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~~. depletion

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

constant

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 intern 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~~ 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.

Small-Signal Diode Biasing

- When reversed-biased, a *pn* junction diode becomes functionally equivalent to a capacitor, whose capacitance decreases as the reverse bias increases.
- Biasing additional a.c. signal v_a can be viewed as a small oscillation of the depletion width about the steady state value.

$V_0 << V_A$

$$Y = G + j\omega C$$

R_S : serial resistance
C : capacitance
G : conductance
Y : admittance

Total *pn* Junction Capacitance

$$C_J = A\frac{\varepsilon_s}{W}$$

Junction / depletion capacitance, due to variation of depletion charges

Minority carrier lifetime

$$C_D = \frac{\tau I_{DC}}{kT/q}$$

Diffusion capacitance, due to variation of stored minority charges in the quasineutral regions

- **C_J dominates at low forward biases, reverse biases.**
- **C_D dominates at moderate to high forward biases.**

Relation Between C_J and V_A

- For asymmetrical step junction,

$$W = \sqrt{\frac{2\varepsilon_s}{qN_B}(V_{bi} - V_A)}$$

N_B : bulk semiconductor doping, N_A or N_D as appropriate.

- Therefore,

$$\boxed{\frac{1}{C_J^{\,2}} = \frac{W^2}{A^2\varepsilon_s^{\,2}} \cong \frac{2}{qN_B\varepsilon_S A^2}(V_{bi} - V_A)}$$

RECAP

- pn Junctions (cont'd)

  – small-signal model

Small-Signal Model of the Diode

Small signal equivalent circuit:

$$i = Gv_a + C\frac{dv_a}{dt}$$

Small-signal ***conductance*** :

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

$$G = \frac{q}{kT} I_0 e^{qV_A/kT} \cong \frac{I_{DC}}{kT/q}$$

Review: Charge Storage in pn-Diode

2 types of capacitance associated with a pn junction:

1. C_J ***depletion capacitance***
   (due to variation of depletion charge)
2. C_D ***diffusion capacitance***
   (due to variation of stored minority charge in the quasi-neutral regions)

For a one-sided p^+n junction, $Q_P >> Q_N$

so $Q = Q_P + Q_N \cong Q_P$:

$$C_D = \left| \frac{dQ}{dV_A} \right| = \tau_p \frac{dI}{dV_A} = \tau_p G = \frac{\tau_p I_{DC}}{kT/q}$$

Depletion Capacitance

$$C_{\mathrm{J}} \equiv \left| \frac{dQ_{\mathrm{dep}}}{dV_{\mathrm{A}}} \right| = A \frac{\varepsilon_s}{W}$$

What are three ways to reduce C_{dep}?

Total pn-Junction Capacitance

$$C_J = A\frac{\varepsilon_s}{W}$$

$$C_D = \frac{\tau I_{DC}}{kT/q} \propto \left(e^{qV_A/kT} - 1\right)$$

- C_D dominates at moderate to high forward biases
- C_{dep} dominates at low forward biases, reverse biases

C_J-vs.-V_A (Reverse Bias)

$$\frac{1}{C_J^{\,2}} = \frac{W^2}{A^2 \varepsilon_s^{\,2}} \cong \frac{2(V_{bi} - V_A)}{A^2 q \varepsilon_S N}$$

Example

If the slope of the $(1/C_{dep})^2$ *vs.* V_A characteristic is -2×10^{23} $F^{-2}\,V^{-1}$, the intercept is 0.84V, and A is 1 μm^2, find the lighter and heavier doping concentrations N_l and N_h.

Solution:

$$N_l = 2/(slope \times q\varepsilon_s A^2)$$
$$= 2/(2\times10^{23}\times1.6\times10^{-19}\times12\times8.85\times10^{-14}\times10^{-8}\,\text{cm}^2)$$
$$= 6\times10^{15}\ \text{cm}^{-3}$$

$$V_{bi} = \frac{kT}{q}\ln\frac{N_h N_l}{n_i^2} \quad\Rightarrow\quad N_h = \frac{n_i^2}{N_l}e^{\frac{qV_{bi}}{kT}} = \frac{10^{20}}{6\times10^{15}}e^{\frac{0.84}{0.026}} = 1.8\times10^{18}\ \text{cm}^{-3}$$

Summary: Small Signal Model

$$I_{DC} = I_0(e^{qV_A/kT} - 1)$$

$$C = C_J + C_D$$

Depletion capacitance $C_J = \dfrac{A\varepsilon_s}{W}$

Conductance $G \cong \dfrac{I_{DC}}{kT/q}$

Diffusion capacitance $C_D = \dfrac{\tau I_{DC}}{kT/q}$

Metal-semiconductor (MS) junctions

Many of the properties of pn junctions can be realized by forming an appropriate metal-semiconductor rectifying contact (Schottky contact)

- Simple to fabricate
- Switching speed is much higher than that of p-n junction diodes

Metal-Semiconductor junctions are also used as ohmic-contact to carry current into and out of the semiconductor device

Ideal MS contacts

Assumptions - Ideal MS contacts

- M and S are in immediate contact, on atomic scale
- No oxides or charges at the interface
- No intermixing at the interface

MS contacts

Vacuum level, E_0 - corresponds to energy of free electrons.

The difference between vacuum level and Fermi-level is called workfunction, Φ of materials.

- **Workfunction, Φ_M** is an invariant property of metal. It is the minimum energy required to free up electrons from metal. (3.66 eV for Mg, 5.15eV for Ni etc.)

The semiconductor **workfunction, Φ_s,** depends on the doping.

$$\Phi_s = \chi + (E_C - E_F)_{FB}$$

where $\chi = (E_0 - E_C)|_{SURFACE}$ is a a fundamental property of the semiconductor. (Example: χ = 4.0 eV, 4.03 eV and 4.07 eV for Ge, Si and GaAs respectively)

Energy band diagrams for ideal MS contacts

Figure 14.2

(a) and (c) An instant after contact formation

(b) and (d) under equilibrium conditions

$\Phi_M > \Phi_S$

$\Phi_M < \Phi_S$

MS (n-type) contact with $\Phi_M > \Phi_S$

Soon after the contact formation, electrons will begin to flow from S to M near junction.

Creates surface depletion layer, and hence a built-in electric field (similar to p^+-n junction).

Under equilibrium, net flow of carriers will be zero, and Fermi-level will be constant.

A barrier Φ_B forms for electron flow from M to S.

$\Phi_B = \Phi_M - \chi$ ... ideal MS (n-type) contact. Φ_B is called "barrier height".

Electrons in semiconductor will encounter an energy barrier equal to $\Phi_M - \Phi_S$ while flowing from S to M.

MS (n-type) contact with $\Phi_M > \Phi_S$

Response to applied bias for n-type semiconductor

Note: An applied positive voltage lowers the band since energy bands are drawn with respect to electron energy.

Figure 14.3

MS (n-type) contact with $\Phi_M < \Phi_S$

No barrier for electron flow from S to M.

So, even a small $V_A > 0$ results in large current.

As drawn, small barrier exists for electron flow from M to S, but vanishes when $V_A < 0$ is applied to the metal. Large current flows when $V_A < 0$.

The MS(n-type) contact when $\Phi_M < \Phi_S$ behaves like an ohmic contact.

Electrical nature of ideal MS contacts

	n-type	**p-type**
$\Phi_M > \Phi_S$	rectifying	ohmic
$\Phi_M < \Phi_S$	ohmic	rectifying

Schottky diode

$$V_{\mathrm{bi}} = \frac{1}{q}\left[\Phi_{\mathrm{B}} - (E_{\mathrm{C}} - E_{\mathrm{F}})_{\mathrm{FB}}\right]$$

$$\rho \approx qN_{\mathrm{D}} \quad \text{for } 0 \le x \le W$$
$$\approx 0 \quad \text{for } x > W$$

$$\frac{\mathrm{d}\mathcal{E}}{\mathrm{d}x} = \frac{\rho}{\varepsilon_{\mathrm{Si}}} = \frac{qN_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}} \quad \text{for} \quad 0 \le x \le W$$

$$\mathbf{E}(x) = -\frac{q \quad N_{\mathrm{D}}}{\varepsilon_{\mathrm{Si}}}(W - x)$$

$$\mathbf{E}(x = 0) = -\frac{q \quad N_{\mathrm{D}} \quad W}{\varepsilon_{\mathrm{Si}}}$$

$$V(x) = -\frac{qN_D}{2\varepsilon_{si}}(W - x)^2 \qquad 0 \le x \le W$$

$$W = \left[\frac{2\varepsilon_{\mathrm{Si}}}{q N_{\mathrm{D}}}(V_{\mathrm{bi}} - V_{\mathrm{A}})\right]^{1/2}$$

Example

Find barrier height, built-in voltage, maximum E-field, and the depletion layer width at equilibrium for W-Si (n-type) contact.

Given: $\Phi_M = 4.55\text{eV}$ for W; $\chi(\text{Si}) = 4.01\text{eV}$; Si doping = $10^{16}\,\text{cm}^{-3}$

Solution:

Find $E_F - E_i$ $\quad E_F - E_i = 0.357\text{eV}$

Find $E_C - E_F$ $\quad E_C - E_F = 0.193\text{eV}$

$$\Phi_B = \Phi_M - \chi = 0.54\text{eV}$$

$$\Phi_S = \chi + (E_C - E_F)_{FB} = 4.203\text{eV}$$

$V_{bi} = 0.347$ V

$W = 0.21\ \mu\text{m}$

$\mathcal{E}(x = 0) = \mathcal{E}_{max} = 3.4 \times 10^4$ V/cm

Walter H Schottky

Schottky effect

Schottky barrier

Schottky diode

Born: July 23, 1886 in Zurich, Switzerland

Grew up in Germany

Doctorate from Humboldt University in 1904 (Physics)
-thesis on Special Theory of Relativity

Tutor was Max Planck (Quantum Theory)

Many Different Discoveries:

Vacuum Electronics	Semiconductors	Misc.
“3/2 law”	*Thermodynamik*	Ribbon Microphone
Schottky Effect	Schottky Diode	superhet

Timeline

- Vacuum Tubes and other random trivia
  - 1913 – independently discovers three-halves law, relating vacuum valve current to applied voltage
  - 1915 – invents screen-grid vacuum tube
  - 1919 – invents tetrode, first multi-grid vacuum tube

Timeline

- Vacuum Tubes and other random trivia
  - 1918 – publishes paper identifying two types of noise in amplifiers (and electronic devices)
  - Thermal noise – from random thermal motion of molecules
  - Shot noise (Schott noise) – from random velocities of emitted electrons

Schottky diodes

- In 1938, Schottky formulated a theory predicting the Schottky effect, now used in Schottky diodes.

- Schottky diode uses a metal-semiconductor junction as a Schottky barrier instead of a semiconductor-semiconductor junction as in conventional diodes.

- Two major advantages:
  1. Low forward voltage drop
  2. Very fast switching action

- limitations of Schottky diodes:
  1. Relatively low reverse voltage rating
  2. Relatively high reverse current

Interesting Inventions:

- Ribbon Microphone (1924):
  - Thin piece of Aluminum placed between poles of a magnet
  - Vibration within magnetic field produces a voltage
  - Capture high frequency detail
- Superhet (1918):
  - **Supersonic Heterodyne Receiver**
  - Using oscillation, all incoming signals are converted to a constant lower frequency
  - Radio is tuned by adjusting the oscillator frequency
  - Just about all radio receivers now use the superheterodyne principle.

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SCHOTTKY BARRIER DIODE

- The Schottky diode (named after German physicist Walter H. Schottky; also known as hot carrier diode) is a semiconductor diode with a low forward voltage drop and a very fast switching action.

- When current flows through a diode there is a small voltage drop across the diode terminals. A normal silicon diode has a voltage drop between 0.6–1.7 volts, while a Schottky diode voltage drop is between approximately 0.15–0.45 volts. This lower voltage drop can provide higher switching speed and better system efficiency.

CONSTRUCTION

- A metal–semiconductor junction is formed between a metal and a semiconductor, creating a Schottky barrier (instead of a semiconductor–semiconductor junction as in conventional diodes).
- Typical metals used are **molybdenum, platinum, chromium or tungsten**; and the semiconductor would typically be N-type silicon.
- The metal side acts as the anode and N-type semiconductor acts as the cathode of the diode. This Schottky barrier results in both very fast switching and low forward voltage drop.

Gold leaf metal contact
Anode (+)
Metal
Silicon dioxide screen
Metal semiconductor junction
Metal contact
Cathode (-)

WORKING

- The electrons of N-side having low energy level than that of metal . So electrons cant cross the junction barrier called

  schottky barrier.

- In Forward bias the electrons in N side gain enough energy to cross the junction barrier and plunge into the metal with very large energy .They are called it hot carriers and diode is called hot carrier diode.

VI characteristics of Schottky diode

REVERSE RECOVERY TIME

- The most important difference between the p-n and Schottky diode is reverse recovery time, when the diode switches from conducting to non-conducting state. Where in a p-n diode the reverse recovery time can be in the order of hundreds of nanoseconds and less than 100 ns for fast diodes, Schottky diodes do not have a recovery time, as there is nothing to recover from (i.e. no charge carrier depletion region at the junction).

SOME IMPORTANT POINTS ABOUT SCHOTTKY DIODE

- Schottky diode is metal to semiconductor junction.
- Schottky diode is a majority carrier device unlike to normal pn junction diode
- It does not have charge storage region there for very fast speed
- Semiconductor used is usually N-type.
- Semiconductor region is lightly doped.
- It is operated at high frequencies from few MHZ to GHZ range.

LIMITATIONS

- The most evident limitations of Schottky diodes are the relatively low reverse voltage ratings for silicon-metal Schottky diodes, typically 50 V and below, and a relatively high reverse leakage current. Some higher-voltage designs are available; 200V is considered a high reverse voltage.
- Reverse leakage current, because it increases with temperature, leads to a thermal instability issue. This often limits the useful reverse voltage to well below the actual rating.
- While higher reverse voltages are achievable, they would be accompanied by higher forward voltage drops, comparable to other types; such a Schottky diode would have no advantage

APPLICATIONS

- Voltage clamping and clipping circuits
- Reverse current and discharge protection
- Rectify high frequencies signal.
- Low power TTL logic.
- As a switching devices.

VARACTOR DIODE

INTRODUCTION

Varactor diode is a special type of **PN** junction diode, in which PN junction **capacitance** is controlled using **reverse bias** voltage. When the diode is forward biased, current will flow through the diode. When the diode is reverse biased, charges in the P and N semiconductors are drawn away from the PN junction interface and hence forms the **high resistance depletion zone**.

OTHER NAMES

The Varactor diode is also known as:

- **Vari**able **cap**acitance (Varicap) diode
- Voltage – Variable Capacitor (VCC) diode
- Tuning diode
- Variable reactance diode

SCHEMATIC SYMBOL

BASIS OF OPERATION

- Operates in **reverse bias** and this gives rise to **three regions**. At either end of the diode are the **P** and **N regions**. However around the junction is the **depletion region** where no current carriers are available. As a result, current can be carried in the P and N regions, but the depletion region is an **insulator**.

- Same as capacitor construction. It has conductive plates separated by an insulating **dielectric**.

- The capacitance of a capacitor is dependent on a number of factors including the **plate area**, **the dielectric constant of the insulator** between the plates and **the distance between the two plates**. In the case of the **varactor diode**, it is possible to **increase and decrease** the width of the **depletion region** by changing the level of the reverse bias. This has the effect of changing the distance between the plates of the capacitor.

BASIS OF OPERATION

C – V CHARACTERISTICS

MATERIAL CONSTRUCTION

Varactor diodes are manufactured with **gallium arsenide. GaAs** has a higher operating frequency (***up to nearly 1000 GHz***)

I – V CHARACTERISTICS

APPLICATIONS

- Variable reactor in microwave circuits.
- It is used in variable resonant tank LC circuit. Here C part is varied using varactor diode.
- AFC (Automatic Frequency Control) where in varactor diode is used to set LO signal.
- Varactor is used as frequency modulator in **Radios** and **Television** sets.
- It is used as frequency multiplier in microwave receiver LO.
- It is used as RF phase shifter.

CONCLUSION

Varactor diodes in reverse bias operates as variable capacitor as reverse voltage varies, where:

- Depletion region : Dielectric (Insulator)
- P - N Regions : Plates of capacitor
- Width of Depletion region : Distance of separation

TUNNEL DIODE

Introduction

- Invented by Dr. Leo Esaki in 1958.
- Also called Esaki diode.
- Basically, it is heavily doped PN- junction.
- These diodes are fabricated from germanium, gallium arsenide (GaAs), and Gallium Antimonide.
- Symbol:

Description

- Tunnel diode is a semi-conductor with a special characteristic of negative resistance.
- By negative resistance, we mean that when voltage is increased, the current through it decreases.
- Highly doped PN- junction. Doping density of about 1000 times greater than ordinary junction diode.

Construction

- Heavy Doping Effects:

i. Reduces the width of depletion layer to about 0.00001 mm.

ii. Produces negative resistance section in characteristics graph of diode.

iii. Reduces the reverse breakdown voltage to a small value approaches to zero.

iv. Small forbidden gaps in tunnel diode.

v. Allows conduction for all reverse voltages.

Basic principle of operation:

- The operation depends upon quantum mechanics principle known as “tunneling”.
- The movement of valence electrons from valence energy band to conduction band with no applied forward voltage is called “tunneling”.
- Intrinsic voltage barrier (0.3V for Ge) is reduced which enhanced tunneling.
- Enhanced tunneling causes effective conductivity.

Working:

- In a conventional diode, forward conduction occurs only if the forward bias is sufficient to give charge carriers the energy necessary to overcome the potential barrier.
- When the tunnel diode is slightly forward biased, many carriers are able to tunnel through narrow depletion region without acquiring that energy.
- The carriers are able to tunnel or easily pass because the voltage barrier is reduced due to high doping.

Working(contd.)

- Forward Bias operation:

At first voltage begin to increase,

1. Electrons tunnel through pn junction.
2. Electron and holes states become aligned.

Voltage increases further:

1. States become misaligned.
2. Current drops.
3. Shows negative resistance (V increase, I decrease).

As voltage increase yet further:

1. The diode behave as normal diode.
2. The electrons no longer tunnel through barrier.

Working(contd.)

- Reverse Bias Operation:

When used in reverse direction, they are called as Back Diodes.

In this,

i. The electrons in valence band of p-side tunnel directly towards the empty states present in the conduction band of n-side.

ii. Thus, creating large tunneling current which increases with application of reverse voltage.

I/V Characteristics

As forward bias is applied, significant I is produced.

After continuous increase of V, the current achieves its minimum value called as Valley Current. After further increase in V, current start increasing as ordinary diode.

Figure 6.3: Tunnel Diode

I/V Characteristic(contd.)

- The Tunnel diode reverse I-V is similar to the Zener diode.
- The Zener diode has a region in its reverse bias characteristics of almost a constant voltage regardless of the current flowing through the diode.

Applications:

- It is used as an ultra- high speed switch due to tunneling (which essentially takes place at speed of light). It has switching time of nanoseconds or picoseconds.
- Used as logic memory storage device.
- In satellite communication equipment, they are widely used.
- Due to its feature of –ive resistance, it is used in relaxation oscillator circuits.

Applications(contd.):

- Tunnel diodes are resistant to the effects of magnetic fields, high temperature and radioactivity. That's why these can be used in modern military equipments - NMR machines.
- Due to low power requirement, they are used in FM receivers.

Photodiode Working Principle, Characteristics and Applications

Photodiode Working Principle, Characteristics and Applications

Introduction:

- A photodiode is a PN-junction diode that consumes light energy to produce electric current. Sometimes it is also called as photo-detector, a light detector, and photo-sensor. These diodes are particularly designed to work in reverse bias condition, it means that the P-side of the photodiode is associated with the negative terminal of the battery and n-side is connected to the positive terminal of the battery.

What is a Photodiode

- A photodiode is one type of light detector, used to convert the light into current or voltage based on the mode of operation of the device.
- It comprises of optical filters, built-in lenses and also surface areas.
- These diodes have a slow response time when the surface area of the photodiode increases.
- Photodiodes are alike to regular semiconductor diodes
- They may be either visible to let light reach the delicate part of the device.
- Several diodes intended for use exactly as a photodiode will also use a PIN junction somewhat than the usual PN junction.

- Some photodiodes will look like a light emitting diode.
- They have two terminals coming from the end.
- The smaller end of the diode is the cathode terminal.
- While the longer end of the diode is the anode terminal.

See the following schematic diagram for the anode and cathode side.

Photodiode symbol

Photodiode

- Under forward bias condition, conventional current will flow from the anode to the cathode, following the arrow in the diode symbol.

- Photocurrent flows in the reverse direction.

- Although there are numerous types of photodiode available in the market .
- They all works on the same basic principles, though some are improved by other effects.
- The working of different types of photodiodes work in a slightly different way.
- But the basic operation of these diodes remains the same.

Types of Photodiode

- The types of the photodiodes can be classified based on its construction and functions as follows:

  - PN Photodiode
  - Schottky Photo Diode
  - PIN Photodiode
  - Avalanche Photodiode

- These diodes are widely used in different applications, where the detection of the presence of light, colour, position, intensity is required.

Photodiode Working Principle, Characteristics and Applications

- The main features of these diodes include the following.

- The linearity of the diode is good with respect to incident light
- Noise is low.
- The response is wide spectral
- Rugged mechanically
- Light weight and compact
- Long life

Materials to Make a Photodiode

- The required materials to make a photodiode and the range of electromagnetic spectrum wavelength range includes the following

- **For silicon material:** The electromagnetic spectrum wavelength range will be (190-1100) nm

- **For Germanium material:** The electromagnetic spectrum wavelength range will be (400-1700) nm

- **For Indium gallium arsenide material:** The electromagnetic spectrum wavelength range will be (800-2600) nm

Materials to Make a Photodiode

- For Lead (II) sulfide material: The electromagnetic spectrum
  wavelength range will be <1000-3500) nm

- For Mercury, cadmium Telluride material: The electromagnetic spectrum wavelength range will be (400-14000) nm

➢ Because of their better band gap, Si-based photodiodes produce
lower noise than Ge-based photodiodes.

Working of Photodiode

- When a photon of ample energy strikes the diode.
- It makes a couple of an electron-hole.
- This mechanism is also called as the inner photoelectric effect.
- If the absorption arises in the depletion region junction.
- Then the carriers are removed from the junction by the inbuilt electric field of the depletion region.

Working of Photodiode

- The holes in the region move toward the anode, and electrons move toward the cathode, and a photocurrent will be generated.
- The entire current through the diode is the sum of the absence of light and the photocurrent.
- So the absent current must be reduced to maximize the sensitivity of the device.

Working of Photodiode

PN Junction Diode

Modes of Operation

- The operating modes of the photodiode include three modes, namely

  - Photovoltaic mode.
  - Photoconductive mode.
  - Avalanche diode mode.

Photovoltaic Mode:

- This mode is also known as zero bias mode.
- In which a voltage is produced by the lightened photodiode.
- It gives a very small dynamic range & non-linear necessity of the voltage formed.

Photoconductive Mode

- The photodiode used in this photoconductive mode is more usually reverse biased.
- The reverse voltage application will increase the depletion layer's width.
- Which in turn decreases the response time & the junction capacitance.
- This mode is too fast and displays electronic noise.

Avalanche Diode Mode

- Avalanche diodes operate in a high reverse bias condition.
- which permits multiplication of an avalanche breakdown to each photo-produced electron-hole pair.
- This outcome in an internal gain in the photodiode, which slowly increases the device response.

I. Characteristics of Photodiode

- A photodiode continually operates in a reverse bias mode.
- The photocurrent is nearly independent of reverse bias voltage which is applied.
- For zero luminance, the photocurrent is almost zero excluding for small dark current.

V-I Characteristics of Photodiode

- It is of the order of nano amperes.
- As optical power rises the photo current also rises linearly.
- The max photocurrent is incomplete by the power dissipation of the photo diode.

V-I Characteristics of Photodiode

- The characteristics of the photodiode are shown clearly in the following figure.

Applications of Photodiode

- The applications of photodiodes involve in similar applications of photodetectors like charge-coupled devices, photoconductors, and photomultiplier tubes.

- These diodes are used in consumer electronics devices like smoke detectors, compact disc players, televisions and remote controls in VCRs.

- It uses in consumer devices like clock radios, camera light meters, and street lights.

Applications of Photodiode

- Photoconductors are more frequently used rather than photodiodes.
- Photodiodes are frequently used for exact measurement of the intensity of light in science & industry.
- Generally, they have an enhanced, more linear response than photoconductors.

Applications of Photodiode

- Photodiodes are also widely used in numerous medical applications like instruments to analyze samples, detectors for computed tomography and also used in blood gas monitors.

- These diodes are much faster & more complex than normal PN junction
diodes.

- It is frequently used for lighting regulation and in optical communications.

Conclusion

- A photodiode is a kind of light detector, which involves the conversion of light into voltage or current, based on the mode of operation of the device. A photodiode is a semi-conductor device, with a p-n junction and an intrinsic layer between p and n layers.

Solar Cell

Introduction

- Solar cell is the photovoltaic device that convert the light energy (which come from sun) into electrical energy .
- this device work on the principle of photovoltaic effect.
- ***Photovoltaic Device:-*** The generation of voltage across the PN junction in a semiconductor due to the absorption of light radiation is called photovoltaic effect. The Devices based on this effect is called photovoltaic device.

Principle of Solar Cell

The solar cells are based on the principles of photovoltaic effect. The ***Photovoltaic Effect*** is the photogeneration of charge carriers in a light absorbing materials as a result of absorption of light radiation.

Single Solar cell

Construction of Solar Cell

- Solar cell (crystalline Silicon) consists of a ***n-type semiconductor (emitter)*** layer and ***p-type semiconductor layer (base).*** The two layers are sandwiched and hence there is formation of ***p-n junction.***
- The surface is coated with ***anti-refection coating*** to avoid the loss of incident light energy due to reflection.
- A proper ***metal contacts*** are made on the n-type and p-type side of the semiconductor for electrical connection.

Working of solar cell

Working

- When a solar panel exposed to sunlight , the light energies are absorbed by a semiconductor materials.
- Due to this absorbed energy, the electrons are liberated and produce the external DC current.
- The DC current is converted into 240-volt AC current using an inverter for different applications.

Types of Solar Cell

Based on the types of crystal used, soar cells can be classified as,

1. ***Monocrystalline silicon cells***
2. ***Polycrystalline silicon cells***
3. ***Amorphous silicon cells***

1. The Monocrystalline silicon cell is produced from ***pure silicon (single crystal).*** Since the Monocrystalline silicon is pure and defect free, the efficiency of cell will be higher.

2. In polycrystalline solar cell, ***liquid silicon*** is used as raw material and polycrystalline silicon was obtained followed by ***solidification process***. The materials contain various crystalline sizes. Hence, the efficiency of this type of cell is less than Monocrystalline cell.

3. Amorphous silicon was obtained by ***depositing silicon film on the substrate like glass plate.***

- The layer thickness amounts to less than 1μm – the thickness of a human hair for comparison is 50-100 μm.

- The efficiency of amorphous cells is much lower than that of the other two cell types.

- As a result, they are used mainly in low power equipment, such as watches and pocket calculators, or as facade elements.

Comparison of Types of solar cell

Material	*Efficiency (%)*
Monocrystalline silicon	14-17
Polycrystalline silicon	13-15
Amorphous silicon	5-7

Generation of Solar Cell

First Generation – Single Junction Silicon Cells

- Limit efficiency 31%
- Single crystal silicon - 16-19% efficiency
- Multi-crystal silicon - 14-15% efficiency
- Best efficiency by Sun Power 22%

- ✓ 87.4% of 2007 Production
- ✓ 45.2% Single Crystal Si
- ✓ 42.2% Multi-crystal SI

Silicon Cell Average Efficiency

Second Generation – Thin Film Cells

- New materials and processes to improve efficiency and reduce cost.

- Thin film cells use about 1% of the expensive semiconductors compared to First Generation cells.

- Single Crystal Si 4.7% & multi Crystal Si 0.5% of 2007 Production

- Single Crystal Si has 8–11% efficiency.

- Multi Crystal Si has 7-11% efficiency.

Third Generation – Multi-junction Cells

- Enhance poor electrical performance while maintaining very low production costs.

- Current research is targeting conversion efficiencies of 30-60% while retaining low cost materials and manufacturing techniques.

- Multi-junction cells – 30% efficiency (40-43% demonstrated)

Advantages of solar cell

- It is clean and non-polluting.
- It is a renewable energy.
- Solar cells do not produce noise and they are totally silent.
- They require very little maintenance.
- They have long life time.
- There are no fuel costs or fuel supply problems.

Disadvantages of solar cell

- Soar cells (or) solar panels are very expensive.
- Energy has not be stored in batteries.
- Air pollution and whether can affect the production of electricity.
- They need large are of land to produce more efficient power supply.
- Sun does not shine consistently.
- Less efficient and costly equipment.
- Reliability Depends On Location

Applications of solar energy

- Domestic power supply.
- Electric power generation in space.
- Drying Agricultural Products.
- Solar pumps are used for water supply.
- Water Heating.
- Generating Electrical Power.
- To providing electrical power to satellites.