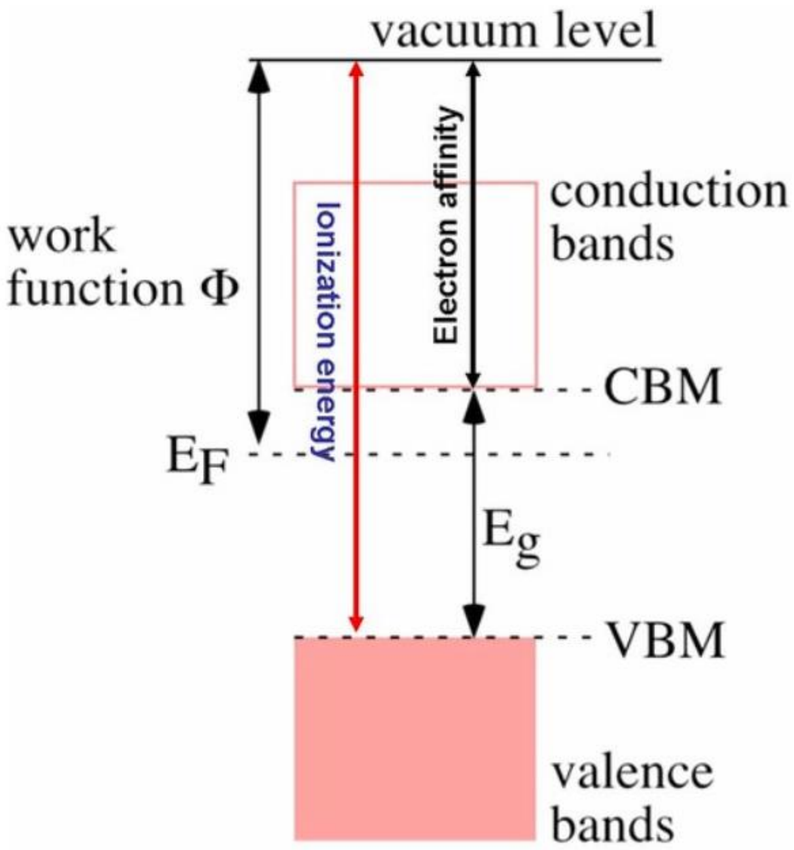
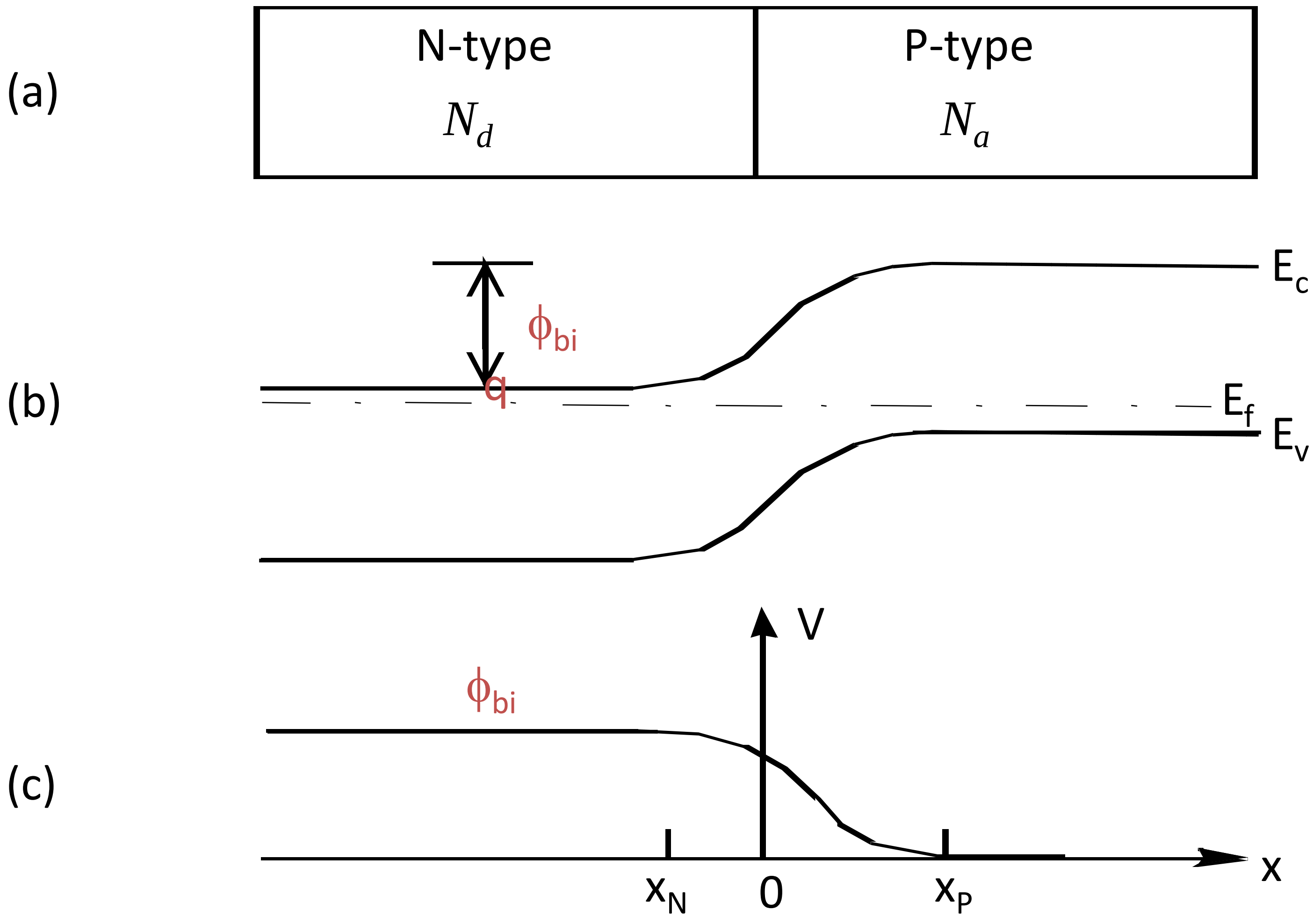


Figure: a schematic energy diagram of a n-type semiconductor.

Built-in Potential



Can the built-in potential be measured with a voltmeter?

Mass-Action Law

- n_0 : thermal-equilibrium concentration of electrons
- p_0 : thermal-equilibrium concentration of holes
- $n_0 p_0$ = ni ^2 = f(T) (function of temperature)
- The product of n0 and po is always a constant for a given semiconductor material at a given temperature.

Equilibrium Electron and Hole Concentrations

- n_0 : thermal-equilibrium concentration of electrons
- p_0 : thermal-equilibrium concentration of holes
- n_d : concentration of electrons in the donor energy state
- p_a : concentration of holes in the acceptor energy state
- N_d : concentration of donor atoms
- N_a : concentration of acceptor atoms
- N_d^+ : concentration of positively charged donors (ionized donors)
- N_a^- : concentration of negatively charged acceptors (ionized acceptors)

Built-in Potential

N-region $$n = N_d = N_c e^{-qA/kT} \Rightarrow A = \frac{kT}{q} \ln \frac{N_c}{N_d}$$

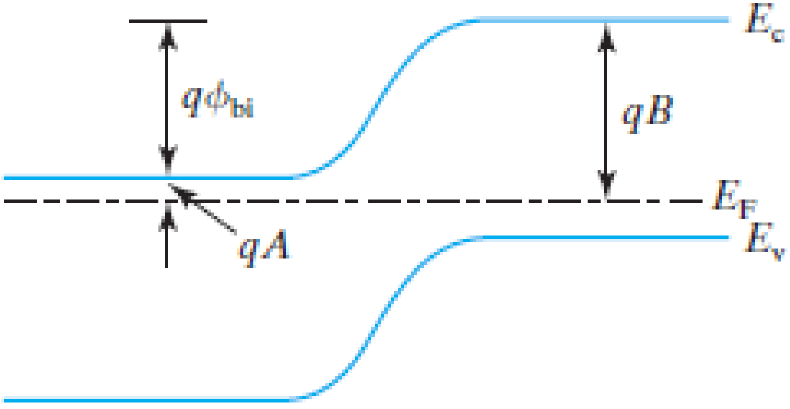
donor density

P-region $$n = \frac{n_i^2}{N_a} = N_c e^{-qB/kT} \Rightarrow B = \frac{kT}{q} \ln \frac{N_c N_a}{n_i^2}$$

acceptor density

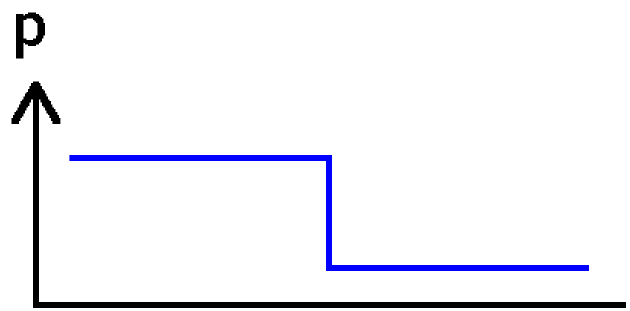
$$\phi_{bi} = B - A = \frac{kT}{q}\left(\ln \frac{N_c N_a}{n_i^2} - \ln \frac{N_c}{N_d} \right)$$

$$\boxed{\phi_{bi} = \frac{kT}{q} \ln \frac{N_d N_a}{n_i^2}}$$



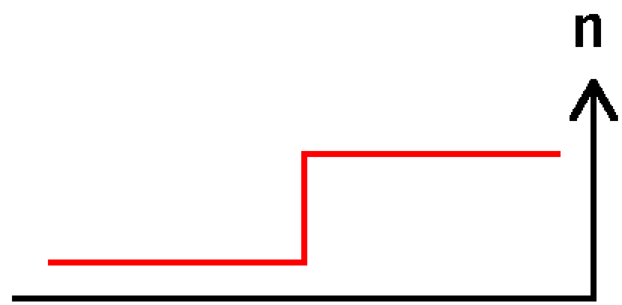
Gradients drive diffusion

Hole gradient

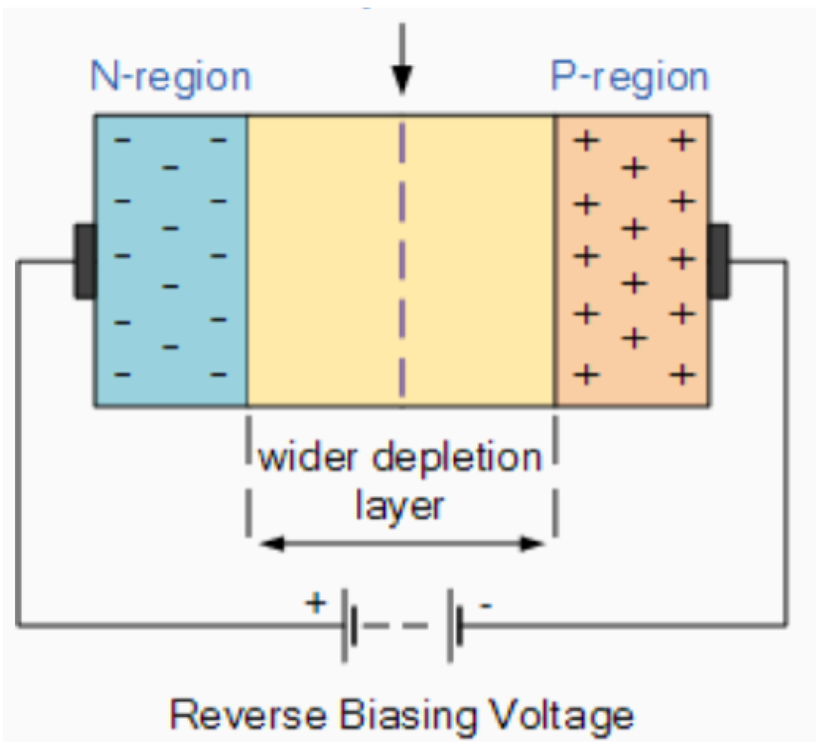


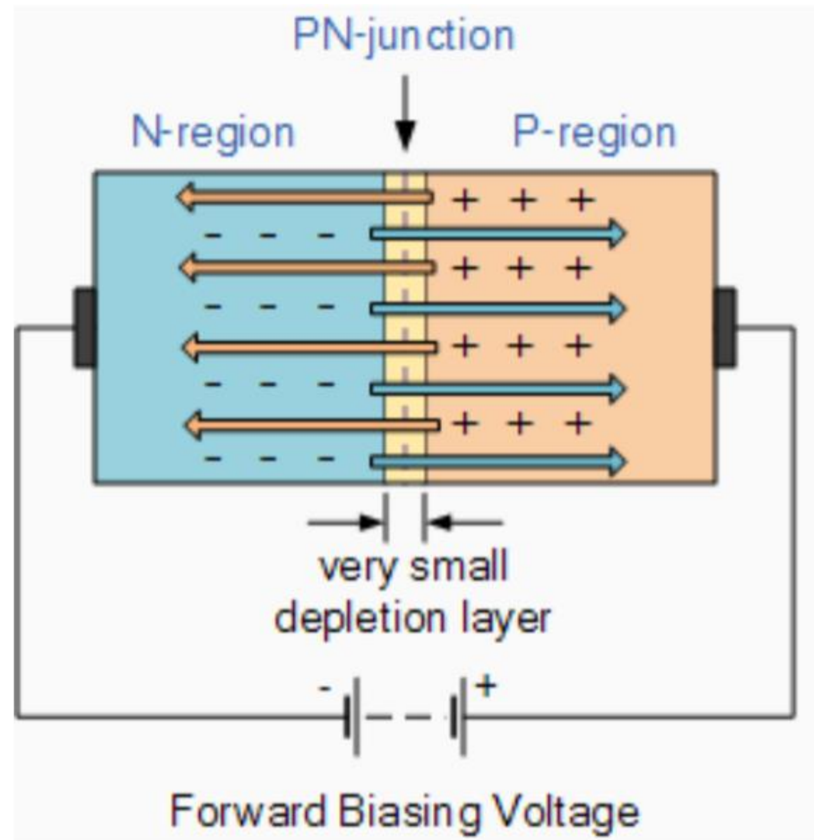
$J_{p,\ diffusion} = -qD_p\ dp/dx$ = current right, holes right

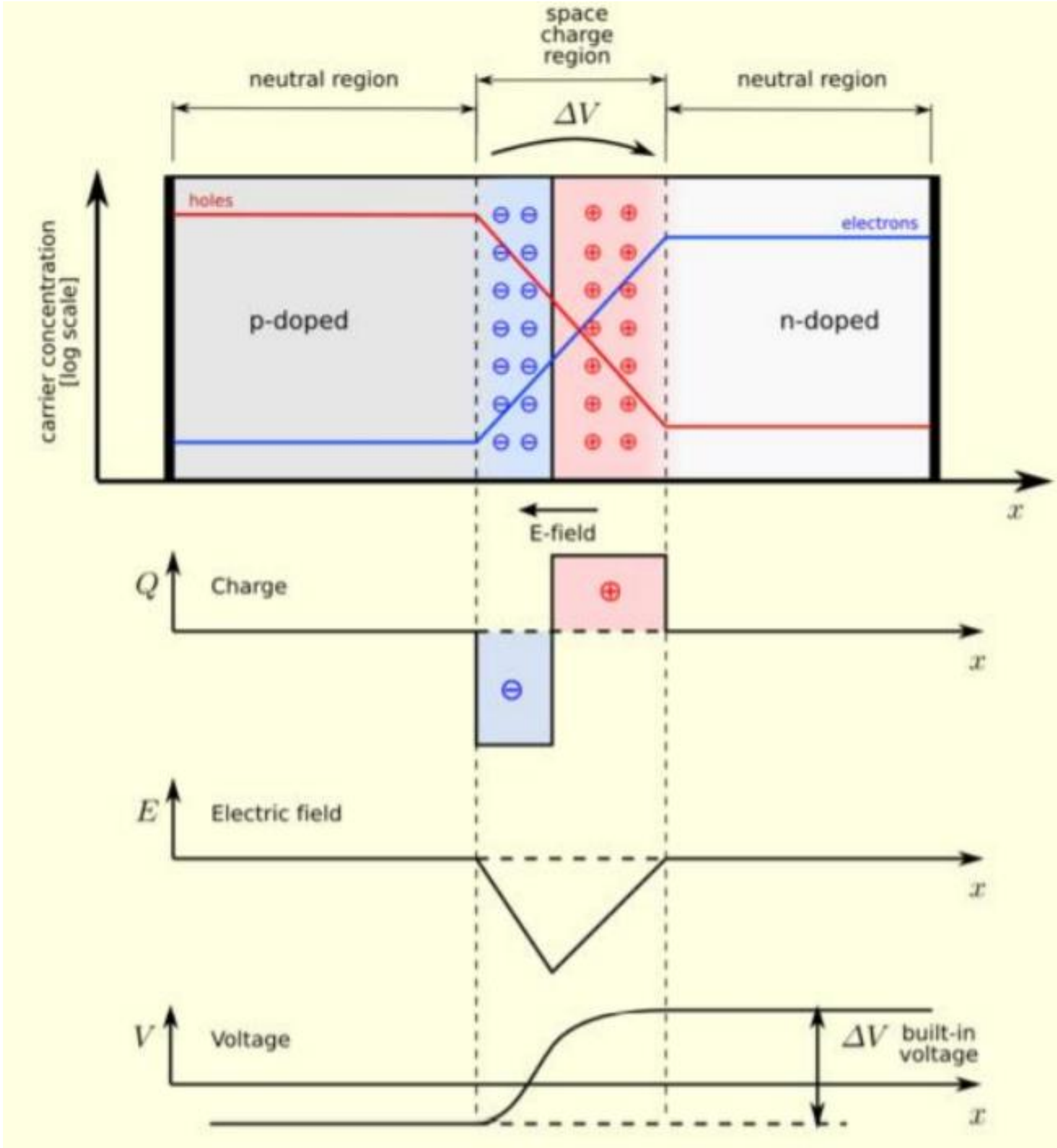
Electron gradient



$J_{n,diffusion} = -qD_n\ dn/dx$ = current right, electron left


N-region
P-region
wider depletion
layer
+
-
Reverse Biasing Voltage


PN-junction
N-region
P-region
very small
depletion layer
-
+
Forward Biasing Voltage


space
charge
region
neutral region
neutral region
ΔV
holes
electrons
p-doped
n-doped
carrier concentration
[log scale]
x
E-field
Q
Charge
x
E
Electric field
x
V
Voltage
ΔV
built-in
voltage
x

DIFFUSION CURRENT

- It is possible for an electric current to flow in a semiconductor even in the absence of the applied voltage provided a concentration gradient exists in the material.
- A **concentration gradient exists** if the number of either elements or holes is greater in one region of a semiconductor as compared to the rest of the Region.
- the change carriers have the **tendency to move** from the region of higher concentration to that of lower concentration of the same type of charge carriers.
- Thus the movement of charge carriers takes place resulting in a current called **diffusion current**.
- Since the hole density p(x) decreases with increasing x, dp/dx is negative and the minus sign in equation is needed in order that Jp has positive sign in the positive x direction

Diffusion current density = Charge × Carrier flux

Diffusion current density due to electron Jn and holes Jp is given by

$$J_n^{diff} = qD_n \frac{dn}{dx} \quad A/cm^2$$

$$J_p^{diff} = -qD_p \frac{dp}{dx} \quad A/cm^2$$

$Dp = \lambda_2/\tau_c$ is the diffusion coefficient

Average carrier velocity = Vth = 10^7 cm/s
Average interval between collisions = τc = 10-13 s = 0.1 picoseconds
mean free path = λ = $Vth\ \tau_C$ = 10^-6 cm = 10 nm

DIFFUSION CURRENT

DRIFT CURRENT

- When an electric field is applied across the semiconductor material, the charge carriers attain a certain drift velocity Vd , which is equal to the product of the mobility of the charge carriers and the applied Electric Field intensity E .

- Drift velocity Vd = mobility of the charge carriers X Applied Electric field intensity. ($V_d = -\mu nE$)

- Holes move towards the negative terminal of the battery and electrons move towards the positive terminal of the battery. This combined effect of movement of the charge carriers constitutes a current known as **— the drift current.**

- Thus the drift current is defined as the flow of electric current due to the motion of the charge carriers under the influence of an external electric field.

- Drift current due to the charge carriers such as free electrons and holes are the current passing through a square centimeter perpendicular to the direction of flow.

Drift current density: ∝ Carrier drift velocity

∝ Carrier concentration

∝ Carrier charge

$$J_n^{drift} = -qnv_{dn} = qn\mu_n E$$

$$J_p^{drift} = qpv_{dp} = qp\mu_p E$$

n - Number of free electrons per cubic centimetre

P - Number of holes per cubic centimetre

μ(n) – Mobility of electrons in cm2 / Vs

μ(p) – Mobility of holes in cm2 / Vs

E – Applied Electric filed Intensity in V /cm

q – Charge of an electron = 1.6 x 10-19 coulomb.

DRIFT CURRENT

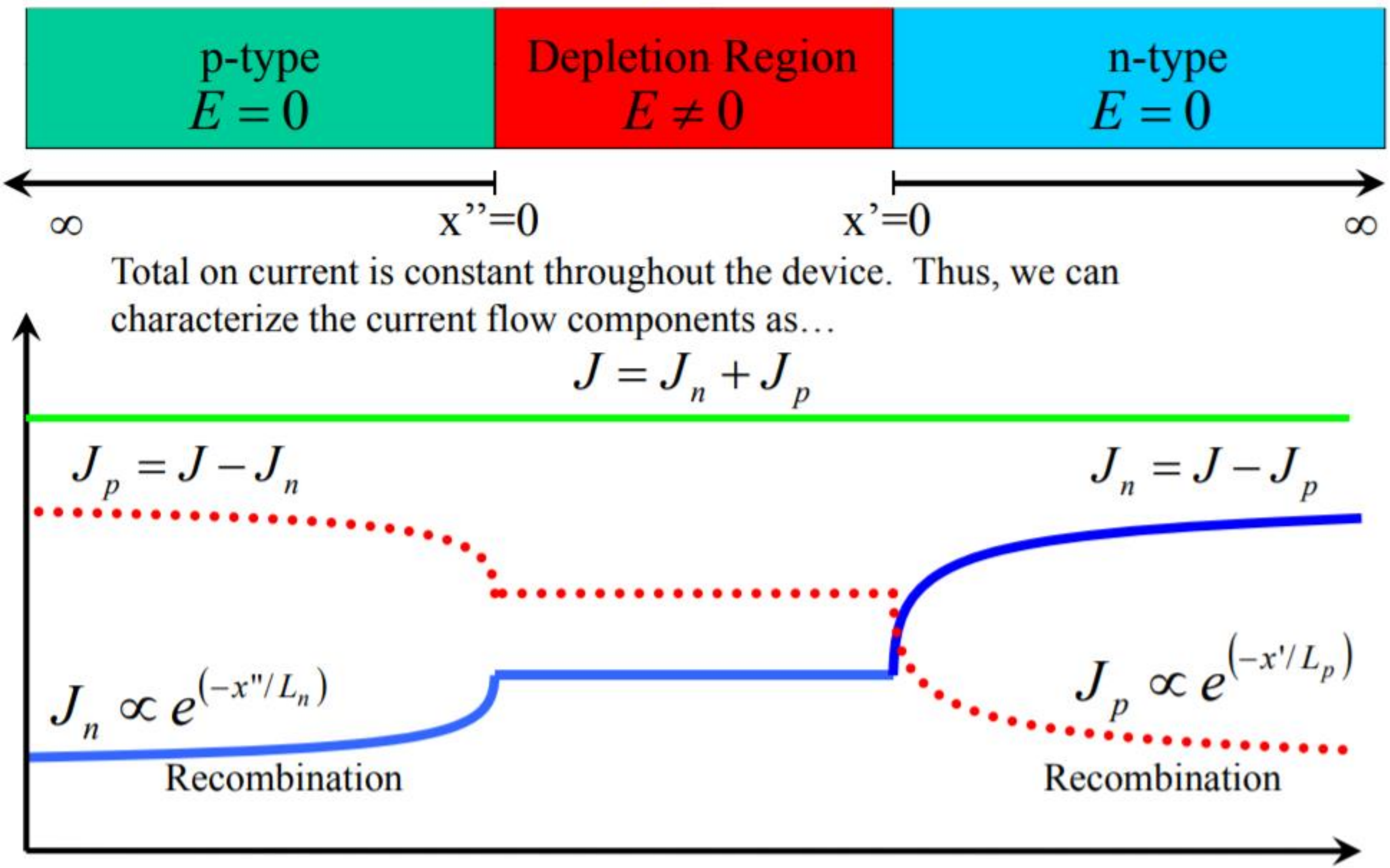
Total Current

The total current in a semiconductor (N type and P type) is the sum of both drift and diffusion currents that is given by

$$\mathbf{J_n = J_n^{drift} + J_n^{diff} = qn\mu_n E + qD_n \frac{dn}{dx}}$$

$$\mathbf{J_p = J_p^{drift} + J_p^{diff} = qp\mu_p E - qD_p \frac{dp}{dx}}$$

Quantitative PN Diode Solution



PN Diode Current

Thus, evaluating the current components at the depletion region edges, we have…

$$\mathrm{J} = \mathrm{J_n}(\mathrm{x''}=0) + \mathrm{J_p}(\mathrm{x'}=0) = \mathrm{J_n}(\mathrm{x''}=0) + \mathrm{J_p}(\mathrm{x''}=0) = \mathrm{J_n}(\mathrm{x'}=0) + \mathrm{J_p}(\mathrm{x'}=0)$$

$$\mathrm{J} = q\left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}\right)\left(e^{qV_A/kT} - 1\right) \quad \textit{for all } x$$

or

$$\boxed{\mathrm{I} = I_o\left(e^{qV_A/kT} - 1\right) \quad \text{where } I_o = qA\left(\frac{D_n n_i^2}{L_n N_A} + \frac{D_p n_i^2}{L_p N_D}\right)}$$

I_o *is the "reverse saturation current"*

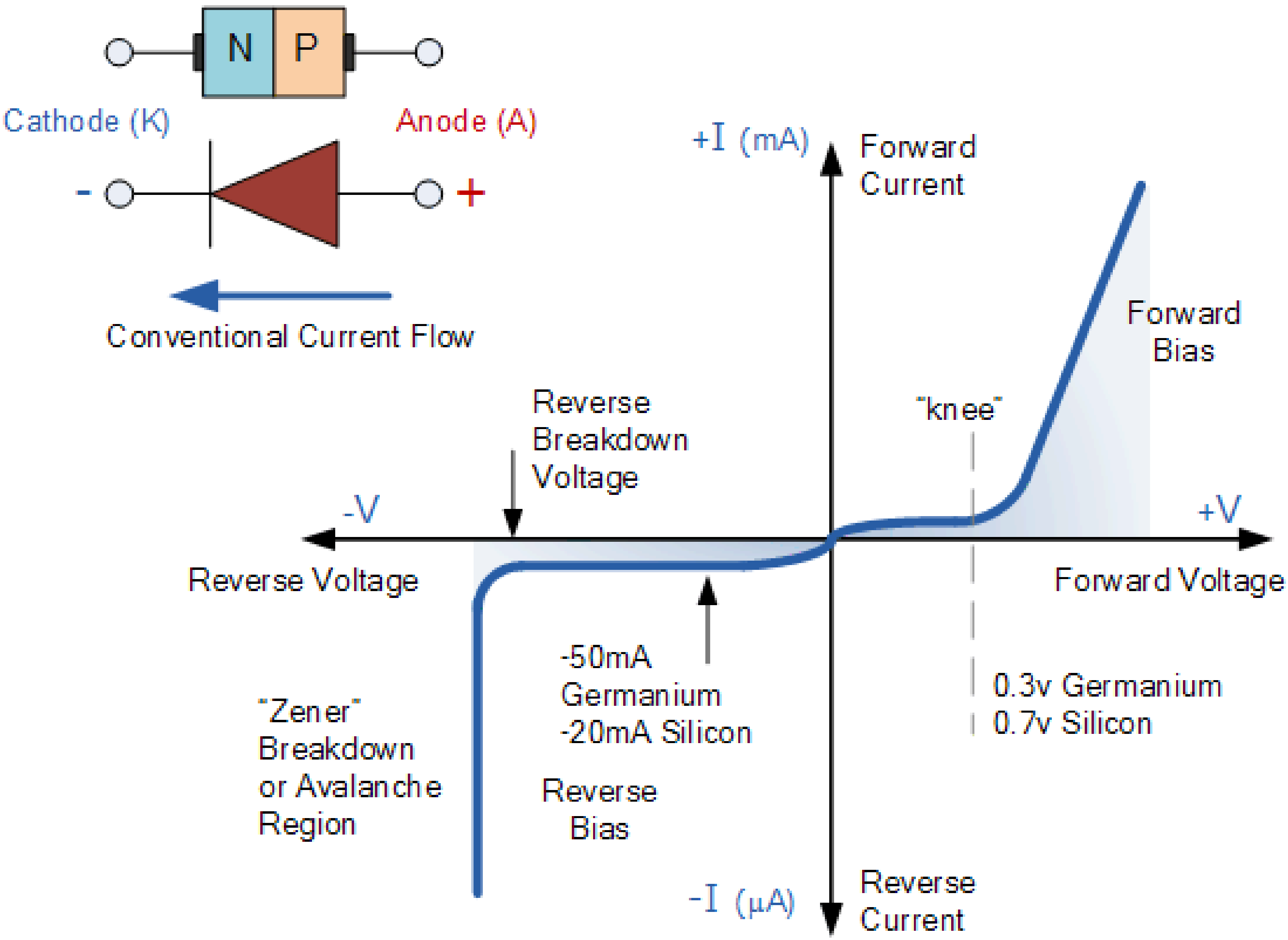
PN Diode Current

- Diode is **non-linear component** of an electrical circuit, which allow current in forward biasing and block current in reverse biasing.
- The behavior of a diode can be identified using VI characteristic. Current of the diode depends upon the voltage across the diode.
- The diode current can be expressed in the form of diode current equation.

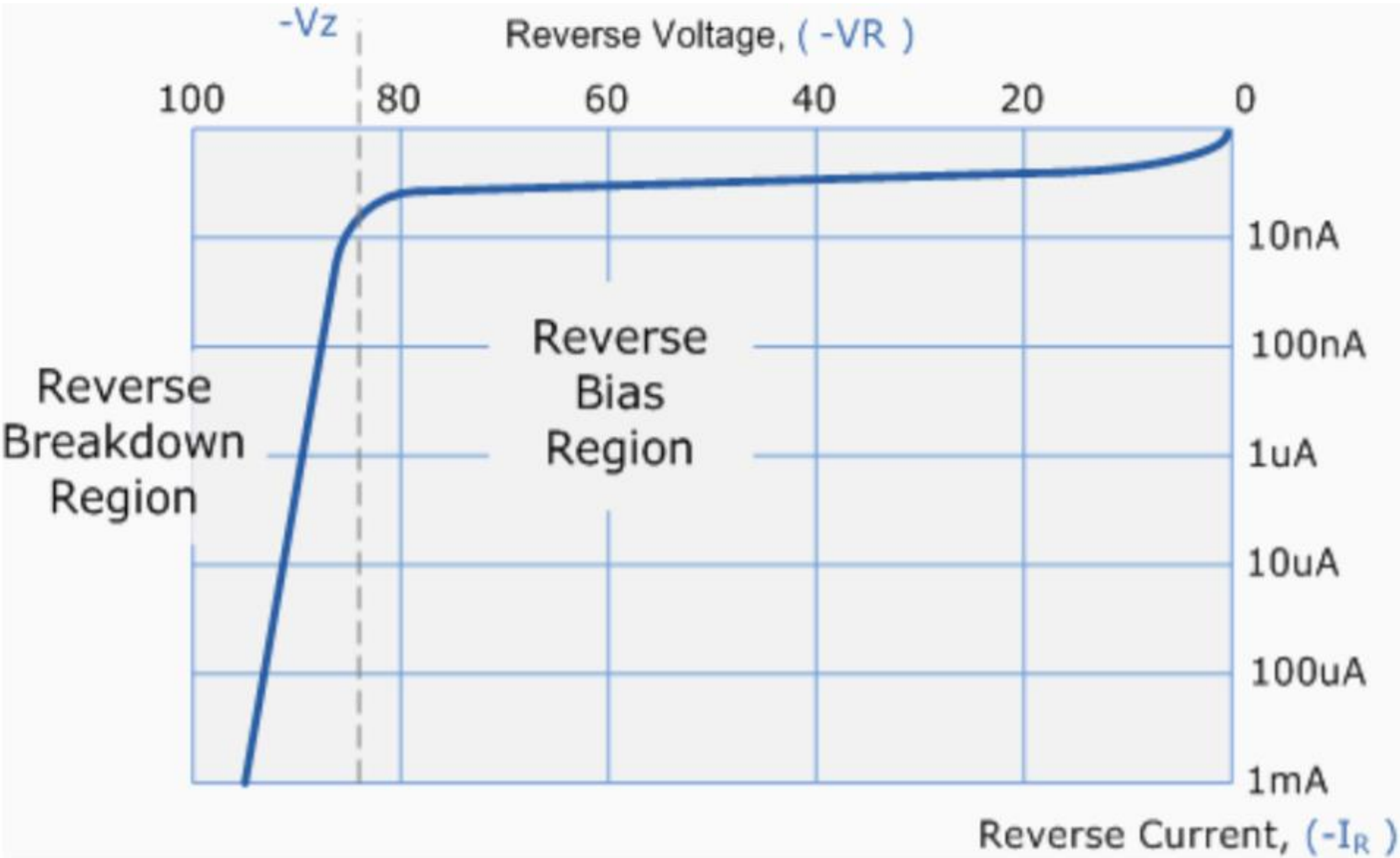
$$\boldsymbol{I = I_0\,[e^{V/\eta V_T} - 1]}$$

- I – Diode Current
- Io- Diode reverse saturation current at room temperature
- V- External Voltage applied to the diode
- η – A constant, two for Silicon and one for Germanium
- $V_T - \frac{kT}{q}$ = T/11600 Volts-equivalent of temperature, thermal voltage

V-I Characteristics of PN Junction Diode



V-I Characteristics of PN Junction Diode Reverse Bias



~~Junct~~

Junction's

1) Metal - Metal

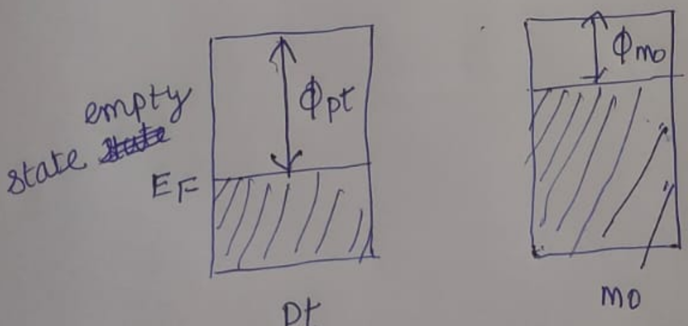
2) Metal-Semiconductor (ohmic contact (or) Schotty)

3) Semi conductor-Semiconductor (PN-Junction)

1) Metal - Metal Junction's

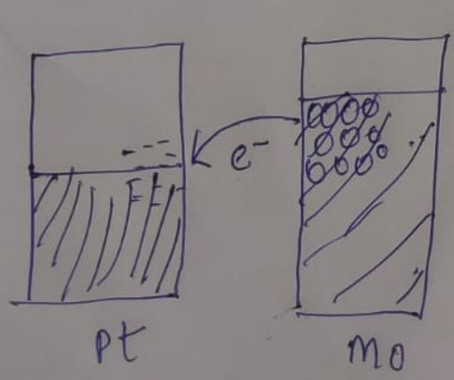
Rule :- whenever you have Junctions formation the Fermi level will line up at thermal equilibrum (No external potential applied).

Before Junction formation



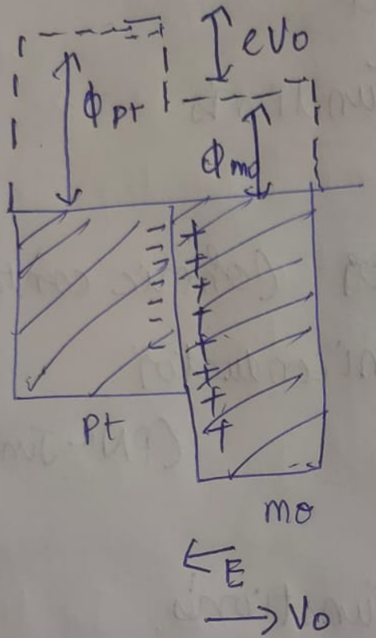
$\phi = 5.36\,eV$ $\quad$ $\phi_{mo} = 4.2\,eV$

$\phi_{pt} > \phi_{mo}$



net positive on mo

net negative charge on pt. because it's gain electron's which mean's, an electric field will be setup when a Junction formed.



$$eV_0 = \phi_{pt} - \phi_{mo}$$

$$= 5.35 - 4.2$$

$$= 1.16\ eV$$

$$V_0 = 1.16\ V.$$

V_0 opposes Further motion of ~~el~~ electron e^-

≡ Junctions equilibrum.

Application :- Seeback effect.

(a) Thermo electric

ϕ_{mo}
-4.2
eV
$1.16V$.
ione$^-$

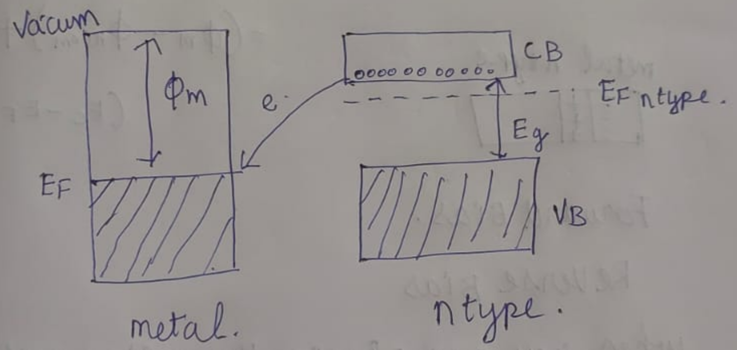
2) Metal - semi conductor :-

$\phi_m - \phi_{semi}$

condition.

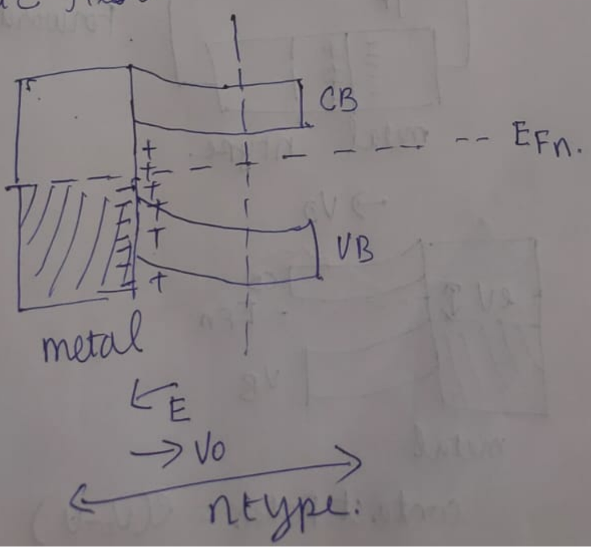
1) $\phi_m > \phi_{semi} \rightarrow$ schottky
2) $\phi_m < \phi_{semi} \rightarrow$ ohmic.

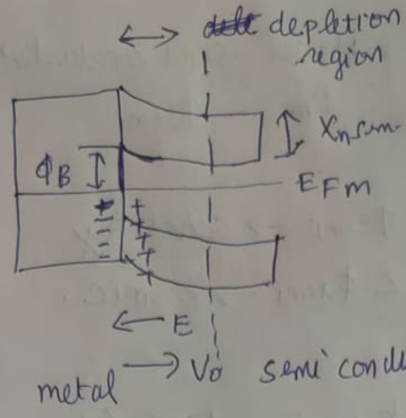
1) Schottky Junction ($\phi_m > \phi_{semi}$)



condition :-

Bond Bending goes up in the direction of electric field.





(space charge layer)

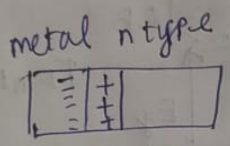
$e V_0 = \phi_m - \phi_{nsem}$

ϕ = schottky barrier

$= \phi_m - \chi_{nsem}$

$= \phi_m - \chi_{nsem}$

$= (\phi_m - \phi_{nsem}) + (E_C - E_{Fn})$

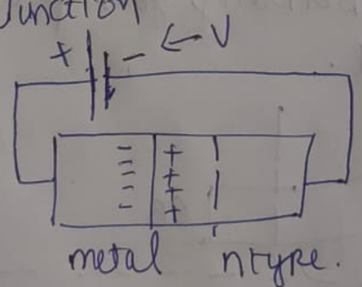


Forward Bias.

Reverse Bias

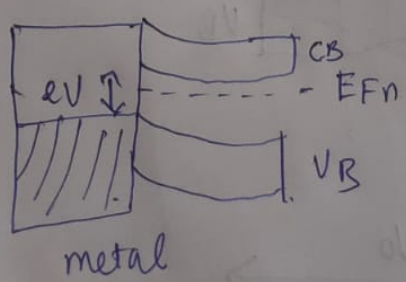
when you are Biasing the system will ~~not~~ not be in equilibrium

Schottky Junction



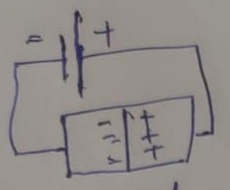
Forward Bias

→ V_0

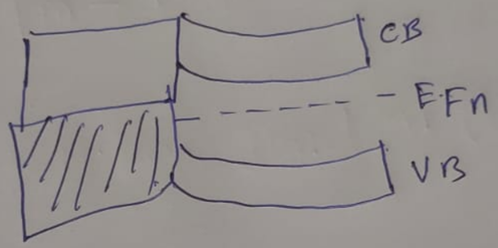


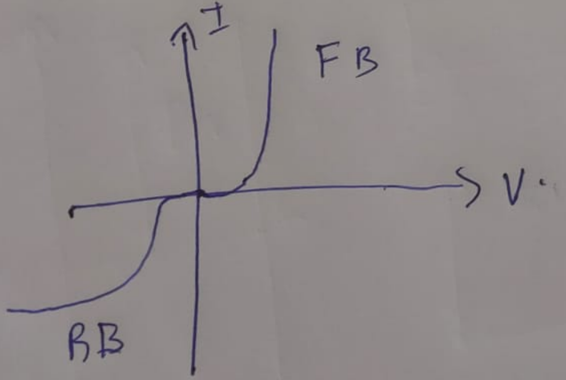
contact Poten $= e(V_0 - V)$

Reverse Bias.



metal.

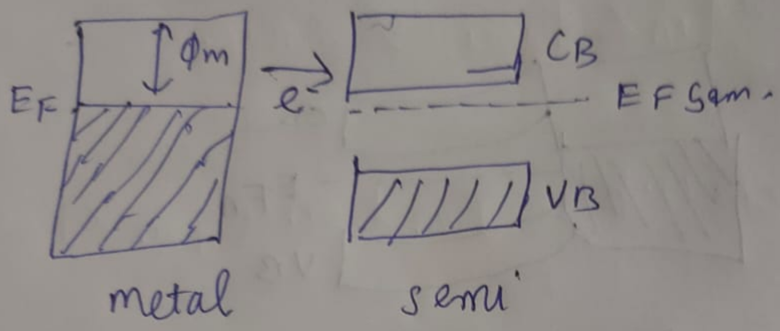




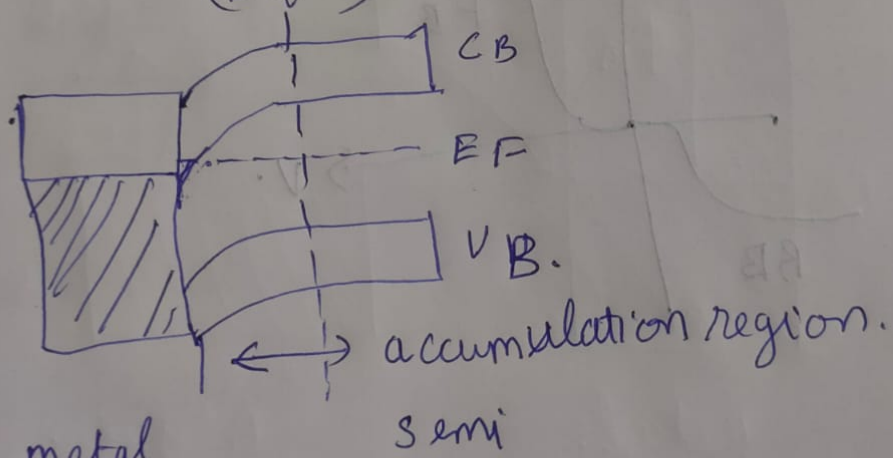
~~ohmic~~

ohmic contact.

($\phi_m < \phi_{semi}$)



(Before) ~~For~~



ohmic Junction - Resistor

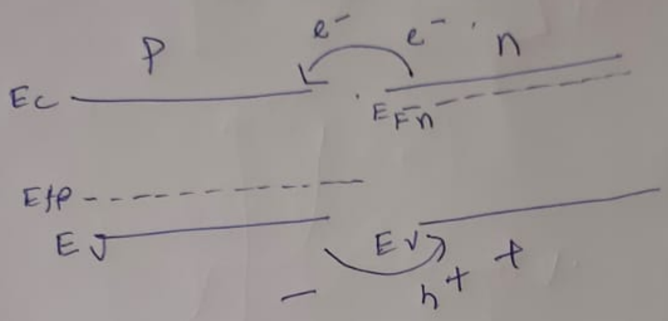
Schottky Junction - Rectifier - conduc
in forward b

Pn Junction

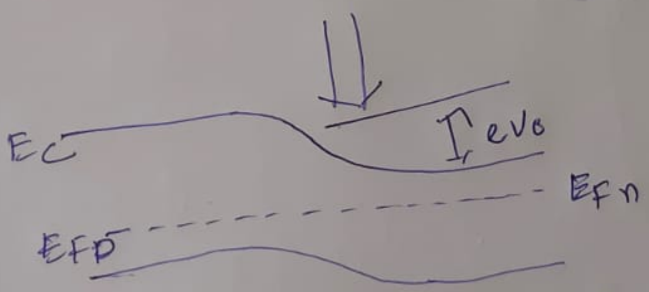
Homo Junction P & n type are from same material

Hetero Junction :- P & n type are different materials.

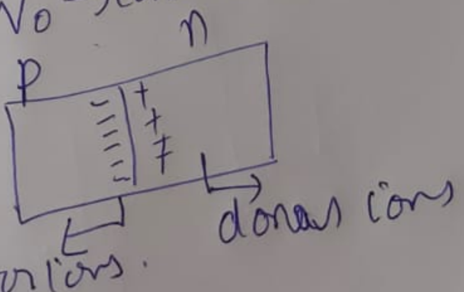
Si standard materials



Electric field.



$V_0 \rightarrow$ contact potential.



e^- from $n \rightarrow P$
h^+ from $P \rightarrow n$] depletion region.

Pn Junction

e^+ from $n \to P$

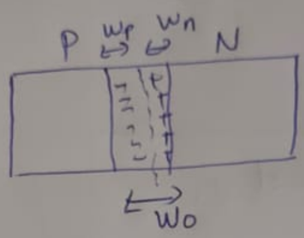
h^+ from $P \to n$

$N_A \to$ acceptor conc N_A

$N_D \to$ donor conc N_D

$N_A > N_D$

P side   n side



w_0 = total width of depletion region

$$w_0 = W_p + W_n$$

A = cross sectional area of Junction

Total charge on depletion region

in p-side $= \underset{\text{conc}}{N_A} \, \underset{\text{volume)}}{(AW_p)}$

Total charge on n-side

$= N_D \, (AW_n)$

$$\cancel{A} W_p N_A = \cancel{A} W_n N_D$$

$$\Downarrow$$

$$W_p N_A = W_n N_D$$

$$\frac{W_P}{W_n} = \frac{N_D}{N_A}$$

The ratio of depletion region widths is inversely proportional to the conc of dopants.

if $N_A > N_D$

$W_p < W_n$

$p^+ n \rightarrow N_A >> N_D \Rightarrow W_p << W_n$

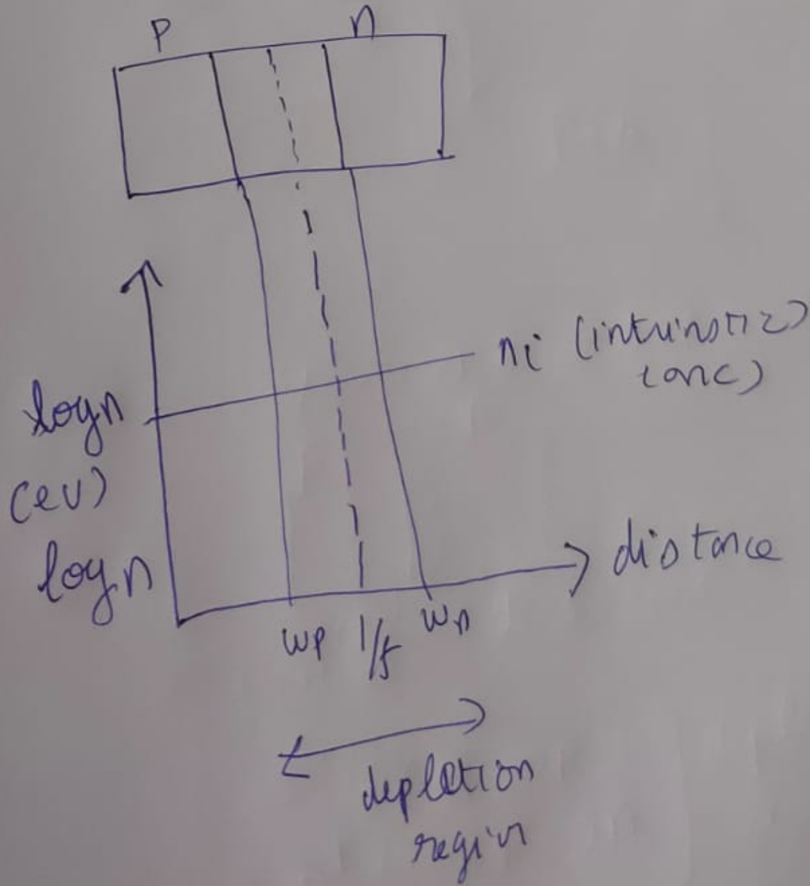
↓

heavily doped.

So depletion region almost on the n type.

Calculate the builtin potential

$N_A > N_D$



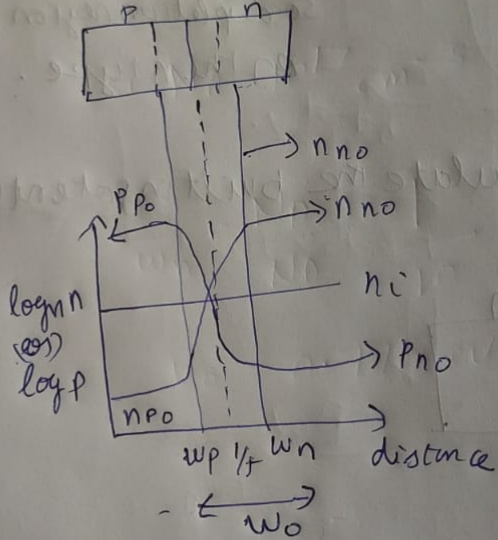
$n_{no} = N_D$

$p_{no} = \frac{n_i^2}{N_D} << n_{no}$

$p_{po} = N_A$

$n_{po} = \frac{n_i^2}{N_A}$

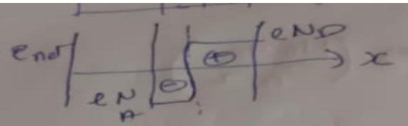
$N_A > N_D$



V_0 = built in pot t

$$\frac{n_{po}}{n_{no}} = \exp\left(-\frac{eV_0}{KT}\right)$$

$$V_0 = \frac{KT}{e} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$



$E(x) = \frac{1}{\varepsilon} \int e_{net}(x)\, dx$

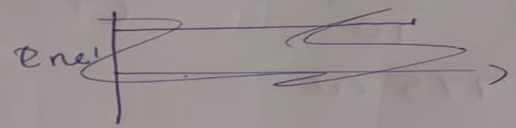
substitution

$P_{net} = -eN_A$ (P side)

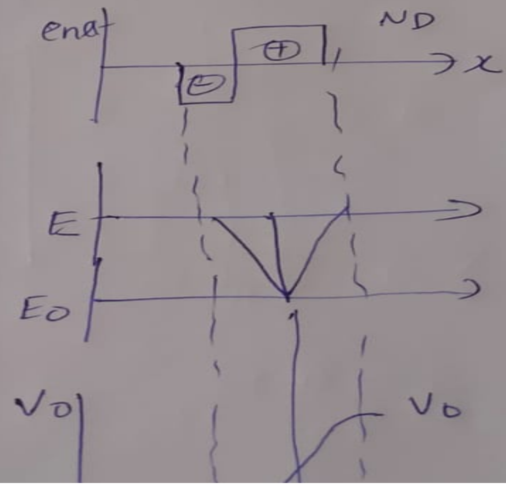
$= eN_D$ (N side)

$$E(x) = \frac{eN_d}{\varepsilon} x \quad (or) \quad -\frac{eN_A}{\varepsilon} x$$

$$E_0 = -\frac{eN_d w_n}{\varepsilon} = -\frac{eN_A w_p}{\varepsilon}$$



$$E_x = \frac{dV}{dx} = V \int E\, dx$$



~~$V_0 = W_0$~~

$$V_0 = -\frac{1}{2} E_0 w_0$$

$$= \frac{e N_A N_D w_0^2}{2(\varepsilon (N_A +$$

$$\frac{w_p}{w_n} = \frac{N_D}{N_A}$$

$\varepsilon = \varepsilon_0 \varepsilon_r$ $\qquad$ Si $\varepsilon_r = 11.9$

Si $N_A = 10^{17}\ cm^{-3}$ $\qquad$ $N_D = 10$

$n_i = 10$

$(T =$

$$\frac{w_p}{w_n} = \frac{N_D}{N_A} = \frac{1}{10}$$

$V_0 = 0.775\ eV$

Diode capacitances

Diode capacitances

- Electronic devices are inherently sensitive to **very high frequencies**.

- Most shunt capacitive effects that can be ignored at **lower frequencies** because the reactance $X_C = {}^{1}/_{2\pi fC}$ is very large (open circuit equivalent).

- This, however, cannot be ignored at **very high frequencies**. X_C will become sufficiently small due to the high value of f to introduce a low-reactance "shorting" path.

Diode capacitances

- In the p-n semiconductor diode, there are two capacitive effects to be considered.

- In the reverse-bias region we have the **transition- or depletion region capacitance (CT).**

- while in the forward-bias region we have the **diffusion (CD) or Storage capacitance.**

Diode capacitances

- Recall that the basic equation for the capacitance of a **parallelplate capacitor** is defined by

$$C = \in {}^{A}/_{d}$$

- where € is the permittivity of the dielectric (insulator) between the plates of area A separated by a distance d.
- In the reverse-bias region there is a depletion region that behaves essentially like an insulator between the layers of opposite charge.
- Since the depletion width (d) will increase with increased reverse-bias potential, the resulting transition capacitance will decrease.
- The fact that the **capacitance is dependent** on the applied reverse-bias potential has **application** in a number of electronic systems.

Diode capacitances

- Although the effect described above will also be present in the forward-bias region,

- it is over shadowed by a capacitance effect directly dependent on the rate at which charge is injected into the regions just outside the depletion region.

Transition and Diffusion Capacitance

- **Transition capacitance:** The capacitance which appears between positive ion layer in n-region and negative ion layer in p-region.
- **Diffusion capacitance**: This capacitance originates due to diffusion of charge carriers in the opposite regions.
- The transition capacitance is very small as compared to the diffusion capacitance.

- In reverse bias, transition capacitance is the dominant and is given by:

$$\boldsymbol{C_T} = \in {}^{\boldsymbol{A}}/_{\boldsymbol{W}}$$

where $\boldsymbol{C_T}$ - transition capacitance

A - diode cross sectional area

W - depletion region width

Transition and Diffusion Capacitance

In forward bias, the diffusion capacitance is the dominant and is given by:

$$\boxed{C_D = dQ/dV = \tau * dI/dV = \tau * g = \tau/r \text{ (general)}}$$

where C_D - diffusion capacitance

dQ - change in charge stored in depletion region

V - change in applied voltage

τ - time interval for change in voltage

g - diode conductance

r - diode resistance

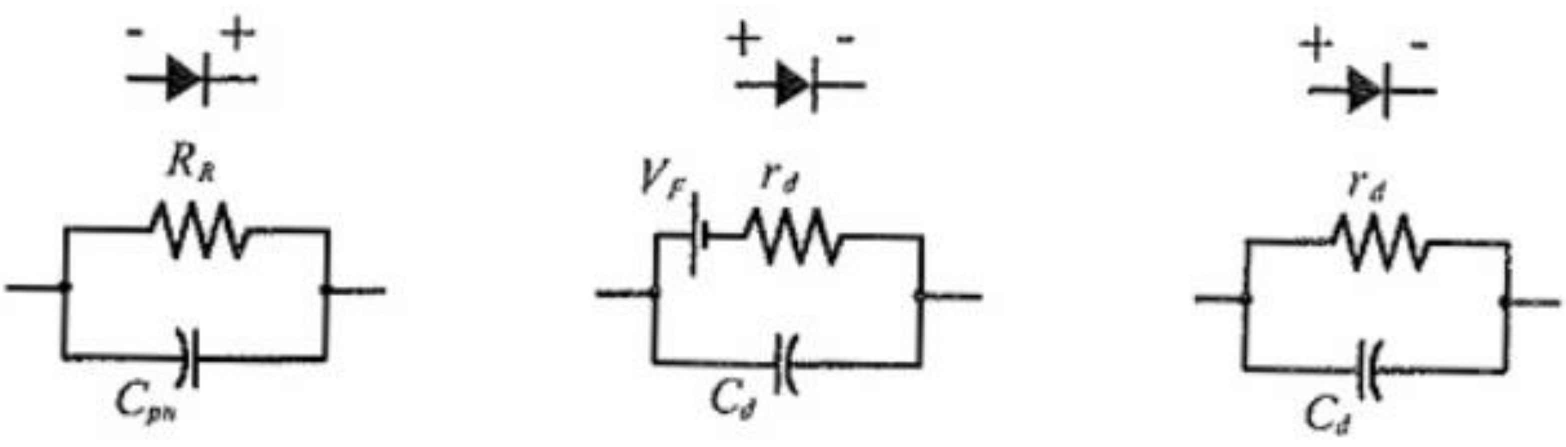
The diffusion capacitance at low frequencies is given by the formula:

$$\boxed{C_D = \tau * g/2 \text{ (low frequency)}}$$

Equivalent circuit

- The capacitive effects described above are represented by a capacitor in parallel with the ideal diode,

- For low- or mid-frequency applications (except in the power area), however, the capacitor is normally not included in the diode symbol.



(a) Equivalent circuit for a reverse-biased diode

(b) Equivalent circuit for a forward-biase diode

(c) AC equivalent circuit for a forward-biased diode

Break Down Mechanisms

Break Down Mechanisms

- When an ordinary **P-N junction diode** is reverse biased, normally only very small reverse saturation current flows.

- This current is due to movement of **minority carriers**.

- It is almost **independent** of the voltage applied.

- However, if the reverse bias is increased, **a point** is reached when the junction breaks down and the reverse current increases abruptly.

- This current could be **large enough** to destroy the junction.

Break Down Mechanisms

- If the reverse current is **limited** by means of a **suitable series resistor**,
- the power dissipation at the junction will not be **excessive**, and the device **may be operated continuously** in its breakdown region to its normal (reverse saturation) level.

- It is found that for a **suitably designed diode**, the breakdown voltage is very stable over a wide range of reverse currents.

- This quality gives the breakdown diode many useful applications as a voltage reference source.

Break Down Mechanisms

- The critical value of the voltage, at which the breakdown of a P-N junction diode occurs, is called the *breakdown voltage*.

- The breakdown voltage depends on the **width of the depletion region**, which, in turn, depends on the **doping level.**

- The junction offers almost **zero resistance** at the breakdown point.

- There are two mechanisms by which breakdown can occur at a reverse biased P-N junction:

  1. ***Avalanche breakdown***

  2. ***Zener breakdown.***

Avalanche breakdown

- The **minority carriers**, under reverse biased conditions, flowing through the junction acquire a **kinetic energy** which increases with the increase in reverse voltage.
- At a sufficiently **high reverse voltage** (say 5V or more), the kinetic energy of minority carriers becomes **so large** that they **knock out electrons** from the covalent bonds of the semiconductor material.
- As a result of collision, the liberated electrons in turn **liberate more electrons** and the current becomes very large leading to the breakdown of the crystal structure itself. This phenomenon is called the avalanche breakdown.
- The breakdown region is the **knee of the characteristic curve**.
- Now the current is not controlled by the junction voltage but rather by the external circuit.

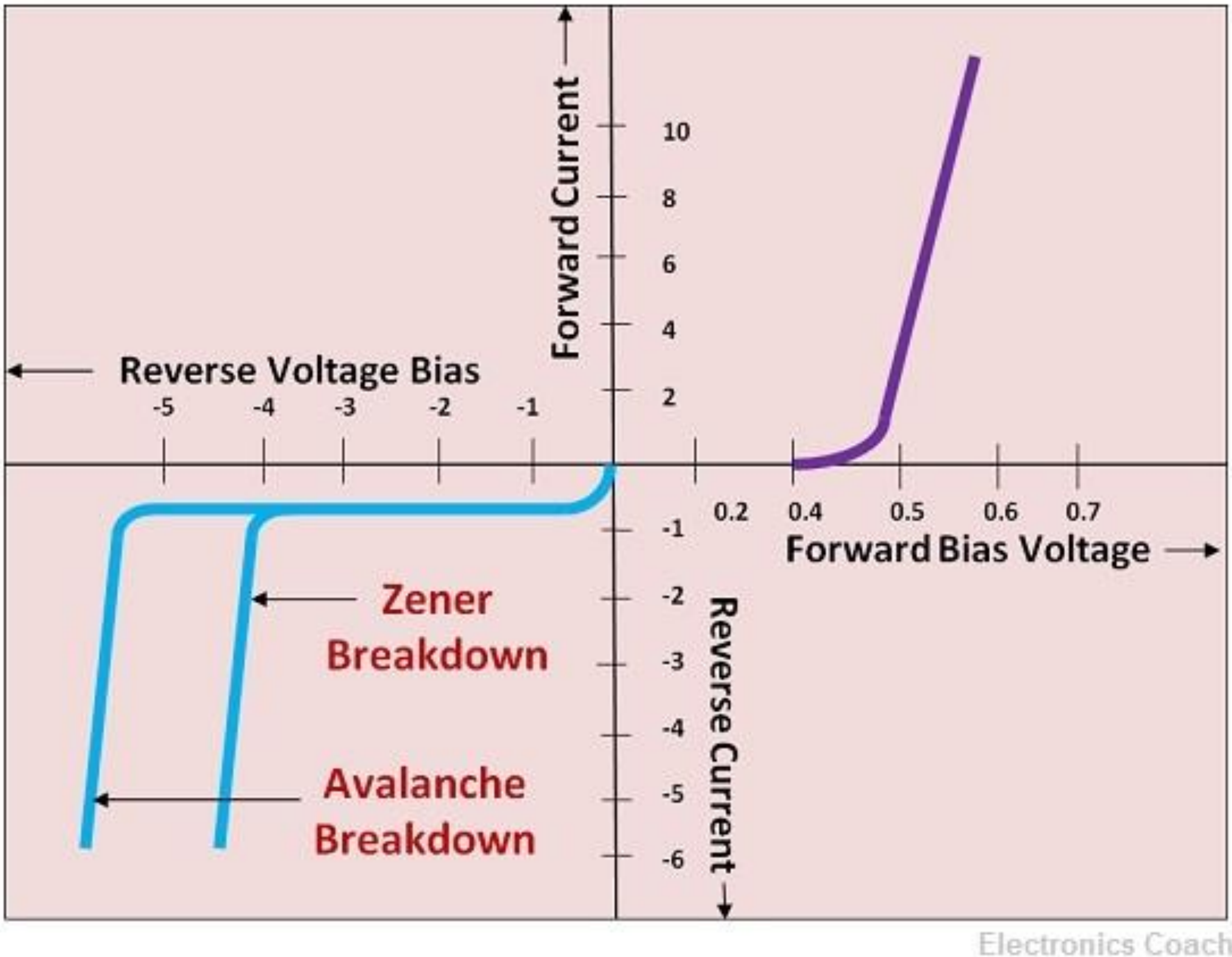
Zener breakdown

- Under a very high reverse voltage, the **depletion region expands** and the **potential barrier increases** leading to a ***very high electric field across*** the junction.

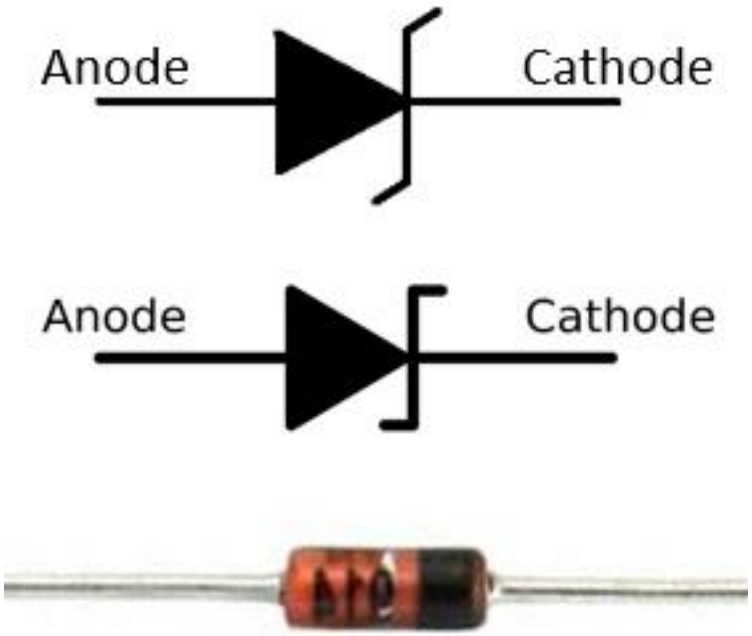
- The ***electric field*** will **break** some of the covalent bonds of the semiconductor atoms leading to a large number of **free minority** carriers, which suddenly increase the reverse current. This is called the Zener effect.

- The breakdown occurs at a particular and constant value of reverse voltage called the breakdown voltage, it is found that Zener breakdown occurs at electric field intensity of about 3×10^7 V/m.

I-V Characteristics



Zener Diode Symbol



Avalanche vs Zener breakdown

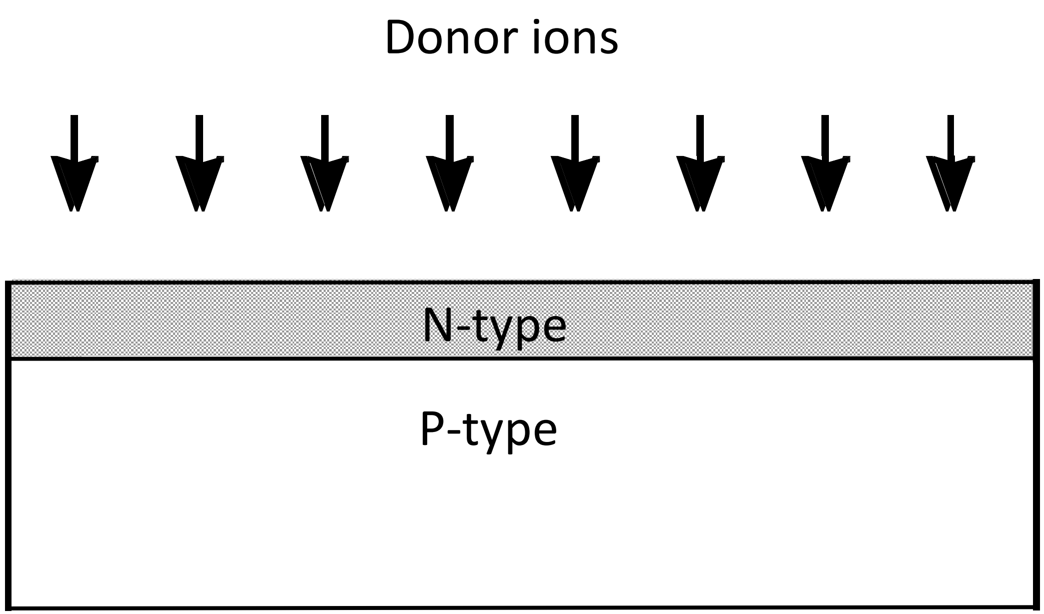
- Either of the two (Zener breakdown or avalanche breakdown) may occur **independently**, or **both** of these may occur simultaneously.
- Diode junctions that breakdown **below 5V** are caused by Zener effect.
- Junctions that experience breakdown **above 5V** are caused by avalanche effect.
- Junctions that breakdown **around 5V** are usually caused by combination of two effects.
- The Zener breakdown occurs in **heavily doped junctions** (P-type semiconductor moderately doped and N-type heavily doped), which produce narrow depletion layers.

Avalanche vs Zener breakdown

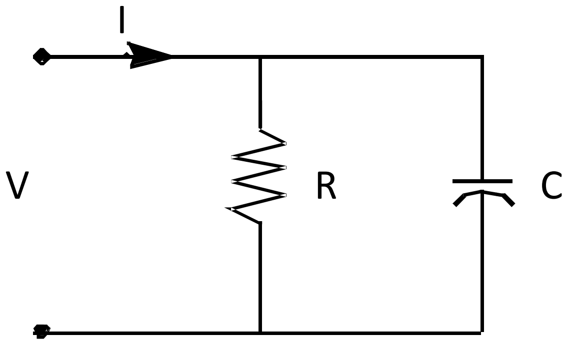
- The avalanche breakdown occurs in **lightly doped junctions**, which produce wide depletion layers.
- With the increase in junction temperature Zener breakdown voltage is reduced while the avalanche breakdown voltage increases.
- The Zener diodes have a **negative temperature coefficient** while avalanche diodes have a **positive temperature coefficient**.
- Diodes that have breakdown voltages around 5V have **zero temperature coefficient**.
- The breakdown phenomenon is **reversible and harmless** so long as the safe operating temperature is maintained.

Fabrication of PN Junction Diode

- a PN junction can be fabricated by implanting or diffusing donors into a P-type substrate such that a layer of semiconductor is converted into N type.
- Converting a layer of an N-type semiconductor into P type with acceptors would also create a PN junction



Small-signal Model of the Diode



$$G \equiv \frac{1}{R} = \frac{dI}{dV} = \frac{d}{dV} I_0(e^{qV/kT} - 1) \approx \frac{d}{dV} I_0 e^{qV/kT}$$

$$= \frac{q}{kT} I_0(e^{qV/kT}) = I_{DC} / \frac{kT}{q}$$

What is G at 300K and I_{DC} = 1 mA?

Diffusion Capacitance:

$$C = \frac{dQ}{dV} = \tau_s \frac{dI}{dV} = \tau_s G = \tau_s I_{DC} / \frac{kT}{q}$$

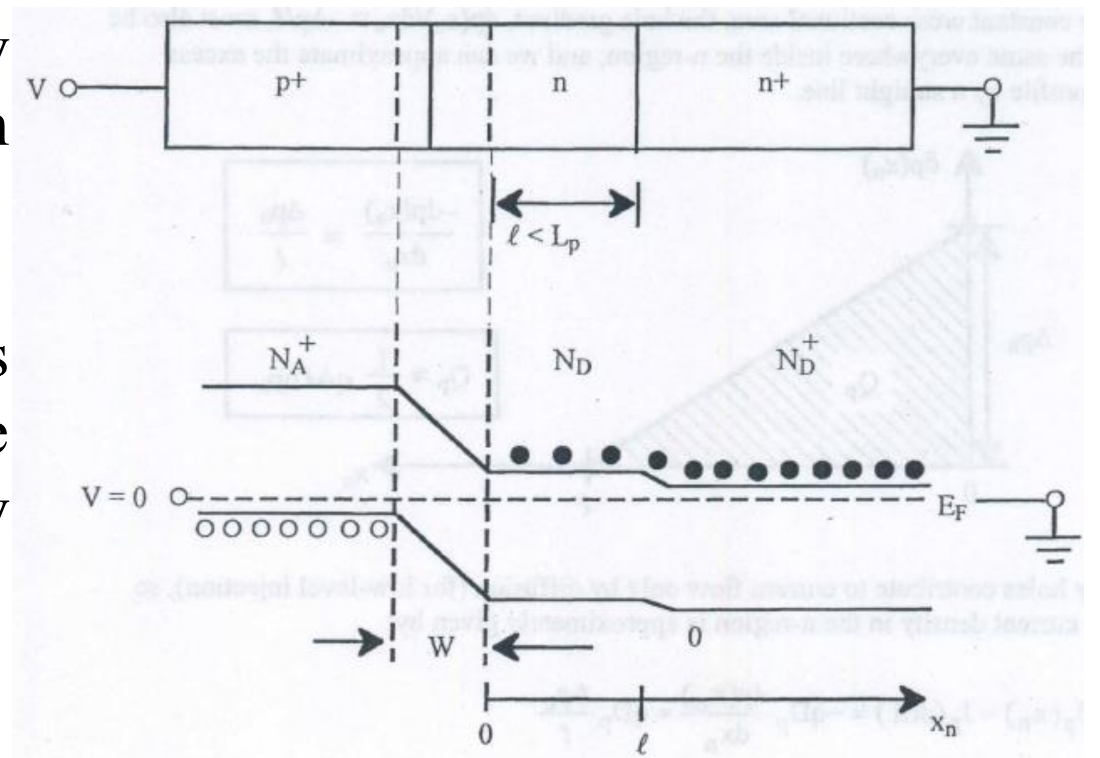
Narrow Base Diode

- The **narrow-base diode** is comprised of: **p+-n diode** and heavily doped **n+ contact**.

- Typically, the neutral portion of the lightly doped region is much less than the average hole diffusion length away.

- Neutral portion of lightly doped n-region is much less than Lp.

- Hole diffusion current is still dominant, as we expect, but the boundary conditions are altered.



Narrow Base Diode

- Minority holes cross Xn = l are assumed to recombine when they enter the n+ contact as the minority lifetime will be extremely small.
- The much larger change in hole concentration across the neutral n-region which sets up a **large diffusion**.
- We already know that only a few holes will recombine within the n-region.
- Each time this happens another electron must flow in from the n+ contact to preserve the charge neutrality.
- In the three terminal p+ - n - p device there exists a small electron base current corresponding to the sum of the electron injection and recombination currents which we can adjust to control the much large hole current.
- Therefore, we get **current multiplication**.

Temperature dependence

Temperature dependence

- Semiconductors exhibit **different types of temperature coefficients**.
- A component that becomes **less resistive** with temperature has a **negative temperature coefficient.**
- A component that becomes **more resistive** with temperature has a **positive temperature coefficient**.

- The Zener diodes have a **negative temperature coefficient** while avalanche diodes have a **positive temperature coefficient**.

- The polarity of the temperature coefficient is easy to spot in a graph of resistance versus temperature.
- As temperature increases, a positive slope indicates a positive temperature coefficient. A negative slope indicates a negative temperature coefficient.

Negative Temperature Coefficient

- An increase in the temperature of a semiconducting material results in an **increase in charge-carrier concentration**.

- This results in a **higher number of charge carriers** available for recombination, increasing the conductivity of the semiconductor.

- The increasing conductivity causes the resistivity of the semiconductor material to decrease with the rise in temperature, resulting in a **negative temperature coefficient of resistance**.

Positive Temperature Coefficient

- In the case of conductors, when temperature increases resistivity increases as electrons collide more frequently with vibrating atoms.

- This reduces drift speed of electrons (and thus current reduces). Thus, conductors have **positive temperature coefficient of resistance**.

- Temperature coefficient affects from major power circuit components can enhance or reduce efficiency.

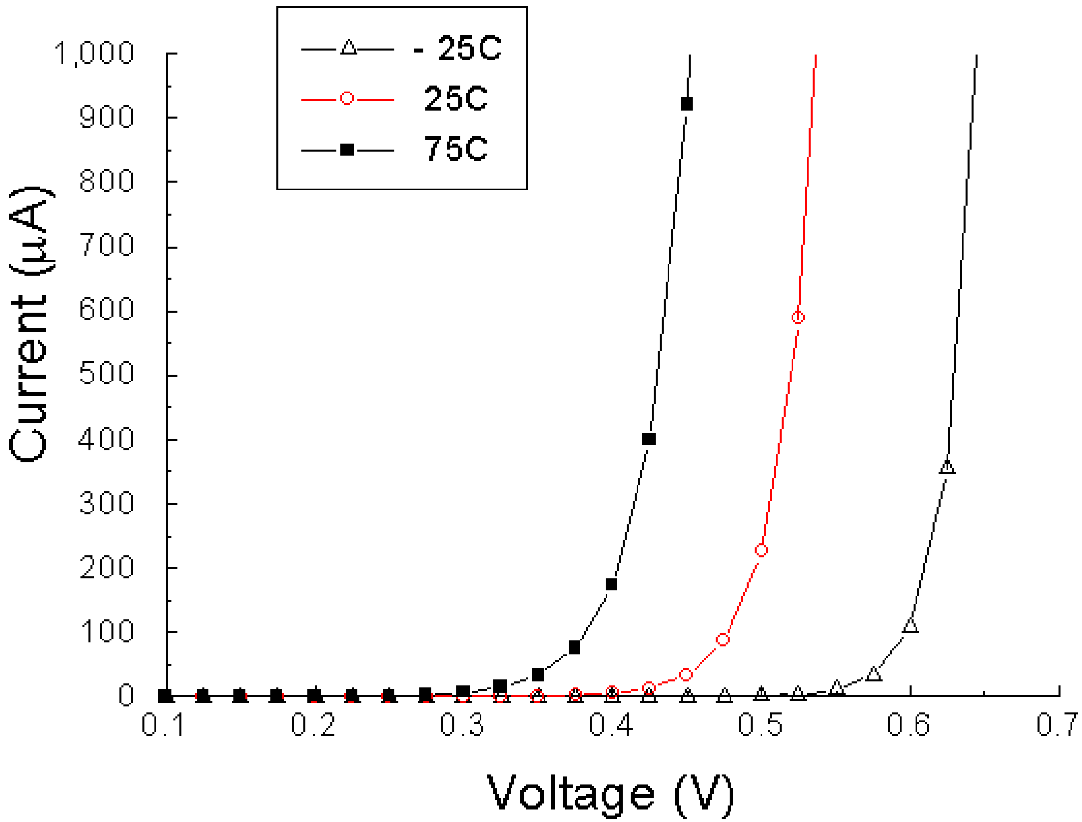
Temperature dependence

- the voltage drop across a forward-biased pn-junction changes with Temperature Effect on Semiconductor Diode by approximately -1.8 mV/°C for a silicon device, and by -2.02 mV/°C for germanium.

- A diode V_F at any temperature can be calculated from a knowledge of V_F at the starting temperature (V_{F1} at T_1), the temperature change (ΔT), and the voltage/temperature coefficient (ΔV_F/°C).

$$V_{F2} = (V_{F1} \text{ at } T_1) + [\Delta T \times (\Delta V_F/^\circ C)]$$

Temperature dependence

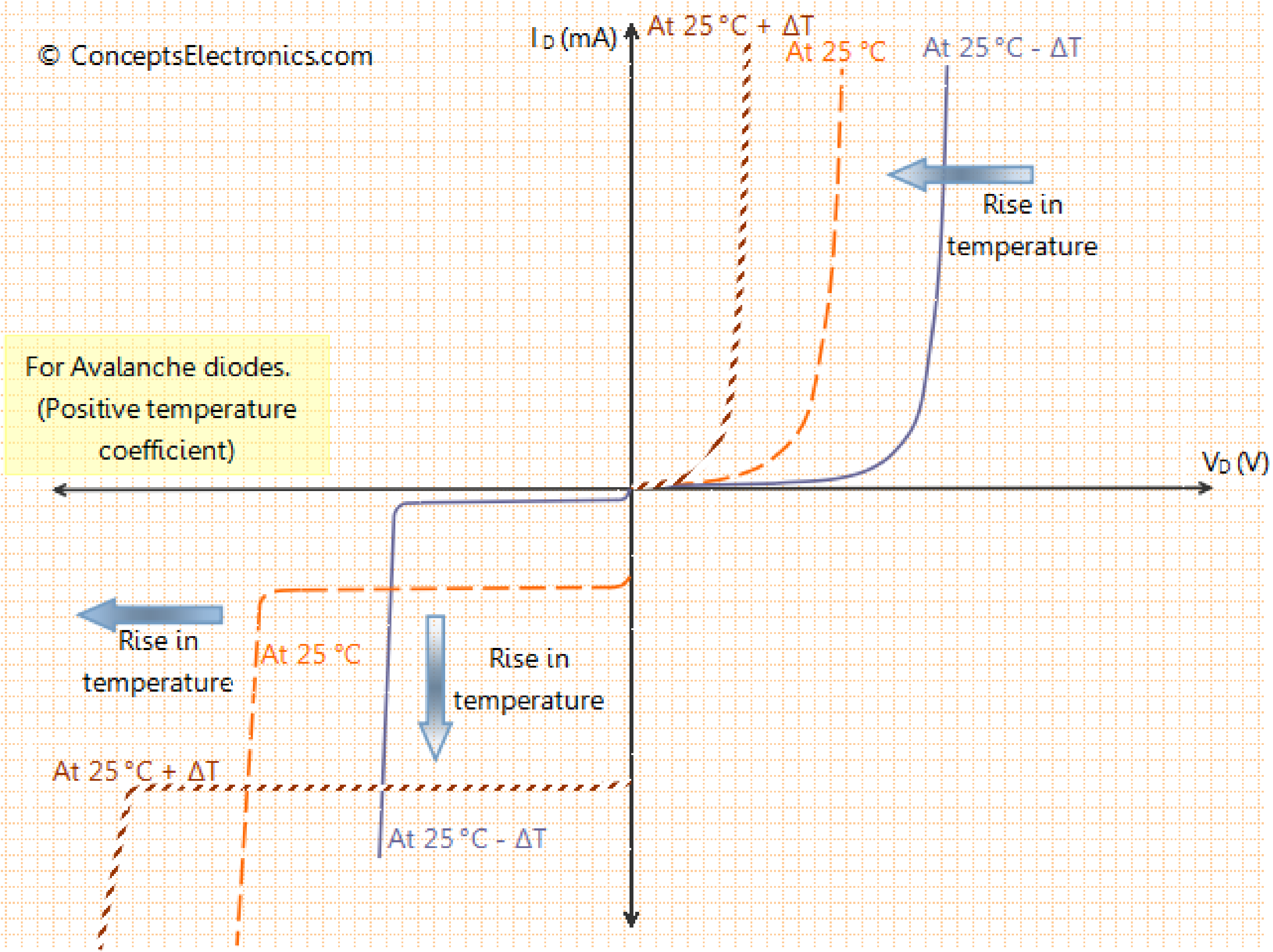


$$I = I_0 (e^{qV/kT} - 1)$$

$$I_0 = Aqn_i^{\,2}\left(\frac{D_p}{L_p N_d} + \frac{D_n}{L_n N_a}\right)$$

What causes the I-V curves to shift to lower V at higher T ?

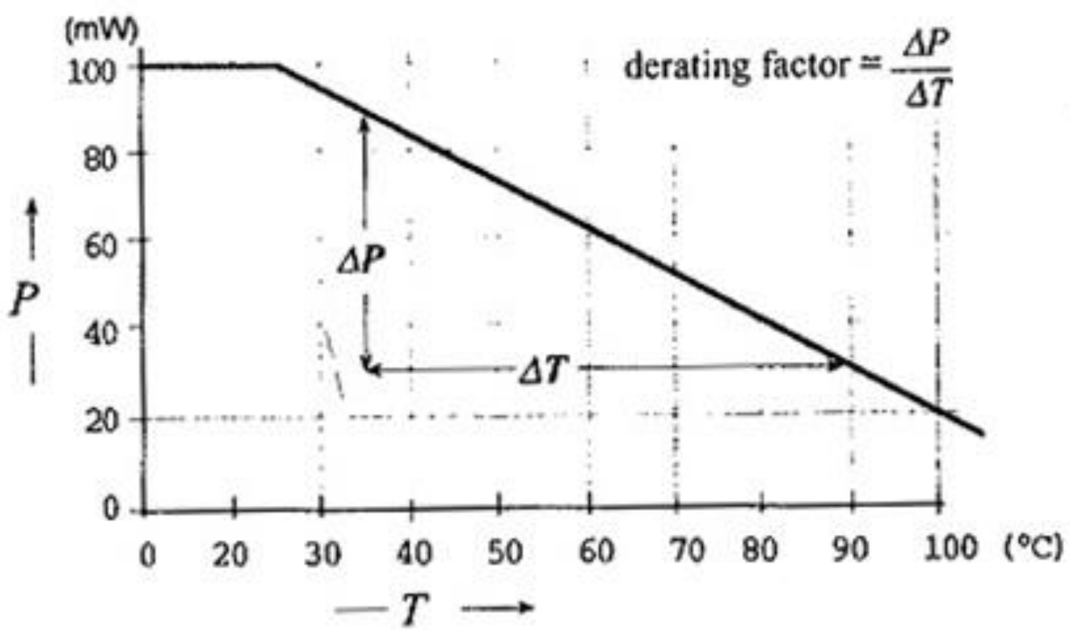
Temperature dependence



Effect of temperature on avalanche diodes

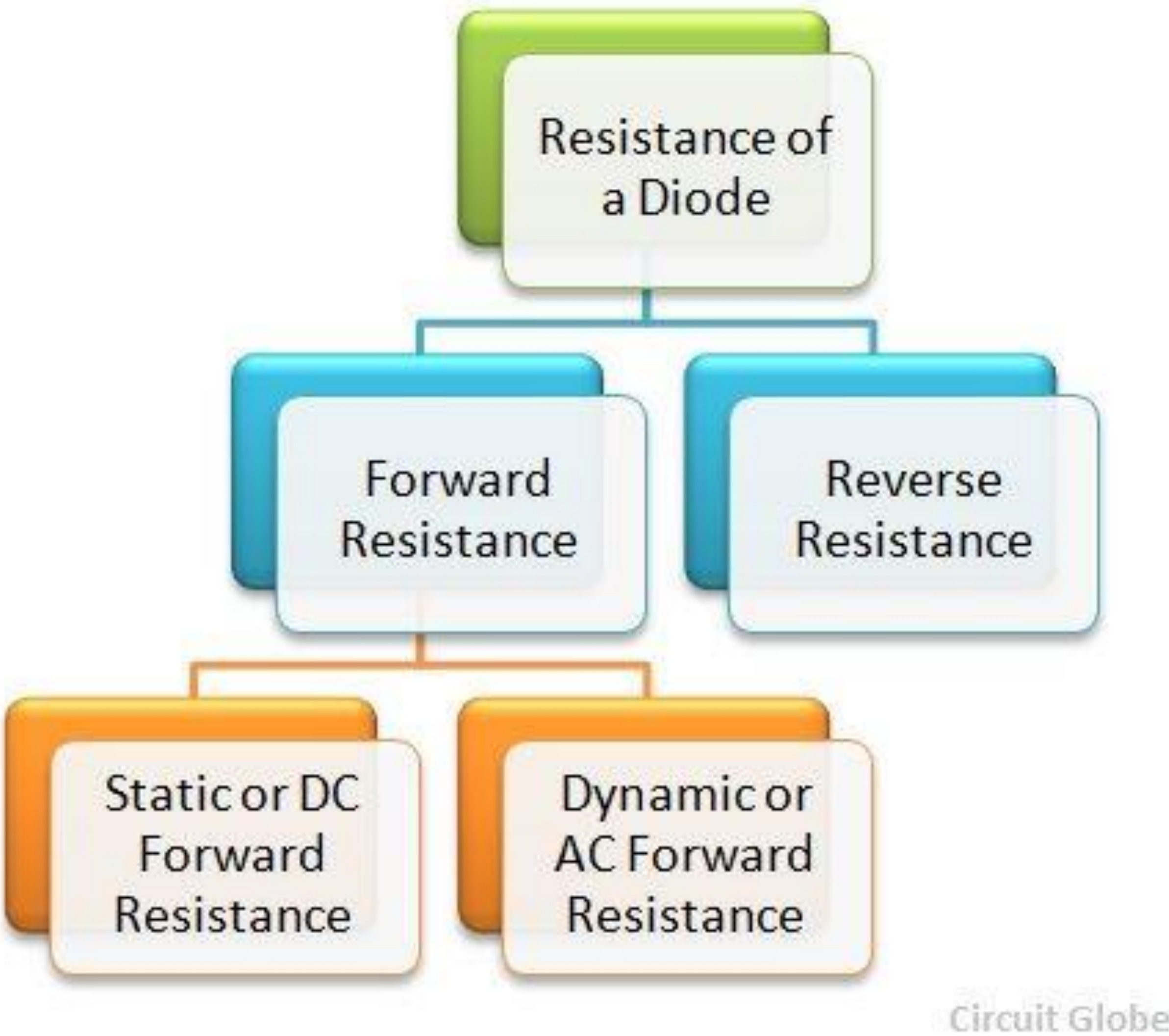
Diode Power Dissipation

- The power dissipation in a diode is simply calculated as the device terminal voltage multiplied by the current level.
- Device manufacturers specify a maximum power dissipation for each type of diode. If the specified level is exceeded, the device will overheat and it may short-circuit or open-circuit.
- When the Temperature Effect on Semiconductor Diode exceeds the specified level, the device maximum power dissipation must be derated.



Diode Resistance

Diode Resistance



DC or Static Resistance

- The resistance of the diode at the operating point can be found simply by finding the corresponding levels of V_D and I_D and applying the following Equation

$$\boldsymbol{R_D = \frac{V_D}{I_D}}$$

- The dc resistance levels at the knee and below will be greater than the resistance levels obtained for the vertical rise section of the characteristics.
- The resistance levels in the reverse-bias region will naturally be quite high.
- The dc resistance of a diode is independent of the shape of the characteristic in the region surrounding the point of interest.

AC or Dynamic Resistance

- If a sinusoidal rather than dc input is applied, the situation will change completely.
- The varying input will move the instantaneous **operating point up and down** a region of the characteristics and thus defines a specific **change in current and voltage**.
- With no applied varying signal, the point of operation would be the Q-point appearing on determined by the applied dc levels.
- The designation Q-point is derived from the word quiescent, which means "still or unvarying."
- A straight-line drawn tangent to the curve through the Q-point will define a particular change in voltage and current that can be used to determine the ac or dynamic resistance for this region of the diode characteristics.

$$\boldsymbol{r_D = \frac{\Delta V_D}{\Delta I_D}}$$

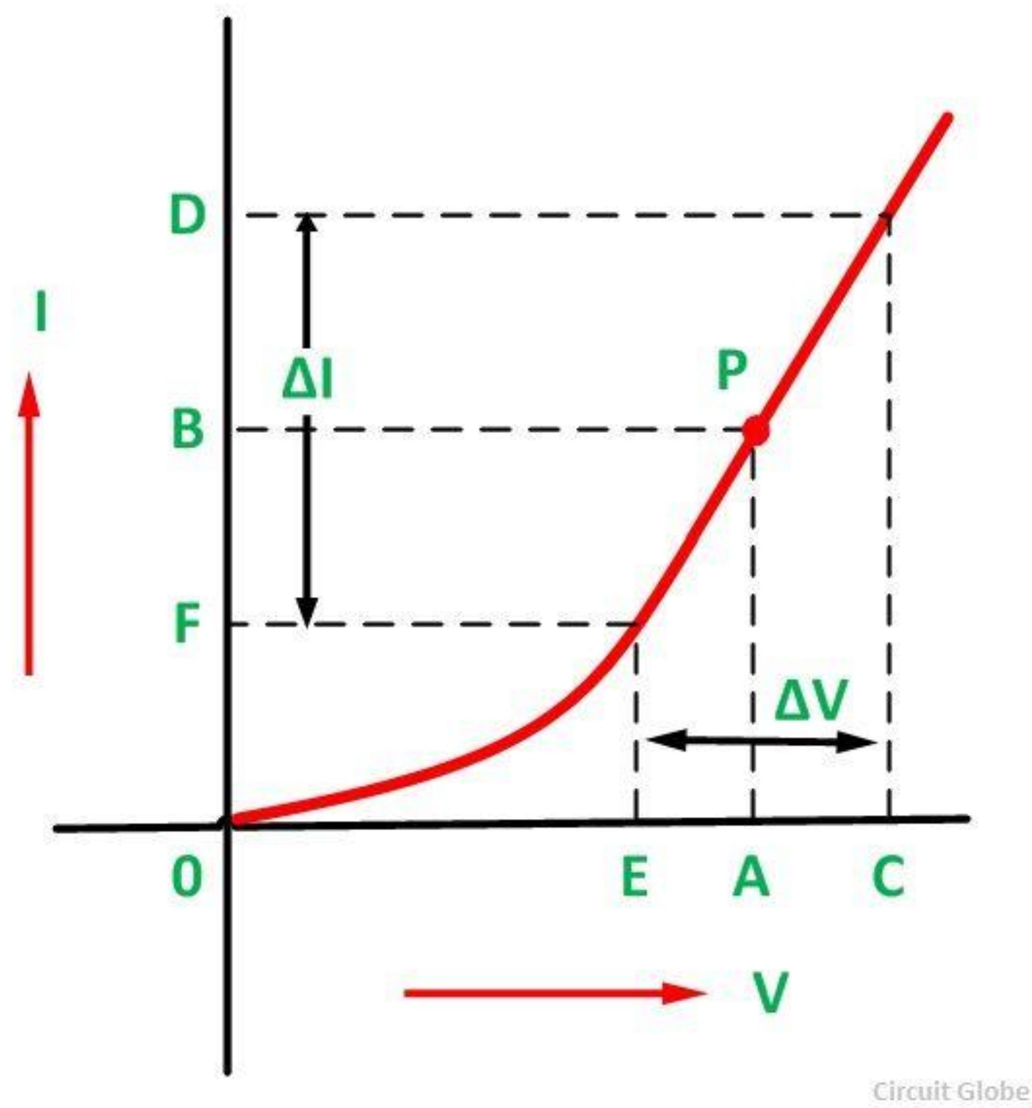
Diode Resistance

DC or Static Resistance

$$R_F = \frac{OA}{OB}$$

AC or Dynamic Resistance

$$r_f = \frac{CE}{DF} = \frac{\Delta V}{\Delta I}$$



Diode Equivalent Circuits

- An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system, or such in a particular operating region.
- In other words, once the equivalent circuit is defined, the device symbol can be removed from a schematic and the equivalent circuit inserted in its place without severely affecting the actual behavior of the system.
- The result is often a network that can be solved using traditional circuit analysis techniques.

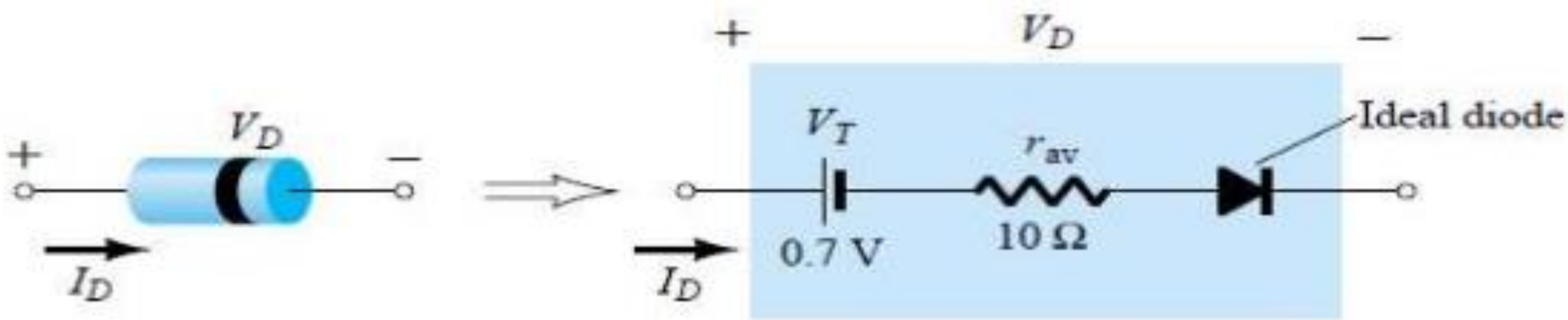
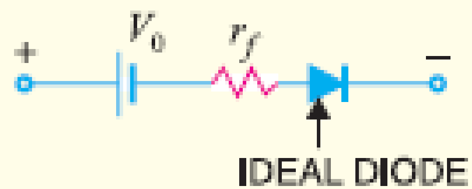
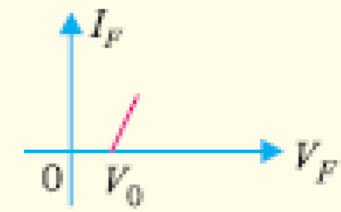
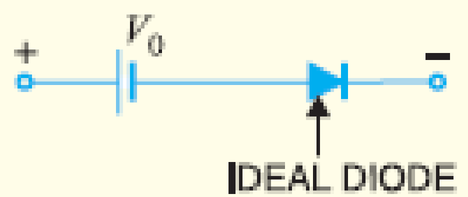
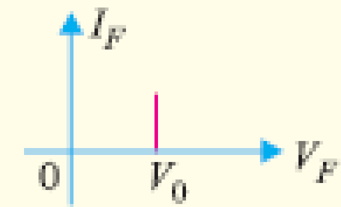
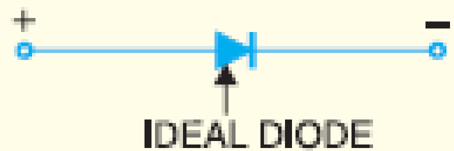
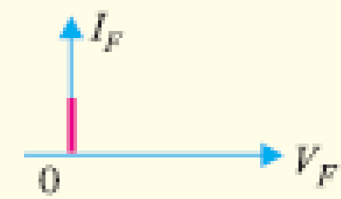


Figure 1.32 Components of the piecewise-linear equivalent circuit.

6.5 Crystal Diode Equivalent Circuits

It is desirable to sum up the various models of crystal diode equivalent circuit in the tabular form given below:

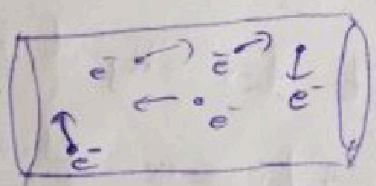
S.No.	Type	Model	Characteristic
1.	Approximate model		
2.	Simplified model		
3.	Ideal Model		

EC-204
Assignment

J. Abhinav
9201150

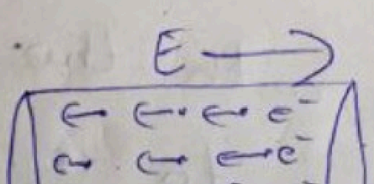
(1) In a conductor when temperature is increased resistivity increases. A conductor contains a large number of loosely bound electrons called as free electrons, also the positive part of the atom i.e nucleus is fixed in its position, this is called lattice. So, in absence of electric field, electrons move freely in all directions. The number of electrons moving from left to right is equal to right to left, so there is no current flow. Sometimes the electron can collide with the positive lattice and come to rest. The path of electron will thus be uncertain. But when electric field is applied, electrons move opposite

to that of electric field, at this time they may be accelerated because of externally applied electric field. At the same time, they can also collide with positive ions i.e lattice and halt and agin move because of electric field. Thus the electron moves with a drift velocity. It is the average velocity of all the electrons



Electrons move in random directions because of thermal energy.

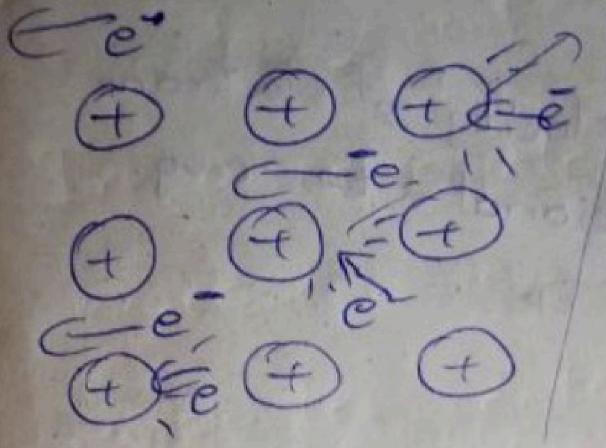
net $I = 0$



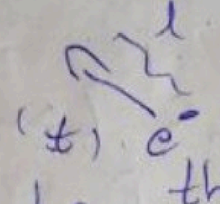
In presence of electric field, they move in ordered motion.

$I \neq 0$

Electrons keep drifting, they halt when they strike lattice and again regain energy becoz of electric field,



The electrons collide frequently with lattice.



Let 'l' be the drift distance travelled by an electron in time 't'.

Then drift velocity

$$V_d = \frac{l}{t}$$

Let the avarage time that an electron takes between successive collisions be 'T', then we know,

$$\left(\because s = ut + \frac{1}{2}at^2,\ u = 0\right)$$

$$l = \frac{1}{2} a_e (T)^2 \qquad m = m_e = \text{mass of } e^-$$

$$F_e = m_e a_e \qquad a_e = \frac{Eq}{m}$$

$$qE = m_e a_e \Rightarrow$$

$$l = \frac{1}{2} \frac{Eq}{m} (T)^2$$

$$V_d = \frac{l}{T} = \frac{1}{2} \frac{Eq \,(T)^{\cancel{2}}}{m \cancel{T}} = \frac{1}{2}\left(\frac{Eq}{m}\right) T$$

$$\boxed{V_d \propto \tau}$$

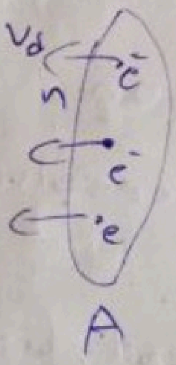
Hence, the drift velocity of electrons is directly proportional to avg. collision time.

we know,

$J \Rightarrow$ Current density

$J = \frac{I}{A} = \sigma E$ ($\because$ Ohm's law $J = \sigma E$)

we also, $J = \frac{I}{A} = \underline{n e V_d}$



Let 'n' no. of electrons move through a cross-sectional area 'A', each having charge 'q', crossing in time Δt, with drift velocity 'V_d'. Then net charge (ΔQ)

$$\Delta Q = n V_d A \Delta t q$$

$$I = \frac{\Delta Q}{\Delta t} = \frac{n V_d A \cancel{\Delta t} q}{\cancel{\Delta t}} = n V_d A q$$

$$J = \frac{I}{A} = \frac{n V_d \cancel{A} q}{\cancel{A}}$$

$$\boxed{J = n V_d q}$$

From Ohm's law

$$J = \sigma E$$

$$\sigma = \frac{1}{\rho}$$ $\rho \rightarrow$ resistivity

$\sigma \rightarrow$ conductivity.

$$n V_d q = \sigma E$$

$$n V_d q = \frac{E}{\rho}$$

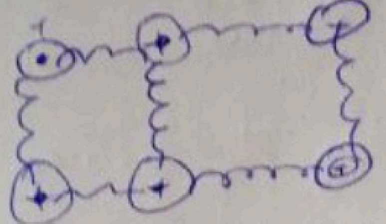
$$\rho = \frac{E}{n V_d q} = \frac{E}{n \left(\frac{1}{2}\right) \frac{E q}{m} \tau q}$$

$$\rho = \left(\frac{2 E m}{n E q^2}\right) \tau$$

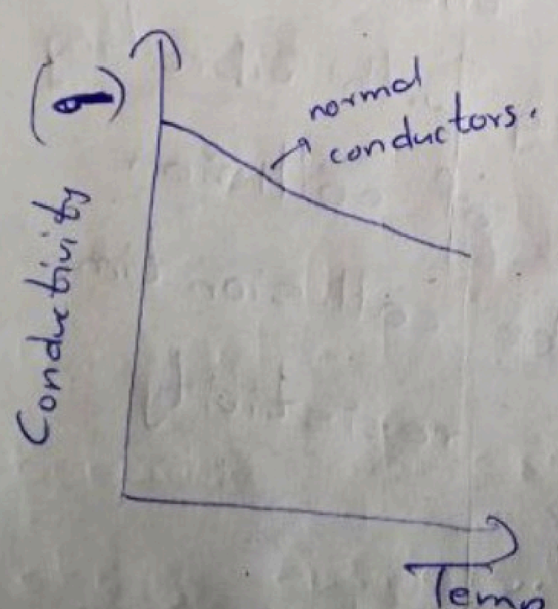
$$\boxed{\rho \propto \frac{1}{\tau}}$$

As, temperature increases, atoms in a conductor start vibrating as they absorb energy. As, now there is more of an electron colliding with vibrating lattice. So, frequency of collision increases $\left(f = \frac{1}{\tau}\right)$, so, the collision time decreases. As $\rho \propto \frac{1}{\tau \downarrow}$, resistivity increases.

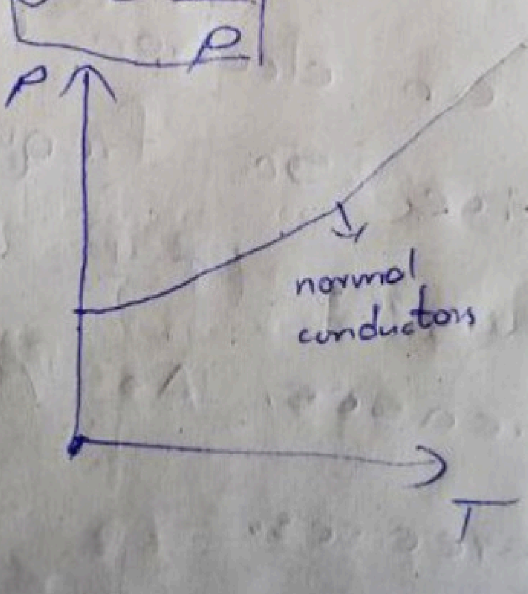
The positive ions keep vibrating about their positions. Like springs are connected between



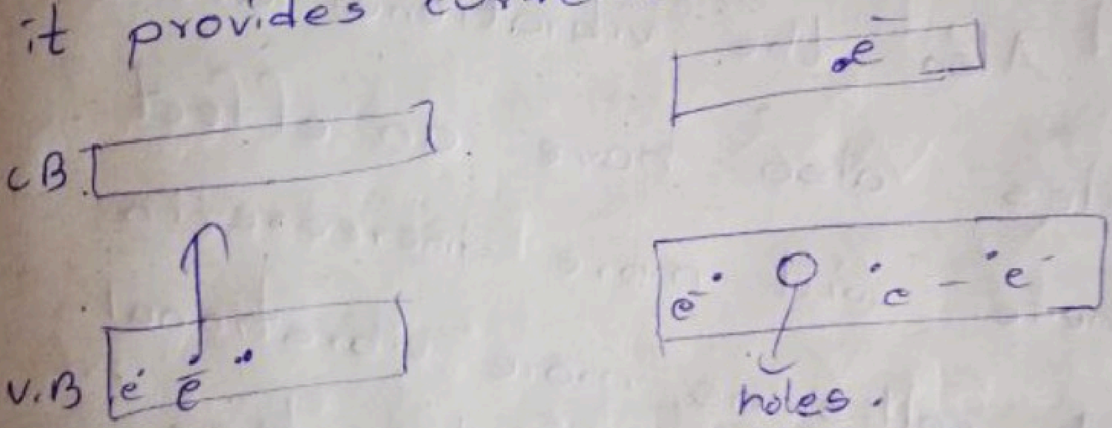
them. More is the temperature, more is the vibrational frequency. Hence lesser the average collision time (or) relaxation time (τ). More is the resistivity as electrons collide more often at higher temperature. This is the case in conductors but in Semiconductors (S.C) there is a cho reverse.



$$\boxed{\sigma = \frac{1}{\rho}}$$



In semiconductor solid, there is
an energy band. One, is the
valence band where electrons are
bounded to nuclei and do not help
in conducting electricity or current.
But if electron is in conduction
band, that e^- is free electron &
it provides current.



The removal of electron from V.B
by supply of heat e.t.c creates
a positive charge carrier called
holes. Both these electrons &
holes are responsible for
conductivity in a semi conductor.

If temperature is
increased, the avg. energy of

electron and positive lattice is also increased. Electrons gain energy and break bonds in V.B and move to conduction band. Similarly holes will also increase. Overall as charge carriers are increased, conductivity increases.

Also, the vibrational lattice molecules also have an effect as there will more increase in thermal collisions, more vibrational frequency, lesser relaxation time

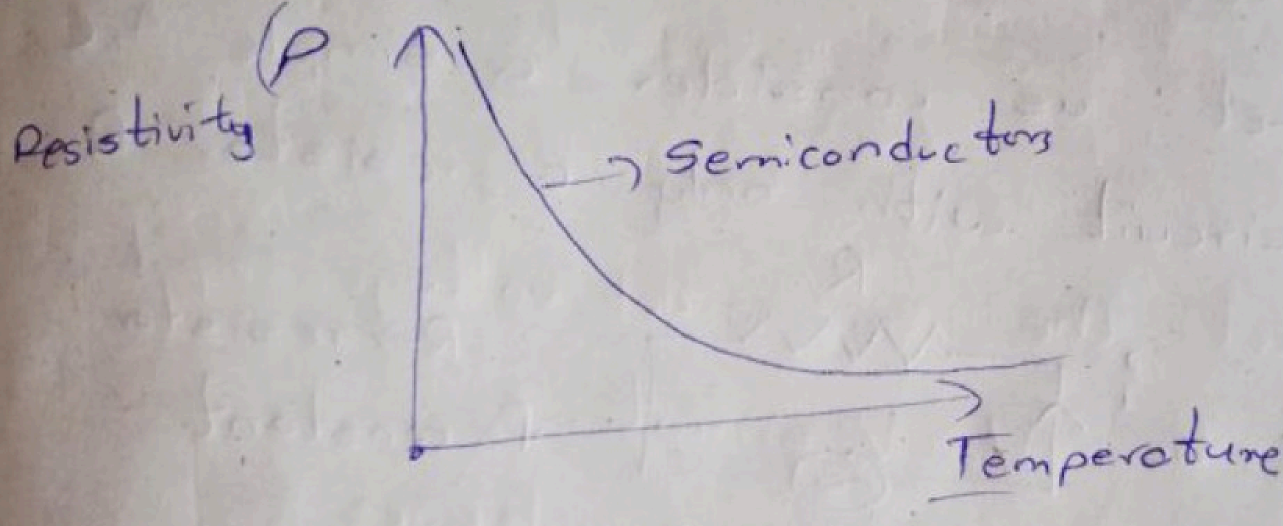
$$\sigma \propto \frac{1}{\rho}$$

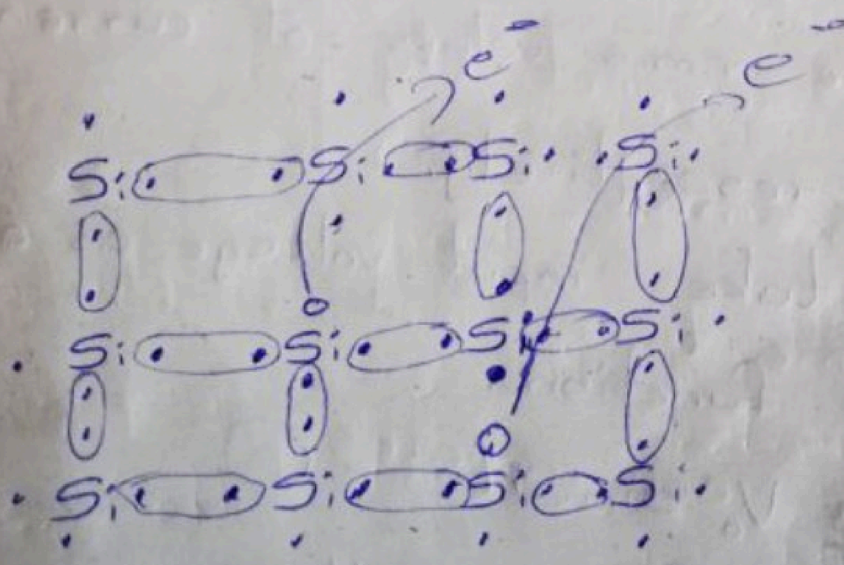
$$\boxed{\rho \propto \frac{1}{\tau}}$$

$\Downarrow$

This effect is neglibible in S.C, because of excessive formation of charge carriers.

Thus, for Semiconductors with increasing temperatures, resistivity decreases (or) conductivity increases. It is exactly opposite of what we saw in metals.





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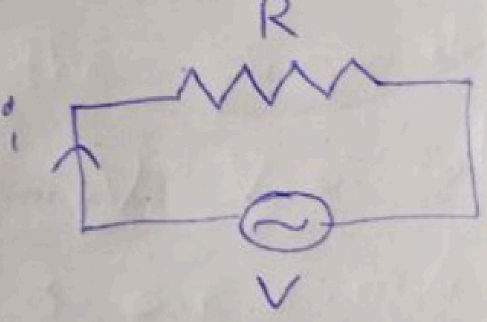
(2) Phase difference ~~is~~ between A.C current & voltage is '0' for resistor & 90° for capacitor (current leads) & -90° for inductor (current lags).

For Resistor:

Let us consider a simple A.C circuit with only a resistor 'R'.



$R \to$ resistor

$f =$ constant

i_{rms} & V_{rms} are r.m.s values of current & voltage respectively.

Let us take input voltage as a sinusoidal function.

$$V_{rms} = V_0 \sin \omega t \quad \text{— (1)}$$

$V_0 \to$ instantaneous voltage

$\omega \to$ frequency

For A.C we know

sinusoidal $\Rightarrow V = \dfrac{V_0}{\sqrt{2}}$ & $i = \dfrac{i_0}{\sqrt{2}}$

From Ohm's law we can write

$V_{rms} = I_{rms} R$ $I_{rms} = i$

$V_0 \sin wt = I_{rms} R$

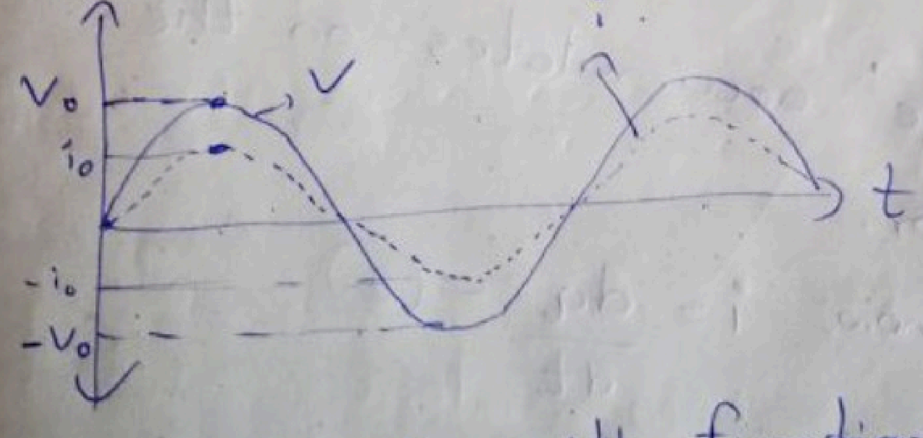
$i = \frac{V_0}{R} \sin wt$

$i_{rms} = i_0 \sin wt$ — ②

Comparing ① & ② we see that V & i are having same phase.

As, they are in same phase the phase difference between current & voltage is '0' for a resistor.

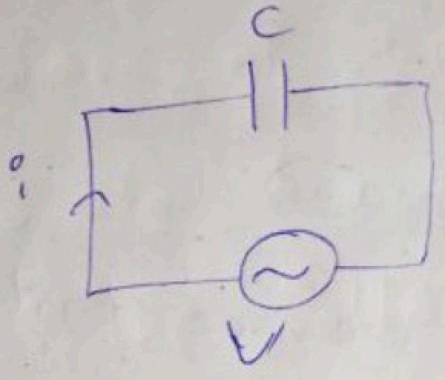
$\xrightarrow[I]{} V$



V & i signals with function of time, assuming 'ω' as constant.

For a Capacitor:

Considering a purely capacitor A.C circuit having sinosoidal voltage source with constant frequency,



Let the sinosoidal voltage input be $V = V_0 \sin\omega t$

V & i are r.m.s voltages & current respectively

$$V = V_0 \sin\omega t \quad -(1)$$

At a time 't' current 'i' flows, where 'q' charge accumulates on the capacitor.

we know, $i = \frac{dq}{dt}$ - (2)

Rate of flow of charge is current.

we know, $C = \frac{Q}{V}$ — (3)

$C \rightarrow$ Capatience.

$V \rightarrow$ Voltage

$Q \rightarrow$ charge

$C = \frac{q}{V}$

$CV = q$

$q = C V_0 \sin \omega t$

Diff. w.r.t 'time'

$\frac{dq}{dt} = C V_0 \frac{d}{dt}(\sin \omega t)$ from eq^n (2)

$i = \omega C V_0 \cos \omega t$

$i = C V_0 \omega \cos \omega t$

let, $C V_0 \omega = i_0$

$V_0 = \frac{i_0}{\omega C}$ comparing with $V = IR$

The resistance component will be $\left(\frac{1}{\omega C}\right)$.

Here we call it as reactance (X_c)

$X_c = \frac{1}{\omega C}$

$i = i_0 \cos\omega t$

$i = i_0 \sin\left(\omega t + \frac{\pi}{2}\right)$ — (4)

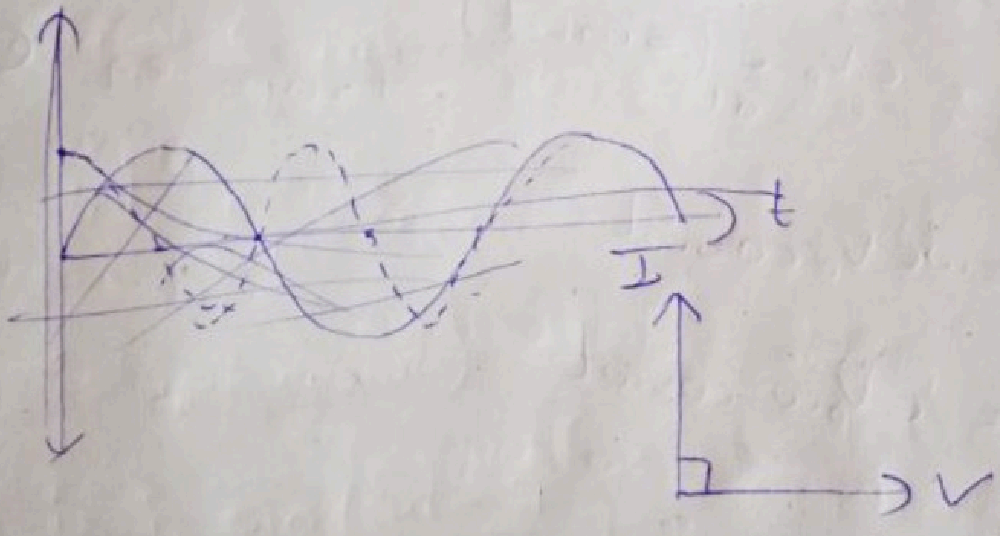
Comparing V & i i.e (1) & (4)

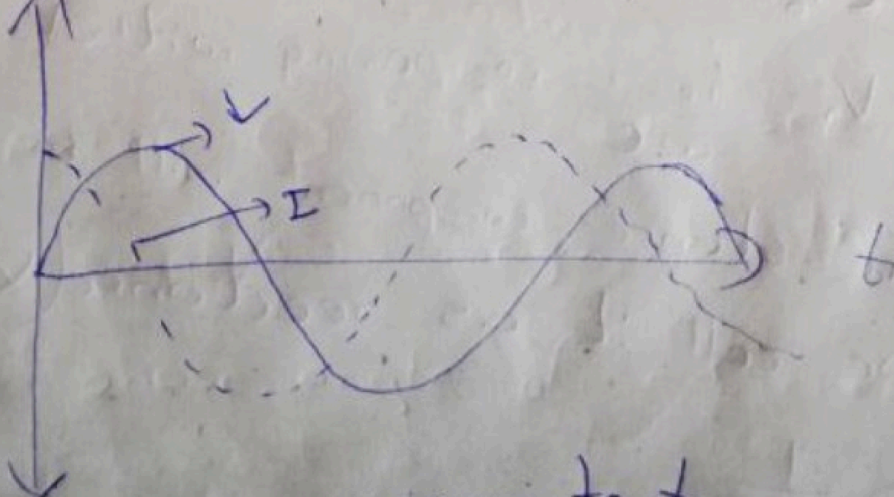
we see i leads voltage by

a phase of $\left(\frac{\pi}{2}\right)$ (or) 90°

Thus, for a capacitor current

leads the voltage by 90° (or) $\frac{\pi}{2}$.



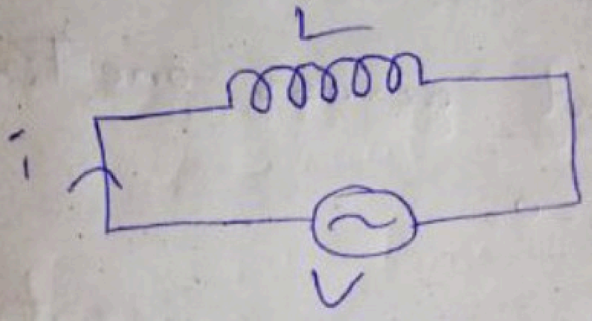


$\omega \Rightarrow$ constant

For an Inductor :

Consider a purely inductive 'AC' circuit. voltage & is sinosoidal, with constant frequency.

V & i are r.m.s voltages & current.



now, $V = V_0 \sin\omega t$ — (1)

we know for an inductor voltage across 'L' is $V_L = L\frac{di}{dt}$

By Kirchoff's Loop law, we get

$$V - V_L = 0$$

$$V_0 \sin\omega t - L\frac{di}{dt} = 0$$

$$V_0 \sin\omega t = L\frac{di}{dt}$$

$$\frac{di}{dt} = \frac{V_0}{L}\sin\omega t$$

Integrating we get,

$$\int \frac{di}{dt} = \int \frac{\epsilon_0}{L} \sin \omega t$$

$$i = -\frac{\epsilon_0}{\omega L} \cos \omega t + c$$

c is a constant, now as we see avg. of $\cos \omega t$ across one Time period is 0. $c = 0$.

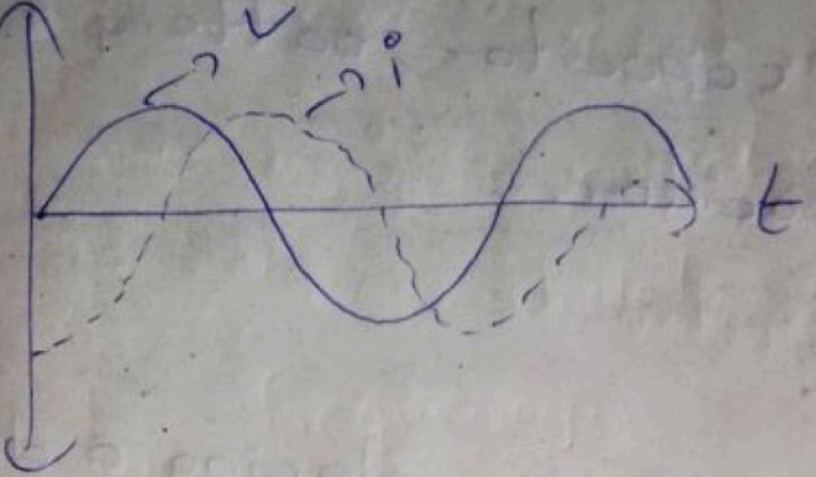
$$i = -\frac{\epsilon_0}{\omega L} \cos \omega t$$

let $\frac{\epsilon_0}{\omega L} = i_0$

$$i = i_0 (-\cos \omega t)$$

$$i = i_0 \sin\left(\omega t - \frac{\pi}{2}\right) \quad - (2)$$

Comparing (1) & (2) we see that current "i" lags with voltage by a phase angle of $-\frac{\pi}{2}$ (or) $-90°$.



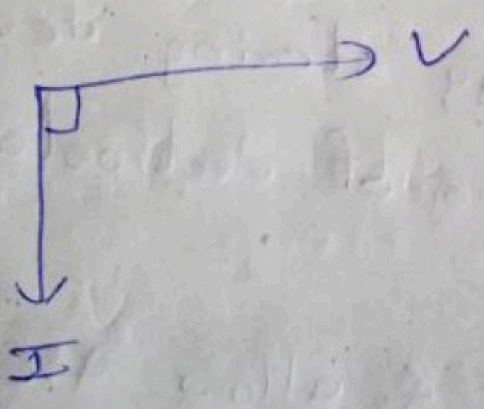
V & i variation with time

$\omega \Rightarrow$ constant

So, for an inductor, current lags the voltage by 90°,

(or)

Voltage leads the current by 90°.



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(3) Diff. b/w capacitor, battery & Supercapacitor.

Capacitor:

→ It is made by placing a dielectric material between the metal plates.

→ They charge and discharge almost instantaneously.

→ It is a passive component.

→ Its range is very small i.e μF to mF.

→ It is a energy storing device and stores in form of electrostatic energy.

→ They block D.C & allow A.C signals.

→ It is widely used as motor starters in domestic appliances.

→ It is almost present in every electronic device.

Battery :

⇒ It also stores energy in the form of chemical energy.

→ It is an active component.

⇒ Used in D.C circuits only

⇒ It charges & discharges slowly

⇒ It releases energy slowly where as capacitor releases bulk energy in a very short time

⇒ There are battery of various ranges.

⇒ Unit to measure battery power is Ampere per hour. (Ah).

⇒ Lifetime is less.

Supercapacitor:

=> It is a double layered capacitor with an electrolyte in place of dielectric.

=> It has higher capatience in range of 1F & 10F.

=> It releases much energy in smaller time.

=> Energy storage capacity is lower than of batters but higher than capacitors.

=> Used in flash lights, laptops e.t.c.

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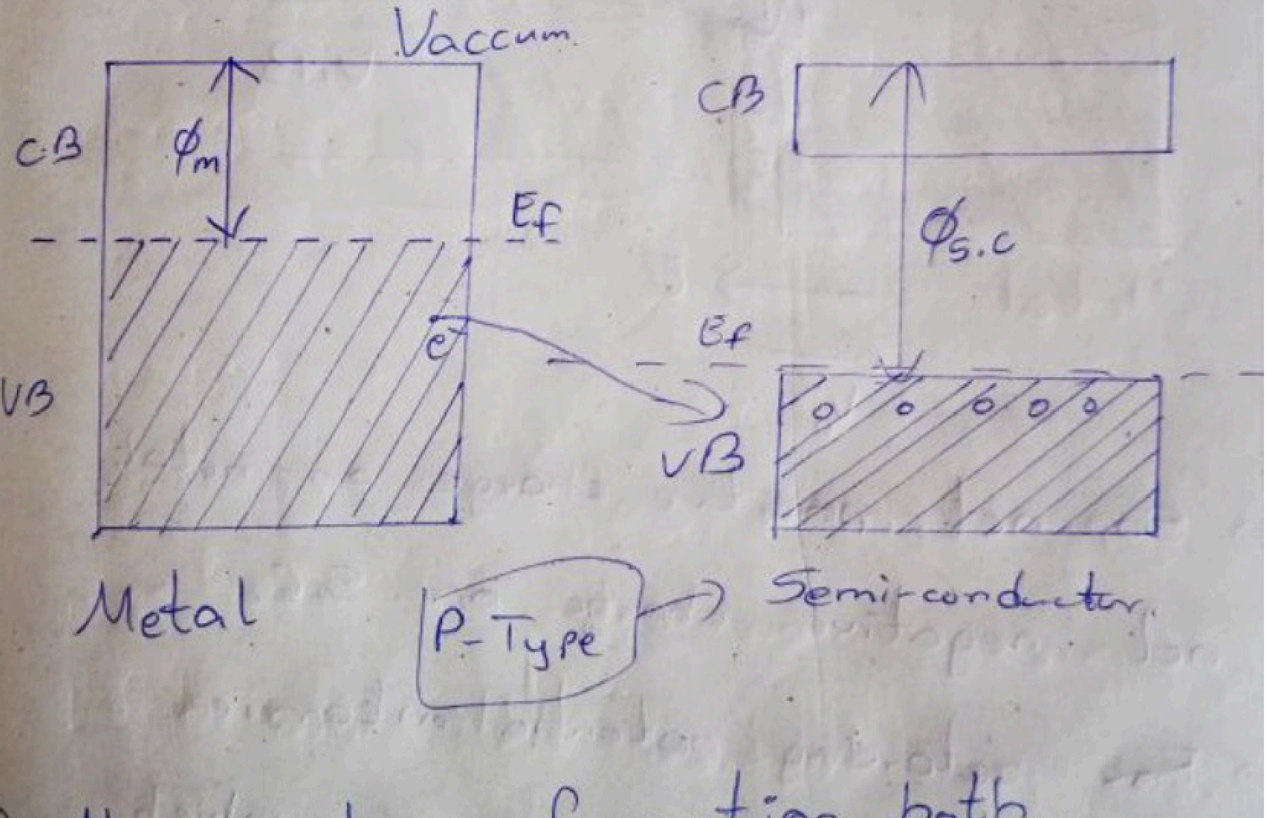
④ Energy band bending diagram for P-type metal-semiconductor.

Schottkey Junction :

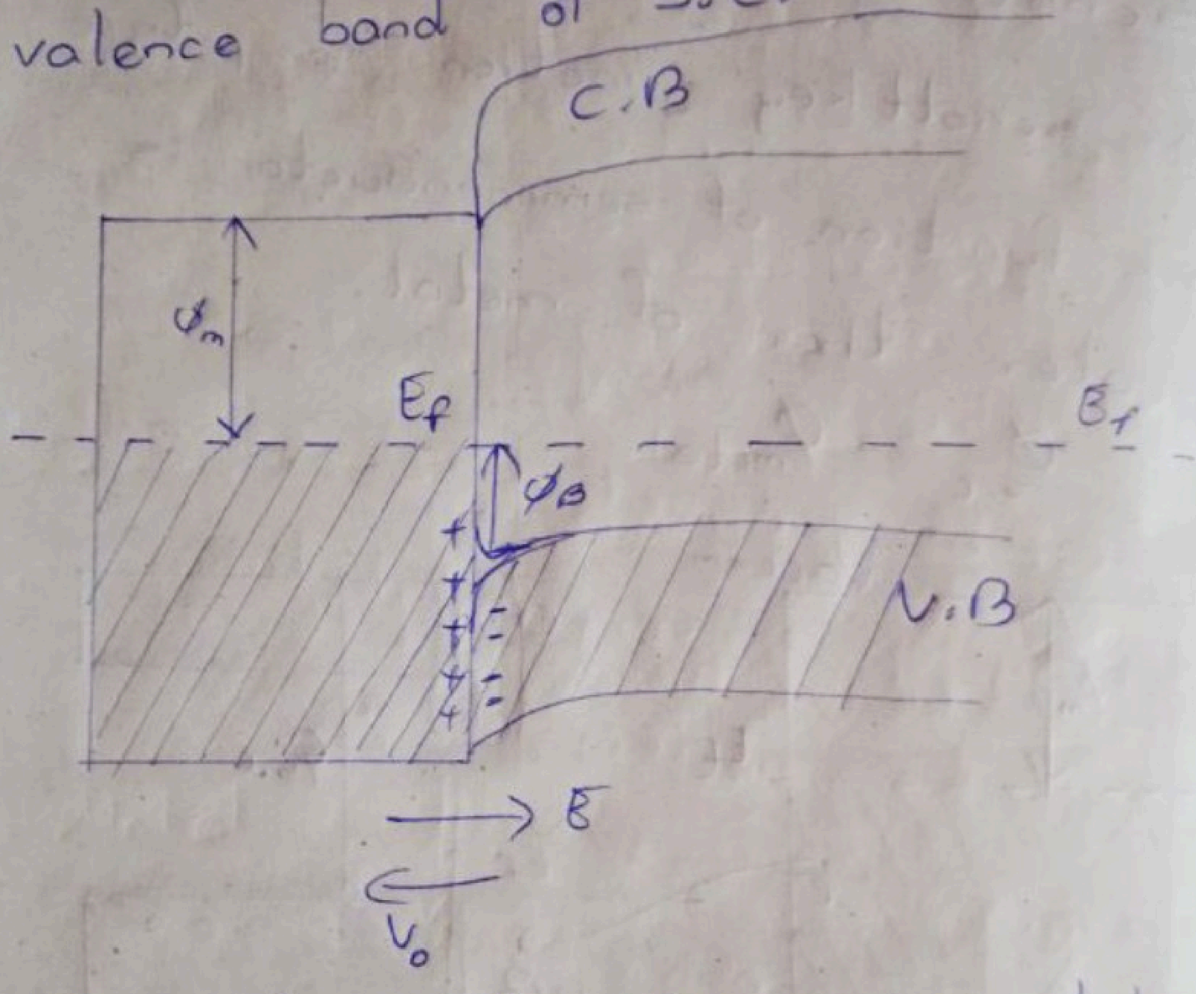
→ In schottkey junction for p-type work function of semiconductor is greater than of metal.

$$\phi_{s.c} > \phi_{metal}$$



→ At junction formation both fermi levels line up at thermal equilibrium. Here, barrier will form.

→ As work function of metal is low w.r.t S.C, electrons from metal move & fill up the holes in valence band of S.C.



→ So, net positive charge on metal. net negative charge on S.C.

→ ~~For~~ retarding potential (or barrier potential of holes is ϕ_B, which must be overcomed in order for current to flow. Hence, current flows only in one direction.

Ohmic Contact

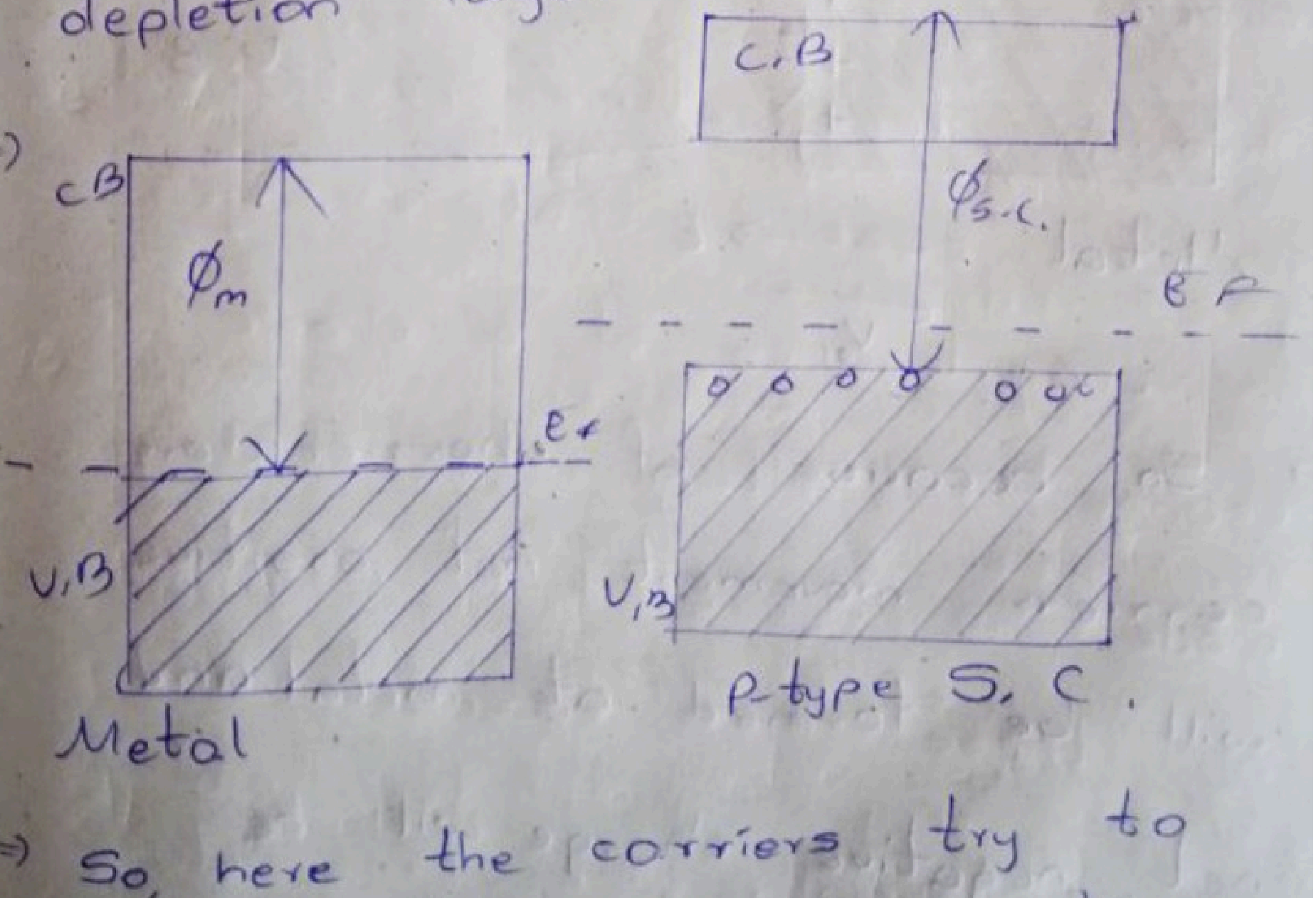
Energy band bending diagrm of p-type.

⇒ In ohmic contact the work function of metals (ϕ_m) is greater than of semiconductor (ϕ_{sm})

$$\phi_m > \phi_{sm}.$$

⇒ Unlike Schottkey junction no depletion layer forms here.

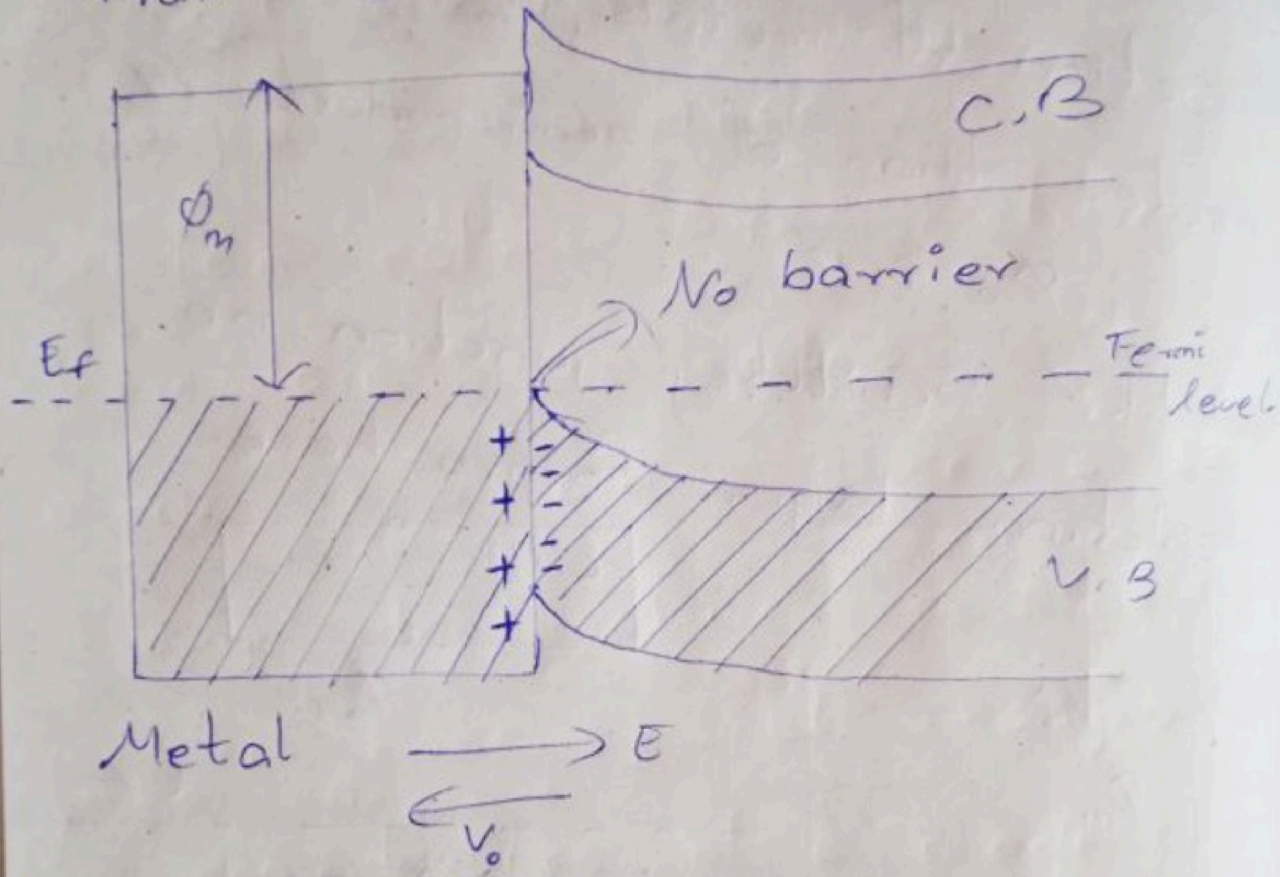
⇒



⇒ So, here the carriers try to move from along the junction

⇒ Hole movement takes place from S.C to metal.

⇒ Electron movement takes place from metal to S.C.



⇒ So, because of ~~charrier~~ charge carriers movement, net positive will be formed at metal and

⇒ net negative charge will be formed at non-metal.

⇒ As, here there are no barriers charges can flow easily.

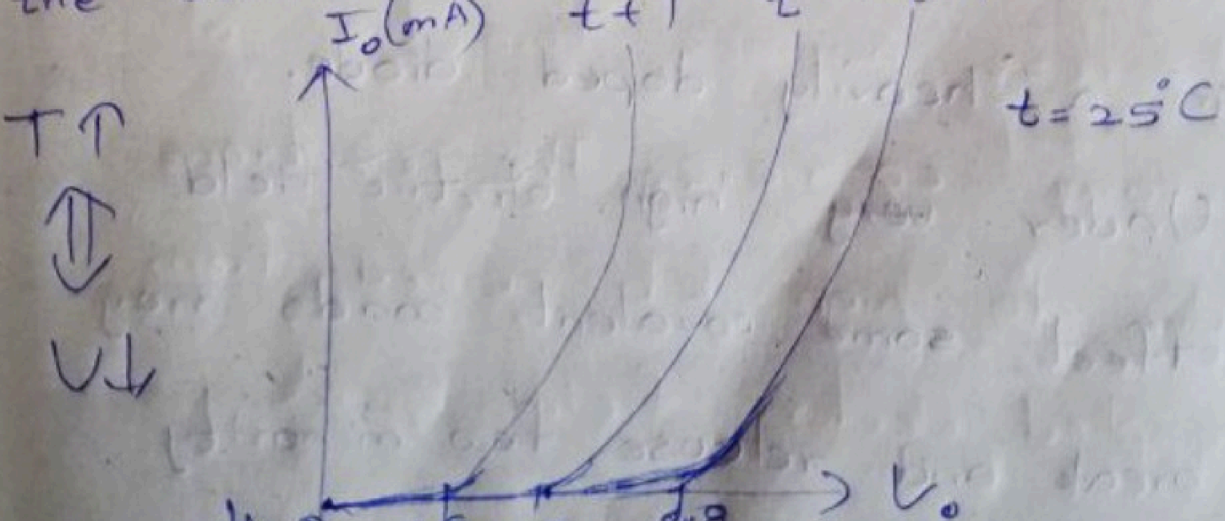
⇒ So, in both modirections movement of carriers takes place. Thus, in ohmic junction current flows in both ways.

J-Abhinav
Q201150

(5) Temperature Coefficient tells us about the change we will get when temperature is changed. In a diode we normally maintain optimum temperature. There are two cases in a diode 1) Forward & 2) Reverse Bias. Through temperature coefficient we can observe what changes in charecteristics of a diode like change in Voltage when the diode is operated in any one of those two cases.

Normally, when temperature is increased, covalent bonds break because of excess energy and form more charge carriers. So, more charges drift through the barrier, that current is called drift current. As drift current increases, the width of depletion layers decreases, as charges get energy to move through the barrier and more charges will be formed near depletion layer. This is the observation under forward bias.

As temperature increases, Lesser the width of depletion layer, lesser the barrier potential.



⇒ A negative ~~positive~~ temp coefficient in F.B, In a forward bias p-n junction diode, the voltage drop decreases with -1.8 mV per C' in Silicon & -2.02 mV per C' in Ge.

Rise in temperature increases e & hole pairs and thus increases conductivity. As a result current(I) through p-n junction also increases. As a result reverse saturation current (I_o) formed due to minority carriers also increases.

Forward Bias ⇒ I ↑ as T ↑

Reverse Bias ⇒ I_o ↑ as T ↑

We also have diode equation $I = I_o\left(e^{\frac{qV}{kT}}-1\right)$ shows how diode current changes with temperature.

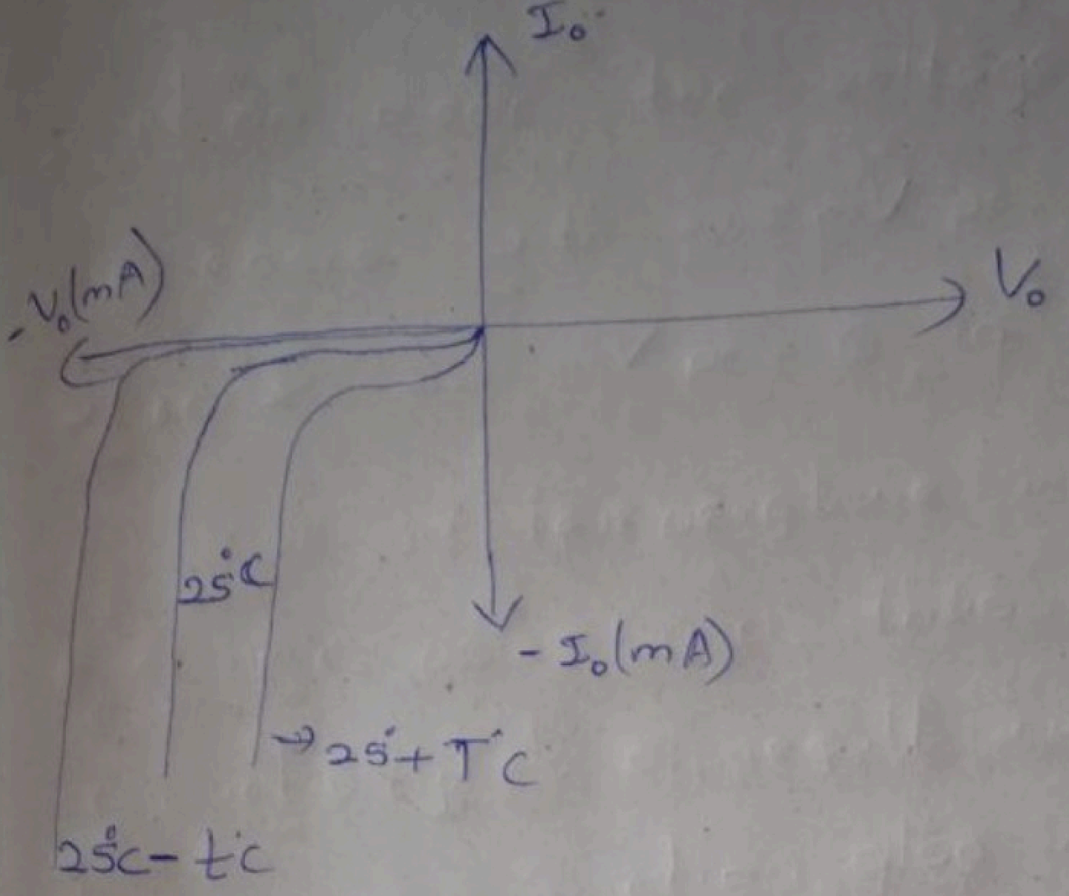
5)
In reverse bias we observe two cases, they are based on doping concentration and other factors. At break down condition in reverse bias we observe two cases

1) Zener break down
2) Avalanche breakdown.

In Zener breakdown condition a negative temperature coefficient is observed. With increase in temperature, break down voltage decreases. Zener Breakdown occurs in a heavily doped diode. Under ~~very high~~ electric field effect, some covalent bonds may break and release few minority charge carriers. Because of high doping, high barrier voltage will be there so high electric field, these few minority carriers under this electric field ~~dis~~ will eventually form large number of minority charge carriers. This results in increase of current in reverse bias. So, as temperature increases more minority charge carriers will form at low electric field than original. So, breakdown voltage will be low for at high temperatures. So, a negative temperature coefficient is observed in reverse bias.

In a lightly doped diode we see avalanche breakdown. There will be some minority charge carriers in a diode under reverse bias. When ~~hi~~ sufficiently high reverse voltage is applied, a sufficiently high electric field generates much kinetic energy to those minority charge carriers, that they disrupt the covalent bond resulting in ~~t~~ excess number formation of charge carriers. The electrons due to high K.E gained from applied electric field break the covalent bonds of the semiconductor. As temperature is increased, the charge carriers will form more, but at the same time, higher external field is required ~~as~~ to energise the charge carriers (or) e^-s so that they can break the covalent bonds. So, here a positive temperature coefficient is observed. With increase in temperature, external electrical field must be increased orelse the break down voltage is increased if field is constant.

In Zener diode.



In Avalanche case