Module 4

Junction Diodes

PN Junction – Equilibrium and biased – Contact potential and space charge phenomena, Current – Voltage relationship, Diode capacitances, One-sided PN junction, Avalanche and Zener breakdown, Zener diode, small-signal model of PN junction. Metal-Semiconductor Contact: Schottky diode, current-voltage characteristics, Ohmic contacts. Varactor diode, Tunnel diode, Photo Diode, Solar Cells.

Topics	Sub Topics	To be covered	No. of hours	Books
PN Junction	**Equilibrium and biased**	PN junction structure, No applied bias, Forward and reverse bias(Built in potential, Depletion Width, Carrier concentration profile)	4	S.O.Kasap, Principles of Electronic Materials and Devices , 2018, 4th Edition, McGraw Hill Education. (or) Ben G Streetman and Sanjay Kumar Banerjee, Solid State Electronic Devices, 2015, 7th Edition, Pearson
	Contact potential and space charge phenomena			
	Current – Voltage relationship	PN junction band diagram		
	Diode capacitances	Depletion capacitance and diffusion capacitance		
	One-sided PN junction	Depletion layer capacitance, built in potential, Carrier concentration profile		Donald A. Neamen, Semiconductor Physics and Devices, 2017,4th Edition, McGraw Hill
	Avalanche and Zener breakdown	Avalanche effect, zener effect, I-V characteristic		S.O.Kasap, Principles of Electronic Materials and Devices , 2018, 4th Edition, McGraw Hill Education
	small-signal model of PN junction	Small signal admittance, Equivalent circuit model		Donald A. Neamen, Semiconductor Physics and Devices, 2017,4th Edition, McGraw Hill

Topics	Sub Topics	To be covered	No. of hours	Books
Zener diode		I-V characteristic, application as voltage regulator	1	Ben G Streetman and Sanjay Kumar Banerjee, Solid State Electronic Devices, 2015, 7th Edition, Pearson or Donald A. Neamen, Semiconductor Physics and Devices, 2017,4th Edition, McGraw Hill
Metal-Semiconductor Contact	Schottky diode, current-voltage characteristics, Ohmic contacts	Energy band diagram, barrier height, depletion width	1	
Varactor diode		Capacitance calculation	1	Donald A. Neamen, Semiconductor Physics and Devices, 2017,4th Edition, McGraw Hill
Tunnel diode		Energy band diagram, I-V characteristic		
Photo Diode		Space charge density, built in field	1	S.O.Kasap, Principles of Electronic Materials and Devices , 2018, 4th Edition, McGraw Hill Education.
Solar cells		Principle, series and shunt resistance, materials and Efficiency		

Unbiased PN Junction

A p-n junction is an interface or a boundary between two semiconductor material types, namely the p-type and the n-type, inside a semiconductor.

Biasing Conditions

- **Zero bias:** There is no external voltage applied to the p-n junction diode.
- **Forward bias:** The positive terminal of the voltage potential is connected to the p-type while the negative terminal is connected to the n-type.
- **Reverse bias:** The negative terminal of the voltage potential is connected to the p-type and the positive is connected to the n-type.

Zero Bias, forward Reverse Bias Characteristics of PN Junction Diode

Case (i) PN Junction diode in Equilibrium with no applied voltage

- In a piece of semiconductor material, if one half is doped by P-type impurity and the other half is doped by N-type impurity, a PN junction is formed.

- The plane dividing the two halves or zones is called PN junction.

- Therefore, at the junction there is a tendency for the free electrons to diffuse over to the P-side and holes to the N-side. This process is called diffusion. As the free electrons move across the junction from N-type to P-type, the donor ions become positively charged.

- Hence a positive charge is built on the N-side of the junction and a net negative charge is established on the P-side of the junction

- This net negative charge on the P-side prevents further diffusion of electrons into the P-side. Similarly, the net positive charge on the N-side repels the hole crossing from P-side to N-side

- Thus a **barrier** is set-up near the junction which prevents further movement of charge carriers, i.e., electrons and holes

- As a consequence of the induced electric field across the depletion layer, an electrostatic potential difference is established between P- and N-regions, which is called the **potential barrier**, junction barrier, diffusion potential, or contact potential, Vo.

- The magnitude of the contact potential Vo varies with doping levels and temperature.
- **Vo is 0.3 V for germanium and 0.72 V for silicon.**

Case 2: Under forward Bias condition

- When positive terminal of the battery is connected to the P-type and negative terminal to the N-type of the PN junction diode, the bias applied is known as forward bias

- As shown in Fig., the applied potential with external battery acts in opposition to the internal potential barrier and disturbs the equilibrium
- As soon as equilibrium is disturbed by the application of an external voltage, the Fermi level is no longer continuous across the junction

Fig. *PN junction under forward bias*

- Under the forward bias condition, the applied positive potential repels the holes in P-type region so that the holes move towards the junction and the applied negative potential repels the electrons in the N-type region and the electrons move towards the junction

- Eventually, when the applied potential is more than the internal barrier potential, the depletion region and internal potential barrier disappear

V-I Characteristics of a diode under forward bias

As the forward voltage (VF) is increased, for $V_F < V_O$, the forward current IF is almost zero (region OA) because the potential barrier prevents the holes from P-region and electrons from N-region to flow across the depletion region in the opposite direction.

For $V_F > V_O$, the potential barrier at the junction completely disappears and hence, the holes cross the junction from P-type to N-type and the electrons cross the junction in the opposite direction, resulting in relatively large current flow in the external circuit.

Fig. *V-I characteristics of a diode under forward bias condition*

- A feature worth to be noted in the forward characteristics shown in Fig. is the cut in or threshold voltage (Vr) below which the current is very small.

- It is 0.3 V and 0.7 V for germanium and silicon, respectively.

- At the cut in voltage, the potential barrier is overcome and the current through the junction starts to increase rapidly.

Fig. *V-I characteristics of a diode under forward bias condition*

Case 3: under reverse Bias condition

When the negative terminal of the battery is connected to the P-type and positive terminal of the battery is connected to the N-type of the PN junction, the bias applied is known as reverse bias

Operation : Under applied reverse bias as shown in Fig., holes which form the majority carriers of the P-side move towards the negative terminal of the battery and electrons which form the majority carrier of the N-side are attracted towards the positive terminal of the battery

Hence, the width of the depletion region which is depleted of mobile charge carriers increases. Thus, the electric field produced by applied reverse bias, is in the same direction as the electric field of the potential barrier.

- Under the reverse bias condition, the thermally generated holes in the P-region are attracted towards the negative terminal of the battery and the electrons in the N-region are attracted towards the positive terminal of the battery

- Consequently, the minority carriers, electrons in the P-region and holes in the N-region, wander over to the junction and flow towards their majority carrier side giving rise to a small reverse current

- This current is known as reverse saturation current, Io. The magnitude of reverse saturation current mainly depends upon junction temperature because the major source of minority carriers is thermally broken covalent bonds.

Fig. *V-I characteristics under reverse bias*

Applications of PN Junction

(1) PN Junction as a diode

Figure shows the current-voltage characteristics of PN junction. The characteristics of the PN junction vary enormously depending upon the polarity of the applied voltage

For a forward-bias voltage, the current increases exponentially with the increase of voltage

A small change in the forward-bias voltage increases the corresponding forward-bias current by orders of magnitude and hence the forward-bias PN junction will have a very small resistance.

Fig. *Ideal I-V characteristics of a PN junction diode*

- The level of current flowing across a forward-biased PN junction largely depends upon the junction area

- In the reverse-bias direction, the current remains small, i.e., almost zero, irrespective of the magnitude of the applied voltage and hence the reverse-bias PN junction will have a high resistance

- The reverse bias current depends on the area, temperature and type of semiconductor material

The semiconductor device that displays these I-V characteristics is called a PN junction diode

Figure shows the PN junction diode with forward-bias and reverse-bias and their circuit symbols

The metal contacts are indicated with which the homogeneous P-type and N-type materials are provided. Thus two metal-semiconductor junctions, one at each end of the diode, are introduced. The contact potential across these junctions is approximately independent of the direction and magnitude of the current

A contact of this type is called an **ohmic contact**, which has **low resistance**. In the forward-bias, a relatively large current is produced by a fairly small applied voltage. In the reverse-bias, only a very small current, ranging from nanoamps to microamps is produced. The diode can be used as a voltage controlled switch, i.e., OFF for a reverse-bias voltage and ON for a forward-bias voltage.

Fig. *(a) Forward-biased PN junction diode and its circuit symbol, (b) Reverse-biased PN junction diode and its circuit symbol*

When a diode is reverse-biased by atleast 0.1V, the diode current is

$$I_R = -I_o$$

As the current is in the reverse direction and is a constant, it is called the diode reverse saturation current

Real diodes exhibit reverse-bias current that are considerably larger than Io. This additional current is called a generation current which is due to electrons and holes being generated within the space-charge region.

A typical value of Io may be 10^{-14} A and a typical value of reverse-bias current may be 10^{-9} A.

(2) PN junction diode as rectifier

- A PN junction diode is a two terminal device that is polarity sensitive.

- When the diode is forward biased, the diode conducts and allows current to flow through it without any resistance, i.e., the diode is ON. When the diode is reverse biased, the diode does not conduct and no current flows through it, i.e., the diode is OFF, or providing a blocking function

- Thus an ideal diode acts as a switch, either open or closed, depending upon the polarity of the voltage placed across it. The ideal diode has zero resistance under forward bias and infinite resistance under reverse bias.

Energy-Band Structure of open-circuited PN Junction

- Consider that a PN junction has P-type and N-type materials in close physical contact at the junction on an atomic scale

- Hence, **the energy band diagrams of these two regions undergo relative shift to equalise the F level**

- The Fermi level EF should be cons throughout the specimen at equilibrium.

Fig. *Energy-band structure*

- The distribution of electrons or holes in allowed energy states is dependent on the position of the Fermi level

- If this is not so, electrons on one side of the junction would have an average energy higher than those on the other side, and **this causes transfer of electrons and energy until the Fermi levels on the two sides get equalised**

- However, such a shift does not disturb the relative position of the conduction band, valence band and Fermi level in any region.

- Equalisation of Fermi levels in the P and N materials of a PN junction is similar to equalisation of levels of water in two containers on being joined together.

- The energy band diagram for a PN junction is shown in Fig., where the Fermi level EF is closer to the conduction band edge E_{cn} in the N-type material while it is closer to the valence band edge Evp in the P-type material

- It is clear that the conduction band edge Ecp in the P-type material is higher than the conduction band edge E_{cn} in the N-type material. Similarly, the valence band edge Evp in the P-type material is higher than the valence band edge E_{vn} in the N-type material.

- As illustrated in Fig., E1 and E2 indicate the shifts in the Fermi level from the intrinsic conditions in the P and N materials respectively. Then the total shift in the energy level Eo is given by

Fig. *Energy-band structure*

This energy Eo (in eV) is the potential energy of the electrons at the PN junction, and is equal to qVo, where Vo is the contact potential (in volts) or contact difference of potential or the barrier potential.

$$E_0 = E_1 + E_2 = E_{cp} - E_{cn} = E_{vp} - E_{vn}$$

The experimental I-V characteristic of a Si

The diode i–v relationship with some scales expanded and others compressed in order to reveal details.

Fig: VI characteristics.

Energy Band Structure of PN Junction Diode

Fermi Level of n-type and p-type semi-conductors

Fermi Level adjustment when PN junction is created

+
-
p-type
n-type
hole
electron
light
conduction band
Fermi level
recombi-
nation
band gap
(forbidden band)
valence band

P
N
Depletion
Region
N
Conduction band
Fermi
Level
P
Valence band
p-n junction

Contact difference of potential

A contact difference of potential exists across an open circuited PN junction. We now proceed to obtain an expression for Eo.

$$E_0 = E_1 + E_2 = E_{cp} - E_{cn} = E_{vp} - E_{vn} \quad (1)$$

To derive E_0:

from the structure, $E_f - E_{vp} = \frac{1}{2}E_G - E_1 \Rightarrow \boxed{E_1 = \frac{1}{2}E_G - E_f + E_{vp}}$ — (2)

$E_{cn} - E_f = \frac{1}{2}E_G - E_2 \Rightarrow \boxed{E_2 = \frac{1}{2}E_G - E_{cn} + E_f}$ — (3)

Combining (2) & (3) we get,

$$E_0 = E_1 + E_2$$

$$= \frac{1}{2}E_G - E_f + E_{vp} + \frac{1}{2}E_G - E_{cn} + E_f .$$

$$\boxed{E_0 = E_G - (E_{cn} - E_f) - (E_f - E_{vp})} \quad \text{— (4)}$$

We know that,

$$n = N_c e^{-(E_c - E_F)/kT}$$

$$p = N_v e^{-(E_F - E_v)/kT}$$

By mass action law, $np = n_i^2$.

$$N_c e^{-(E_c - E_F)/kT} \cdot N_v e^{-(E_F - E_v)/kT} = n_i^2.$$

$$N_c N_v e^{\frac{-E_c + \cancel{E_F} - \cancel{E_F} + E_v}{kT}} = n_i^2.$$

n:electron concentration

p:hole concentration

N_c: *Effective mass of electrons*

N_v: *Effective mass of holes*

$$N_c N_v e^{-E_G/KT} = n_i^2 \qquad [\because E_c - E_v = E_G]$$

Taking ln on both sides,

$$\ln e^{-E_G/KT} = \ln \frac{n_i^2}{N_c N_v}$$

$$\frac{-E_G}{KT} = \ln \frac{n_i^2}{N_c N_v}$$

$$\boxed{E_G = KT \ln \frac{N_c N_v}{n_i^2}} \quad \text{——— (5)}$$

We know that,

for N-type, $E_f = E_c - kT \ln \frac{N_c}{N_D}$.

$$\therefore \boxed{E_{cn} - E_f = kT \ln \frac{N_c}{N_D}} \quad \text{—— (6)}$$

for P-type

$E_f = E_v + kT \ln \frac{N_v}{N_A}$.

$$\boxed{E_f - E_{vp} = kT \ln \frac{N_v}{N_A}} \quad \text{—— (7)}$$

By Law of Mass Action,

$n.P = n_i^2$

$N_V \rightarrow P = \frac{n_i^2}{N_D}$

$\Rightarrow n_i^2 = N_V \times N_D$

|||ly

$N_C \rightarrow n = \frac{n_i^2}{N_A}$

$n_i^2 = N_C \times N_A$

Sub (5), (6) & (7) in (4)

$$E_0 = KT\ln\left(\frac{N_C N_V}{n_i^2}\right) - KT\ln\left(\frac{N_C}{N_D}\right) - KT\ln\left(\frac{N_V}{N_A}\right)$$

$$= KT\ln\left[\frac{N_C N_V}{n_i^2} \div \frac{N_C}{N_D} \div \frac{N_V}{N_A}\right]$$

$$= KT\ln\left[\frac{N_C N_V}{n_i^2} \times \frac{N_D}{N_C} \times \frac{N_A}{N_V}\right]$$

$$E_0 = KT\ln\left[\frac{N_D N_A}{n_i^2}\right]$$ But $E_0 = qV_0$.

$$\boxed{V_0 = \frac{E_0}{q} = \frac{KT}{q}\ln\frac{N_D N_A}{n_i^2}.}$$

Charge densities in N-type & P-type SC

Note: ∵ The Semiconductor is electrically neutral, the magnitude of the +ve charge density = −ve concentration.

$$\boxed{N_D + p = N_A + n} \quad \text{— (1)}$$

For N-type: $N_A = 0$; $n >> p$. $\Rightarrow n \approx N_D \Rightarrow n_n \approx N_D$ — (2)

W.K.T by mass action law, $n_n \cdot p_n = n_i^2$

$$p_n = \frac{n_i^2}{n_n}.$$

$$\boxed{p_n = \frac{n_i^2}{N_D}} \quad \text{(from (2))}$$

(||ly W.K.T)

$$\sigma = q n \mu_n$$

$$\boxed{\sigma_N \approx q N_D \mu_n}$$

For P-type, from ① $\Rightarrow N_D = 0$; $p >> n$;

$$\Rightarrow p \approx N_A$$

$$p_p \approx N_A \quad \text{——— ③}$$

W.K.T by mass action law, $n_p p_p = n_i^2$

$$n_p = \frac{n_i^2}{p_p}$$

$$\boxed{n_p = \frac{n_i^2}{N_A}} \quad \text{from ③}$$

|||ly W.K.T,

$$\sigma = q p \mu_p$$

$$\boxed{\sigma_p = q N_A \mu_p}$$

Transition Capacitance

→ It occurs under reverse bias.

→ When a diode is reverse biased, depletion region width increases.

→ Here, the parallel layers of oppositely charged immobile ions on the 2 sides of the junction form the transition capacitance C_T.

$$C_T = \frac{\varepsilon A}{W}$$

where $\varepsilon \rightarrow$ Permittivity of the material

$A \rightarrow$ cross-sectional Area.

$W \rightarrow$ Width of the depletion layer.

→ <u>Under no bias, when $V=0$</u>; W is the order of 0.5 microns.

The depletion region acts as a dielectric between 2 Conducting P & N regions.

∴ These regions act as a parallel plate capacitor whose transition capacitance $C \approx 20PF$ with no bias.

Derivation:

→ Consider a PN diode which is asymmetrically dop at the junction.

→ Assume that the doping level of P-side is greater than the doping level of n-side (ie) $N_A >> N_D$.

→ As we know, net charge = 0.

$$N_A W_p = N_D W_n.$$

$$\frac{N_A}{N_D} = \frac{W_n}{W_p}.$$

∴ when $N_A >> N_D$

$W_n >> W_p$.

→ By poisson's law,

$$\boxed{\frac{d^2V}{dx^2} = \frac{-qN_A}{\varepsilon}.}$$

Note: Doping ↑ . ↓
Conductivity ↑ . ↓
Depletion layer ↓ ↑

Integrating one time,

$$\frac{dV}{dx} = \frac{-qN_A}{\varepsilon} x.$$

Integrating again, $V = \frac{-qN_A}{\varepsilon} \frac{x^2}{2}$

At $x = W_n = W$.

$$\boxed{V = \frac{-qN_A W^2}{2\varepsilon}.}$$

$$\frac{dV}{dW} = \frac{-qN_A \cancel{2}W}{\cancel{2}\varepsilon}$$

$$\boxed{\frac{dW}{dV} = \frac{-\varepsilon}{qN_A W}} \quad \text{——— (1)}$$

→ If A is the area of the junction, the charge in the depletion layer is

$$Q = qN_A WA.$$

$$\boxed{\frac{dQ}{dV} = qN_A A \frac{dW}{dV}} \quad \text{——— (2)}$$

Sub ① in ②

$$\frac{dQ}{dV} = \cancel{q} \cancel{N_A} A \cdot \left(\frac{-\xi}{\cancel{q} \cancel{N_A} W} \right).$$

$$\Rightarrow \left| \frac{dQ}{dV} \right| = \frac{A\xi}{W}.$$

$$\Rightarrow \boxed{C_T = \frac{A\xi}{W}.}$$

Diffusion Capacitance

Diffusion Capacitance (Storage Capacitance) [occurs under FB]

→ The capacitance that exists in a forward biased junction is called diffusion or storage capacitance. It is denoted by C_D.

→ The value of C_D is much larger than C_T ($C_D >> C_T$)

→ In forward biased Condition, the width of depletion region decreases and the holes from P side get diffused in N side, while electrons from N side move into the P-side. As the applied voltage increases, the Concentration of injected Charged particles increases. This rate of change of injected particles with the applied voltage Constitutes a Capacitance called <u>diffusion capacitance</u>.

→ The expression for diffusion capacitance is,

$$C_D = \frac{dQ}{dV}$$; rate of change of injected charge with applied voltage [e^{-ns} : n to p ; holes : p to n]

dQ → change in the number of minority carriers outside the depletion region.

dV → change in voltage.

$C_D \propto$ forward current I.

C_D → value ranges from 10 to 1000 PF.

C_D → Negligible for a RB PN junction.

$C_D \propto \frac{1}{f}$; C_D high at low freq.
C_D low at high freq.

According to Diode Current equation,

$$I = I_0 \left(e^{V/\eta V_T} - 1 \right).$$

$$= I_0 e^{V/\eta V_T} - I_0.$$

$\because I_0$ is very small, it can be neglected

$$I \simeq I_0 e^{V/\eta V_T} \quad \text{——— (6)}$$

Differentiating,

$$\frac{dI}{dV} = I_0 e^{V/\eta V_T} \left(\frac{1}{\eta V_T} \right) \quad \text{——— (7)}$$

From (5), $\left| \frac{dQ}{dV} \right| = \frac{L_p^2}{D_p} \cdot \frac{dI}{dV}$

Sub (7) here,

$$\left|\frac{dQ}{dV}\right| = \frac{L_p^2}{D_p} \cdot \underbrace{I_0 e^{V/\eta V_T}}_{\text{from (6)}} \left(\frac{1}{\eta V_T}\right).$$

$$\boxed{C_D = \frac{\tau \cdot I}{\eta V_T}}$$

where $\tau \rightarrow$ mean lifetime for holes & electrons.

$I \rightarrow$ diode forward current.

η is a constant, (for Ge; $\eta = 1$.
Si ; $\eta = 2$).

$V_T = \frac{KT}{q}$ Volt equivalent of temp (ie) Thermal voltage.

K is the Boltzmann Constant $= 1.38066 \times 10^{-23} J/k$.

q is the Charge of electron $= 1.602 \times 10^{-19}$ col

T is the temp of diode junction in K.

1) Excess minority charge (holes) Q exist on N side

$$Q = Aq L_p P_n(0) \quad \text{——— (1)}$$

2) Hole current : $$I = \frac{Aq D_p P_n(0)}{L_p} \quad \text{——— (2)}$$

Differentiating (1) w.r.t V

$$\frac{dQ}{dV} = Aq L_p \frac{dP_n(0)}{dV} \quad \text{——— (3)}$$

2) Hole current : $I = \dfrac{A q D_p P_n(0)}{L_p}$ —— ②

Differentiating ① w.r.t V

$$\frac{dQ}{dV} = A q L_p \frac{dP_n(0)}{dV} \quad \text{—— ③}$$

From ②, $P_n(0) = \dfrac{L_p I}{A q D_p}$.

Differentiating w.r.t V,

$$\frac{dP_n(0)}{dV} = \frac{L_p}{A q D_p} \cdot \frac{dI}{dV} \quad \text{—— ④}$$

Sub Eqn (4) in (3),

$$\frac{dQ}{dV} = Aq\,L_p \cdot \frac{L_p}{qA\,D_p} \cdot \frac{dI}{dV}.$$

$$\frac{dQ}{dV} = \frac{L_p^2}{D_p} \cdot \frac{dI}{dV}. \quad \text{——— (5)}$$

$$C_D = \frac{L_p^2}{D_p} \cdot g \Rightarrow \boxed{C_D = \tau \cdot g}$$

where $\tau = \frac{L_p^2}{D_p}$; Mean life time.

Capacitor

PN Junction Diode Connected in Reverse Bias

Junction Capacitance occure in PN junction Diode when it is connected in reverse bias condition because both P and N region act as electrode and depletion region act as dielectric medium

Why can't we use diodes in place of battery? We get 1.4 V in a cheaper cost than battery. But Why we don't use diodes as battery?

- Diodes are not an energy source
- They modify how energy may flow
- Their function is to allow current or electrons or charge to flow in one direction in a circuit much more readily than in the other direction
- A good analogy is to think of them as a non-return valve of one-way-valve in a water flow system.

Depletion Approximation, Electric Field and Potential for np junction

Abrupt junction

- The amount of uncovered negative charge on the left hand side of the junction must be equal to the amount of positive charge on the right hand side of the metalurgical junction. Overall space-charge neutrality condition;

$$N_A x_p = N_D x_n$$

The higher doped side of the junction has the narrower depletion width

when $N_A = N_D \Rightarrow x_n = x_p$

Abrupt junction

- x_n and x_p is the width of the depletion layer on the n-side and p-side of the junction, respectively.

When $N_D >> N_A$ (unequal impurity concentrations)

and $x_p >> x_n$, $W \cong x_p$

- Unequal impurity concentration results an unequal depletion layer widths by means of the charge neutrality condition;

$$N_A . x_p = N_D . x_n$$

W = total depletion region

Abrupt junction

For equal doping densities $W = x_n + x_p$

Total depletion layer width , W

$$W = \left(\frac{1}{N_A} + \frac{1}{N_D}\right)\sqrt{\frac{2\varepsilon_{Si}V_{bi}N_A N_D}{q(N_A + N_D)}}$$

$$\boxed{W = \sqrt{\frac{2\varepsilon_{Si}V_{bi}(N_A + N_D)}{qN_A N_D}}}$$

One-Sided abrupt p-n junction

Abrupt p-n junction

heavily doped p-type

$N_A >> N_D$

x_p can be neglected

One-Sided abrupt p-n junction

$$W \cong x_n = \frac{1}{N_D}\sqrt{\frac{2\varepsilon_{Si}V_{bi}N_A N_D}{q\left(N_A + \boxed{N_D}\right)}} = \frac{1}{N_D}\sqrt{\frac{2\varepsilon_{Si}V_{bi}N_A N_D}{qN_A}}$$

neglegted
since $N_A >> N_D$

$$\boxed{W \cong \sqrt{\frac{2\varepsilon_{Si}V_{bi}}{qN_D}}}$$

obtain a similar equation for $W \cong x_p$

in the case of $N_D >> N_A$

One-sided abrupt junction

One-Sided abrupt p-n junction

at " Rev Bias "

Breakdown in PN junction diodes:

→ In reverse biased condition as long as the reverse voltage is less than the breakdown voltage, the diode current is small and almost constant at I_0. But when reverse voltage increases beyond certain value, a large diode current flows. This is called breakdown of diode and corresponding voltage is called reverse breakdown voltage V_{BR}.

→ Breakdown occurs by 2 Mechanism

1) Avalanche Breakdown
2) Zener Breakdown.

Rev Bias mode PN

Breakdown in PN Junction diodes

Avalanche Breakdown

(Excess Rev. Bias voltage)

Avalanche breakdown:

→ It occurs when P & N sides of a junction are moderately doped & depletion layer is thick.

→ We know, under reverse biased condition, the reverse current flows due to minority charge carriers.

the applied reverse bias increases, the minority charge carriers increasingly accelerate. (ie) the velocity. Hence the the kinetic energy of electron increases. If such an electron dashes against an electron involved in covalent bond, then the collision break its covalent bond. And produces new carriers by removing valence electrons from their bonds. These new carriers will intarn collide with other atoms and will increase the number of electrons & holes available for conduction. Now, the current increases lapidly. This phenomenon is known as carrier-multiplication. This cummulative process of carrier-generation (multiplication) is know as a Avalanche breakdown (or) Avalanche multiplication.

→ This Multiplication effect of free Carriers is represented by

$$M = \frac{1}{1 - \left(\frac{V}{V_{BD}}\right)^n}$$

where M → Carrier Multiplication factor.

V → Applied reverse voltage.

V_{BD} → Reverse breakdown voltage.

n → Constant (depends on the material).

Note:

Avalanche breakdown occurs for lightly doped diodes. It occurs at very high reverse voltage.

Zener Breakdown

excess doping

It occurs when semiconductors are heavily doped and depletion layers are very thin. Even if the initially available carriers do not gain enough energy to disrupt bonds, it is also possible to initiate breakdown through a direct rupture of the bonds because of the existence of strong electric field. Under these circumstances, the breakdown is referred to as <u>zener breakdown</u>.

The breakdown occurs in junctions which are heavily doped. The heavily doped junctions have a narrow depletion layer. When the reverse voltage is increased, the electric field at the junction also increases. This field is enough to pull the electrons out of the valence bands. So this is not due to the collision of carriers with atoms. Such a creation of free electrons is called zener effect. These carriers constitute very large current & mechanism is called <u>zener breakdown</u>.

$\frac{dE}{dt} \propto$

The effect is dominant for heavily doped diodes. For which, the depletion width is small. The field intensity for voltages less than 5-6V becomes intense and hence causes more carriers.

<u>Note</u> :

Zener ⇒ -ve temp coeff.
V_{BR} ↓ses with ↑se temp.

Avalanche ⇒ +ve temp coeff.
V_{BR} ↑ses with ↑se temp.

Fig. *Breakdown in PN junction diodes*

PN diode Applications:

1) Rectifiers in dc power supplies.
2) Switch in digital logic circuits used in computers.
3) Clamping network used as dc restorer in TV receivers and voltage multipliers.
4) Clipping circuits used as wave shaping circuits used in computers, RADARS, Radio and TV receivers.
5) Demodulation (Detector) circuits.

Rectifier Diodes

- A circuit that converts the ac power-line voltage to the required dc value is called a **power supply**.
- The most important components in power supplies are **rectifier diodes**, which convert ac line voltage to dc voltage.
- Diodes are able to produce a dc output voltage because they are <u>unidirectional</u> devices allowing current to flow through them in only one direction.

Rectifier Diodes

- The circuit shown in Fig. 1 (a) is called a **half-wave rectifier**.
- When the top of the transformer secondary voltage is positive, D_1 is forward-biased, producing current flow in the load.
- When the top of the secondary is negative, D_1 is reverse-biased and acts like an open switch. This results in zero current in the load, R_L.
- The output voltage is a series of positive pulses, as shown in the next slide, Fig. 1 (b).

Fig. 1 (*a*)

(*a*)

Rectifier Diodes

$I_{diode} = I_{L(DC)}$
PIV = 42.42
f_{out} = 60 Hz

Fig. 1 (b)

Rectifier Diodes

- The circuit shown in Fig. 2 (a) is called a **full-wave rectifier**.
- When the top of the secondary is positive, D_1 is forward-biased, causing current to flow in the load, R_L.
- When the top of the secondary is negative, D_2 is forward-biased, causing current to flow in the load, R_L.
- The combined output voltage produced by D_1 and D_2 are shown in Fig. 2 (b) in the next slide.

Fig. 2 (*a*)

Rectifier Diodes

Fig. 2 (b)

Rectifier Diodes

- The circuit shown in Fig. 3 (a) is called a full-wave bridge rectifier.
- When the top of the secondary is positive, diodes D_2 and D_3 are forward-biased. producing current flow in the load, R_L.
- When the top of the secondary is negative, $D_1$and D_4 are forward-biased, producing current flow in the load, R_L.

Fig. 3 (*a*)

(*a*)

Fig. 3 (b) illustrates the combined **output voltage** of the full-wave bridge rectifier circuit of Fig. 3 (a) in the previous slide.

Fig. 3 (b)

Ripple Factor

$$R.F = 1/ I_{dc} \sqrt{I^2_{rms} + I^2_{dc}} = \sqrt{(I_{rms} / I_{dc})^2 - 1}$$

Ripple Factor of Half Wave Rectifier

For half-wave rectifier,

$$I_{rms} = I_m/2$$

$$I_{dc} = I_m/ \pi$$

We know the formula of **R.F =** $\sqrt{(I_{rms} / I_{dc})^2 - 1}$

Substitute the above I_{rms} **&** I_{dc} in the above equation so we can get the following.

$$R.F = \sqrt{(Im/2 / I_m/ \pi)^2 - 1} = 1.21$$

Ripple Factor of Full Wave Rectifier

For full-wave rectifier,

$$I_{rms} = I_m/\sqrt{2}$$

$$I_{dc} = 2I_m / \pi$$

We know the formula of **R.F =** $\sqrt{(I_{rms} / I_{dc})^2 - 1}$

Substitute the above I_{rms} & I_{dc} in the above equation so we can get the following.

$$R.F = \sqrt{(Im/\sqrt{2}/ 2Im / \pi)2 - 1} = 0.48$$

Ripple factor for

HWR	FWR
$RF : \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$	$RF : \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$
$I_{rms} = \frac{I_m}{2}$	$I_{rms} = \frac{I_m}{\sqrt{2}}$
$I_{dc} = \frac{I_m}{\pi}$	$I_{dc} = \frac{2 I_m}{\pi}$
$= 1.21$	$= 0.48$

Zener Diode

Introduction

The **zener diode** is a silicon pn junction devices that differs from rectifier diodes because *it is designed for operation in the reverse-breakdown region*. The breakdown voltage of a zener diode is set by carefully controlling the level during manufacture. The basic function of **zener diode** is to maintain a specific voltage across it's terminals within given limits of line or load change. Typically it is used for providing a stable reference voltage for use in power supplies and other equipment.

This particular zener circuit will work to maintain 10 V across the load.

Construction of Zener

Zener diodes are designed to operate in reverse breakdown. Two types of reverse breakdown in a zener diode are *avalanche* and *zener*. The avalanche break down occurs in both rectifier and zener diodes at a sufficiently high reverse voltage. **Zener breakdown** occurs in a zener diode at low reverse voltages.

A zener diode is heavily doped to reduce the breakdown voltage. This causes a very thin depletion region.

The zener diodes breakdown characteristics are determined by the doping process

Zeners are commercially available with voltage breakdowns of 1.8 V to 200 V.

Working of Zener

A **zener diode** is much like a normal diode. The exception being is that it is placed in the circuit in reverse bias and operates in reverse breakdown. This typical characteristic curve illustrates the operating range for a zener. Note that it's forward characteristics are just like a normal diode.

(a) The normal operating regions for a rectifier diode are shown as shaded areas.

(b) The normal operating region for a zener diode is shaded.

Breakdown Characteristics

Figure shows the reverse portion of a zener diode's characteristic curve. As the reverse voltage (V_R) is increased, the reverse current (I_R) remains extremely small up to the "knee" of the curve. The reverse current is also called the zener current, I_Z. At this point, the breakdown effect begins; the internal zener resistance, also called zener impedance (Z_Z), begins to decrease as reverse current increases rapidly.

ZENER BREAKDOWN

- Zener and avalanche effects are responsible for such a dramatic increase in the value of current at the breakdown voltage.

- If the impurity concentration is very high, then the width of depletion region is very less. Less width of depletion region will cause high intensity of electric field to develop in the depletion region at low voltages.

- Lets take an example to understand things clearly.
- Let say the width of depletion region is 200 Å (very small). If a reverse bias voltage of just 4 V is applied to the diode, then the electric field intensity in the depletion region will be

$$\frac{4}{200 \times 10^{-10}} = 2 \times 10^{8}\ \text{V/m}$$

- Merely a voltage of 4 V is responsible to generate an electric field intensity of 2 x 108 V/m (very high intensity).
- This electric field is sufficient to rupture the bonds and separate the valence electrons from their respective nuclei.
- Large number of electrons gets separated from their atoms, resulting in sudden increase in the value of reverse current.
- This explanation was given by scientist C. E. Zener. Such diodes are called Zener diodes.
- **Zener effect predominates in diodes whose breakdown voltage is below 6 V.**

AVALANCHE BREAKDOWN

- Zener effect predominates on diodes whose breakdown voltage is below 6 V. The breakdown voltage can be obtained at a large value by reducing the concentration of impurity atom.

- We know that very little amount of current flows in the reverse biased diode. This current is due to the flow of minority charge carriers i.e., electrons in the p type semiconductor and holes in the n type semiconductor.

- The width of depletion region is large when the impurity concentration is less
- When a reverse bias voltage is applied across the terminals of the diode, the electrons from the p type material and holes from the n-type materials accelerates through the depletion region.
- This results in collision of intrinsic particles (electrons and holes) with the bound electrons in the depletion region. With the increase in reverse bias voltage the acceleration of electrons and holes also increases.
- Now the intrinsic particles collides with bound electrons with enough energy to break its covalent bond and create an electron-hole pair. This is shown in the figure.

Avalanche Breakdown Mechanism

Avalanche breakdown

- The collision of electrons with the atom creates an electron-hole pair.
- This newly created electron also gets accelerated due to electric field and breaks many more covalent bond to further create more electron-hole pair
- This process keeps on repeating and it is called **carrier multiplication**.
- The newly created electrons and holes contribute to the rise in reverse current.
- The process of carrier multiplication occurs very quicklyand in very large numbersthat there is **apparently an avalanche of charge carriers**. Thus the breakdown is called avalanche breakdown.

DIFFERENCE BETWEEN ZENER AND AVALANCHE BREAKDOWN

Zener Breakdown	Avalanche Breakdown
1. This occurs at junctions which being heavily doped have narrow depletion layers	1. This occurs at junctions which being lightly doped have wide depletion layers due to excess reverse bias voltage.
2. This breakdown voltage sets a very strong electric field across this narrow layer.	2.Here electric field is not strong enough to produce Zener breakdown.
3.Here electric field is very strong to rupture the covalent bonds thereby generating electron-hole pairs. So even a small increase in reverse voltage is capable of producing Large number of current carriers.	3.Her minority carriers collide with semi conductor atoms in the depletion region, which breaks the covalent bonds and electron-hole pairs are generated. Newly generated charge carriers are accelerated by the electric field which results in more collision and generates avalanche of charge carriers. This results in avalanche breakdown.
4.Zener breakdown voltage exhibits negative temp: coefficient. 1e. breakdown voltage decreases as temperature increases.	4.Avalanche breakdown voltage exhibits positive temp: coefficient. i.e breakdown voltage increases with increase in temperature.

PN JUNCTION BREAKDOWN CHARACTERISTICS

Ideal Model & Ideal Characteristic Curve of Zener Diode

(a) Ideal model (b) Ideal characteristic curve

Practical Model & Ideal Characteristic Curve of Zener Diode

Zener Diode Applications –

Zener Regulation with a Varying Input Voltage

(a) As the input voltage increases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

(b) As the input voltage decreases, the output voltage remains constant ($I_{ZK} < I_Z < I_{ZM}$).

Zener Limiting

Zener diodes can used in ***ac applications to limit voltage swings to desired levels***.

V_Z: zener voltage

Vd: Diode voltage

Vd = 0.7

A zener diode exhibits a certain change in V z for a certain change in Iz on a portion of the linear characteristic curve between I_{ZK} and I_ZM as illustrated in Figure. What is the Zener impedance?

$$Z_Z = \frac{\Delta V_Z}{\Delta I_Z}$$

$$= \frac{50 \text{ mV}}{5 \text{ mA}}$$

$$= 10\ \Omega$$

less dependency on temperature

Temperature Coefficient

- The temperature coefficient specifies the percent change in zener voltage for each degree centigrade change in temperature.
- For example, a 12 V zener diode with a **positive temperature coefficient of 0.01% /°C** will exhibit a 1.2 mV increase in Vz when the junction temperature increases one degree centigrade.
- The formula for calculating the change in zener voltage for a given junction temperature change, for a specified temperature coefficient, is

$$\Delta V_Z = V_Z \times TC \times \Delta T$$

TC → Temp coef.

Where, Vz is nominal zener voltage at 25°C. When temp. coefficient is expressed in mV/°C

$$\Delta V_Z = TC \times \Delta T$$

An 8.2 V zener diode (8.2 V at 25°C) has a positive temperature coefficient of 0.05%/°C. What is the zener voltage at 60°C?

The change in zener voltage is

$$\Delta V_Z = V_Z \times TC \times \Delta T = (8.2\text{ V})(0.05\%/^\circ\text{C})(60^\circ\text{C} - 25^\circ\text{C})$$
$$= (8.2\text{ V})(0.0005/^\circ\text{C})(35^\circ\text{C}) = 144\text{ mV}$$

Notice that 0.05%/°C was converted to 0.0005/°C. The zener voltage at 60°C is

$$V_Z + \Delta V_Z = 8.2\text{ V} + 144\text{ mV} = \mathbf{8.34\text{ V}}$$

Example

- A 5.0V stabilised power supply is required to be produced from a 12V DC power supply input source.

The maximum power rating Pz of t
diode is 2W. Using the ze
through the zener diode.
circuit calculate:
b) The value of the series
a) The maximum current flowing
resistor, Rs
c) The load current I_L if a load resistor of 1kΩ is connected across the Zener diode.
d) The total supply current Is

W.K.T. $P_Z = V_Z I_Z \Rightarrow I_Z = \frac{P_Z}{V_Z}$

(a) $$\text{Maximum Current} = \frac{\text{Watts}}{\text{Voltage}} = \frac{2w}{5v} = 400mA$$

(b) $$R_S = \frac{V_S - V_Z}{I_Z} = \frac{12 - 5}{400mA} = 17.5\Omega$$

(c) $$I_L = \frac{V_Z}{R_L} = \frac{5v}{1000\Omega} = 5mA$$

(d) $$I_S = I_Z + I_L = 400mA + 5mA = 405mA$$

Zener Diode Voltages

- As well as producing a single stabilised voltage output, zener diodes can also be connected together in series along with normal silicon signal diodes to produce a variety of different reference voltage output values
- The values of the individual Zener diodes can be chosen to suit the application while the silicon diode will always drop about 0.6 - 0.7V in the forward bias condition.
- The supply voltage, V_{in} must of course be higher than the largest output reference voltage

Is
Rs
19.0v
ZD1 = 5.1v
13.9v
ZD2 = 3.3v
10.6v
Vin
D1 = 1N4148
10.0v
ZD3 = 10.0v
Decoupling
capacitor
C
Vout

Summary on Zener Diode

- A zener diode is always operated in its reverse biased condition.
- **A voltage regulator circuit can be designed using a zener diode to maintain a constant DC output voltage across the load in spite of variations in the input voltage or changes in the load current.**
- The zener voltage regulator consists of a current limiting resistor Rs connected in series with the input voltage Vs with the zener diode connected in parallel with the load R_L in this
- reverse biased condition.

The stabilized output voltage is always selected to be the same as the breakdown voltage Vz of the diode.