Junction Diode Characteristics

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Junction Diode

- A diode is the second generation semiconductor family.
- It is a single layer, two region, single junction, two terminal unilateral active semiconductor device.
- A *p-n* junction is formed from a piece of semiconductor by diffusing *p*-type material to one half side and *n*-type material to other half side.
- The plane dividing the two zones is known as a junction.
- A region near the junction is without any free charge particles called depletion region or charged free region or space charge region because there is no charge available for conduction.

Note:
- Depletion layer consists of immobile charged particles i.e. ions only.
- Depletion layer consists of negative ion (Acceptor ions) on the *p*-side and positive ion (Donor ions) on the *n*-side.
- Depletion layer opposes majority carriers in crossing the junction.

Contact Potential or Build in Potential (V_o)

$$V_o = \frac{kT}{q} ln\left[\frac{N_A N_D}{n_i^2}\right]$$

where, V_o = Contact potential
k = Boltzman's constant (1.38×10^{-23} J/K)
q = Electron charge (1.6×10^{-19} Coulomb)
T = Temperature in Kelvin
N_A = Concentration of accepters on *p*-side
N_D = Concentration of donor on *n*-side
n_i = Intrinsic concentration at given temperature

Note:
- In case of Ge diode typical value of V_o is 0.2 Volt and for Si diode it is 0.7 V.
- In unbiased *p-n* junction diode electric field is maximum at the junction and decreases on either side of junction and zero outside of the depletion layer.

Contact potential in the terms of maximum electric field

$$V_o = -\frac{1}{2} E_o w$$

where, E_o = Maximum electric field at junction
w = Width of depletion region

Remember:
Depletion width increases with reverse and decrease with forward biased.

Depletion Width (w)

- Width of depletion region in unbiased condition is given by

$$w = \left[\frac{2 \in V_0}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$

where, $\in$ = permitivity of material used for formation p-n junction diode
V_0 = contact potential
q = electron charge (1.6×10^{-19} Coulomb)
N_a = concentration of acceptors (/cm^3) on p-side
N_d = concentration of donors (/cm^3) on n-side

Note:
- If we reverse bias the diode by voltage V then in formulae of depletion width V_0 is replaced by $|V_0 + V|$.
- It is clear that depletion width increases with reserve and decreases with forward biased.
- $$w \propto \frac{1}{\sqrt{\text{concentration}}}$$

Current Equation of Diode

Boltzman's equation of diode current

$$I = I_o\left[\exp\left(\frac{V}{\eta V_T}\right) - 1\right]$$

where, I = Diode current
I_o = Diode reverse current
V = Diode voltage (Positive for forward bias and negative for reverse bias)

η = 1 for germanium and 2 for silicon
V_T = Thermal voltage
T = Temperature in Kelvin

In forward bias

$$I_F = I_o \exp\left(\frac{V_F}{\eta V_T}\right)$$

In reverse bias

$$I_R \cong -I_o$$

Note:

Reverse current I_o is temperature dependent. It gets double for every 10°C rise.

Resistance of Diode

Resistance of diode can be calculated only when the diode is in forward bias.

(a) **Static resistance (DC resistance):** It is ratio of vo tage and current at any point.

$$R_{DC} = \frac{V}{I}$$

(b) **Dynamic resistance (AC resistance):** It is define as reciprocal of slope, which is the smallest linear region in the entire non-linear curve.

$$R_{AC} = \frac{1}{\text{Slope}} \quad ; \quad R_{AC} = \frac{dV}{dI}$$

$$R_{AC} = \frac{\eta V_T}{I_F} = \frac{\eta kT}{I_F q}$$

Note:

Static resistance is always greater than AC or dynamic resistance.

Capacitance of Diode

1. Diffusion capacitance or storage capacitance

When a diode is forward biased, a capacitance called diffusion capacitance or storage capacitance (C_D) is formed due to junction.

$$C_D = \frac{q_F}{\eta V_T} = \frac{\tau I_F}{\eta V_T}$$

where, C_D = Diffusion capacitance
τ = Mean life time of minority carriers on either side or time constant of diode
η = Recombination of factor, 1 for Ge, 2 for Si
V_T = Thermal voltage
I_F = Forward current

Note:

Diffusion capacitance is proportional to the forward current and forward current depends on forward voltage.

$$C_D \propto \sqrt{\text{Doping}}$$

2. Transition capacitance or space charge capacitance

It is also known as depletion capacitance. It is the capacitance when diode is in reverse bias.

$$C_T = \frac{\epsilon_o \epsilon_r A}{\omega_d}$$

where, C_T = Transition capacitance
ω_d = Width of depletion layer

Also $\omega_d \propto V_r$ (Reverse bias voltage)

So, $$C_T \propto \frac{1}{V_r^n}$$

where, $n = \frac{1}{2}$ = Step graded
$= \frac{1}{3}$ = Linearly graded

The transition capacitance depends upon the magnitude of the reverse voltage applied.

Note:

- Transition capacitance can be used as variable capacitance for tunning the frequencies of television and radio channel.
- Maximum value of C_T is 40 pF.

- Maximum value of C_D is 0.02 μF.
- Diffusion capacitance is always greater than transition capacitance i.e. $C_D > C_T$.

Zener Diode

- It is a heavily-doped *p-n* junction diode which is operated under reverse bias condition in the breakdown region.
- Zener current is independent of the supply voltage and only depends on external circuit resistance. Therefore Zener diode is known as constant voltage or voltage reference device.
- At reverse voltages less than 6 V, Zener breakdown predominates while at about 8 V, Avalanche breakdown predominates.
- Zener breakdown diodes are negative temperature coefficient of voltage and Avalanche breakdown diodes are positive temperature coefficient of voltage.
- These are used for voltage regulators.

Schottky Diode

- It is a metal-semiconductor junction diode without depletion layer.
- In Schottky diode no depletion layer is formed and there will be no holes in this diode.
- Cut-in voltage of this diode is 0.3 V.
- This diode is used at high frequencies.

Photo Diode

- Principle of operation is ***photo conductive effect***.
- Photo sensitive material used are CdS, Se, ZnS.
- It is also called ***light operated switch***.
- Ge-photo diode respond to visible light while Si-photo diode respond to infrared light.
- Photo sensitive coating is provided at junction only.
- Compare to normal diode photo diode has larger depletion width obtained from lower level of doping.
- It is always operated under ***reverse biased condition***.
- Compare to normal diode it is 10 times faster, 100 times higher sensitive but power handling capacity is low.
- Magnitude of photo current increases with increase in intensity of light falling at junction.
- Current in photo diode is given by

$$\boxed{I = I_s + I_0\left[1 - e^{V/\eta V_T}\right]}$$

where, I_s = short circuit current of photo diode
I_0 = reverse saturation current
V = voltage applied
V_T = thermal voltage

- Photo current flows from n to p.
- Photo current is a minority carrier current.
- It does not provide gain.
- Photo current is a ***diffusion current***.
- It is used in remote control sensor, in designing of optocouplers and to read audio track recorded on motion picture film.
- When photo diode is forward biased it behaves as a normal diode and effect of light on current is zero.

Tunnel Diode

- It is fastest switch.
- Its response time is of the order of peco second.
- It is a $p^+ n^+$ diode having doping level of 1 : 10^3.
- Worked on the principle of ***tunneling effect***.
- It has very narrow depletion layer 100 Å to 200 Å.
- It is used as linear device as well as negative resistance device.
- Best material is GaAs having highest swing.
- It is used in designing microwave oscillators, as a relaxation oscillator, in designing of pulse and switching circuits, and as parametric amplifier.

Rectifiers

Ripple factor (γ)

The amount of AC present in the output of rectifier is called as ripple. The amount of AC, from the signal contains AC and DC is calculated by ripple factor.

$$\boxed{\gamma = \frac{\text{rms value of AC component}}{\text{DC value}}} \quad ; \quad \boxed{\gamma = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}}$$

Form factor (F)

$$F = \frac{\text{rms value}}{\text{DC value}} = \frac{V_{rms}}{V_{DC}} \quad ; \quad \gamma = \sqrt{F^2 - 1}$$

Crest factor (C)

$$C = \frac{\text{Peak value}}{\text{rms value}}$$

Efficiency (η)

$$\eta = \frac{\text{Output DC power}}{\text{AC input power}}$$

Half Wave Rectifier

Average value of current and voltage

(a) Ideal case

$$I_{DC} = \frac{I_m}{\pi} \quad \text{and} \quad I_m = \frac{V_m}{R_L}$$

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

where, I_{DC} = Average value of current
V_{DC} = Average value of voltage
I_m = Maximum value of current
V_m = Maximum value of voltage
R_L = Load resistance

(b) Practical case

$$I_{DC} = \frac{I'_m}{\pi} \quad ; \quad V_{DC} = \frac{V'_m}{\pi}$$

$$I'_m = \frac{V_m}{R_s + R_f + R_L} \quad ; \quad V'_m = I'_m R_L$$

where, R_s = Coil resistance
R_f = Diode forward resistance
R_L = Load resistance

RMS value of current and voltage

$$I_{rms} = \frac{I_m}{2}$$

$$V_{rms} = \frac{V_m}{2}$$

Efficiency of half-wave rectifier

$$\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 [R_s + R_f + R_L]} = \frac{4}{\pi^2}\left[\frac{R_L}{R_s + R_f + R_L}\right]$$

- Ripple factor of half wave rectifier

$$\gamma = 1.21$$

- Crest factor of half-wave rectifier

$$C = 2$$

- Form factor of half-wave rectifier

$$F = 1.58$$

Remember:

- Maximum efficiency (when $R_S = R_f = 0$) ideal case

$$\eta = \frac{4}{\pi^2} = 40.6\%$$

- Peak inverse voltage for half wave rectifier $\boxed{PIV = V_m}$.
- Transformer utilization factor (TUF) for half wave rectifier $\boxed{TUF = 0.286}$.
- Output frequency = Input frequency for half wave rectifier.
- Conduction angle for half wave rectifier: $\theta = \pi$ for ideal case

$$\theta = \pi - 2\sin^{-1}\frac{V_\gamma}{V_m} \quad \text{for practical case}$$

V_γ = cut-in voltage of diode ; V_m = maximum voltage

- Ripple frequency (f_r) for half wave rectifier

$$\boxed{f_r = f} \; ; \quad f = \text{input frequency}$$

Full Wave Centre Tap Rectifier

Average value of current and voltage

$\boxed{I_{DC} = \frac{2I_m}{\pi}}$, ideal case $\boxed{V_{dc} = \frac{2V_m}{\pi}}$, ideal case

RMS value of current and voltage

$\boxed{I_{rms} = \frac{I_m}{\sqrt{2}}}$, ideal case $\boxed{V_{rms} = \frac{V_m}{\sqrt{2}}}$, ideal case

For practical case I_m is replaced by I'_m.

where, $\boxed{I'_m = \frac{V_m}{\frac{R_s}{2} + R_f + R_L}}$ and $\boxed{V'_m = I'_m R_L}$

Efficiency

$$\boxed{\eta = \frac{8}{\pi^2} \frac{R_L}{\frac{R_s}{2} + R_f + R_L}}$$

- Ripple factor (γ) = 0.48 for full wave rectifier.
- Form factor (F) = 1.11 for full wave rectifier.
- Crest factor (C) = $\sqrt{2}$ for full wave rectifier.

Remember: ....

- η is maximum when $R_S = R_f = 0 \rightarrow$ ideal case and $\eta_{max} = \frac{8}{\pi^2} = 81.2\%$
- Peak inverse voltage for full wave rectifier (centre tap) is $\boxed{PIV = 2V_m}$.
- Transformer utilization factor (TUF): TUF = 0.693 for full wave centre tap.

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Full Wave Bridge Rectifier

For full wave rectifier (bridge type) in all the formulas $\frac{R_S}{2}$ is replaced by R_S and R_f is replaced by $2R_f$.

Remember: ....

- For bridge type $\boxed{PIV = V_m}$.
- TUF = 0.812 for bridge type.
- Conduction angle: $\theta = 2\pi$ ideal case

$\boxed{\theta = 2\pi - 4\sin^{-1}\frac{V_\gamma}{V_m}}$ for center tap

$\boxed{\theta = 2\pi - 4\sin^{-1}\frac{2V_\gamma}{V_m}}$

$V_\gamma \rightarrow$ cut in voltage of diode

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Remaining parameters are same as full wave centre tap rectifier.

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