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Diodes

Semiconductor Physics

Semiconductor Materials

- The term **conductor** is applied to any material that will support a generous flow of charge when a voltage source of limited magnitude is applied across its terminals.
- An **insulator** is a material that offers a very low level of conductivity under pressure from an applied voltage source.
- A **semiconductor**, therefore, is a material that has a conductivity level somewhere between the extremes of an insulator and conductor.

Band Theory

A bonding of atoms, strengthened by the sharing of electrons, is called **covalent bonding**. In the crystal, closely spaced energy levels form a band called as **energy band**. Each orbit has a separate energy band. A band of energy levels associated with valence shells is called as **valence band**. Electrons from other bands cannot be removed but electrons from valence band can be removed by supplying a little energy. The **conduction band** is

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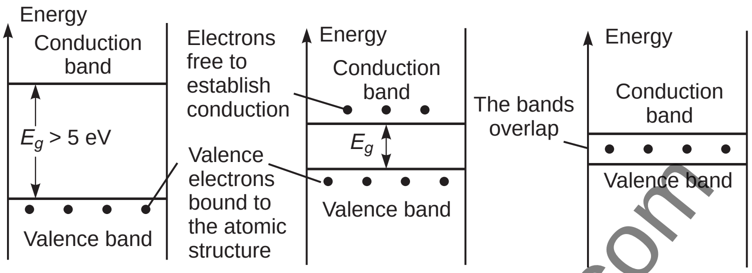
generally empty. The valence band and conduction band are separated by a gap called **forbidden energy gap**.



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

(a) Insulator (b) Semiconductor (c) Conductor

Key Points

- If electron from valence band is supplied with an energy more than forbidden energy gap, it gets drifted to the conduction band and is available as a free electron.
- The energy associated with electron is measured in electron volt (eV).

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

Compound Semiconductors

Such as Gallium Arsenide (GaAs), Cadmium Sulphide (CdS), Gallium Arsenide Phosphide (GaAsP), Gallium Nitride (GaN) are constructed by two or more semiconductor materials of different atomic structures are called compound semiconductors.

Properties of Semiconductor Materials

The various materials are classified based on the width of forbidden energy gap. In metal, there is no forbidden gap and valence and conduction band are overlapped. In insulator, the forbidden gap is very large upto 7eV while in semiconductors it is upto 1eV. The silicon and germanium are widely used semiconductors. Intrinsic materials are those semiconductor that have been carefully refined to reduce the impurities to a very level-essentially as pure as can be made available through modern technology.

- The conductivity of intrinsic semiconductor is very less. The properties like conductivity can be changed by adding impurity to the intrinsic semiconductor. The process of adding impurity is called **doping**.

- A semiconductor doped with trivalent impurity atoms forms *p*-type material. It is called **acceptor impurity** with concentration N_A atoms per unit volume.
- A semiconductor doped with pentavalent impurity atoms forms *n*-type material. It is called **donor impurity** with concentration N_D atoms per unit volume.
- In *p*-type, holes are majority carriers and in *n*-type electrons are majority carriers.
- When a material is subjected to electric field, electrons move in a particular direction with steady speed called **drift speed** and current .

Key Points

- A semiconductor material that has been subjected to the doping process is called an extrinsic material.
- Both *p*-type and *n*-type materials are called **extrinsic conductors**.
- The concentration of free electrons and holes is always equal in an intrinsic semiconductor.

$$n = p = n_i = \text{intrinsic concentration}$$

Negative Temperature Coefficient

Those parameters decreasing with the temperature have negative temperature coefficient, *e.g.*, energy gap (E_g).

where, constant $\beta_0 = 2.2 \times 10^{-4}$ (for Ge)

$= 3.6 \times 10^{-4}$ (for Si)

$$E_g T = E_{g_0} - \beta_0 T$$

Mobility (μ), $\mu \propto T^{-m}$

Positive Temperature Coefficient

Those parameters increasing with temperature have positive temperature coefficient.

Some Important Terms

Some important terms regarding semiconductor materials are as given below

- Drift velocity $v_d = \mu E$
- Current density $J = nq\,\mu E$
- Conductivity $\sigma = nq\,\mu$
- Concentration of free electrons per unit volume $n = \dfrac{dU}{AM}$
- Semiconductor conductivity $\sigma = (n\mu_n + p\,\mu_p)\,q$
- In intrinsic semiconductor, $n = p = n_i$

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Hence, conductivity $\sigma_i = n_i(\mu_n + \mu_p)q$

Intrinsic concentration $n_i = A_0 T^3 e^{-\frac{E_{G0}}{KT}}$

- In **extrinsic semiconductor**, the conductivity is given by,

For n-type, $\sigma_n = (n_n \mu_n + p_n \mu_P) q$

For p-type, $\sigma_p = (n_p \mu_n + p_p \mu_p) q$

But in n-type $p_n << n_n$

N_D = Concentration of donor impurity
N_A = Concentration of acceptor impurity
n_P = Number of electrons (concentration) in p-type
P_P = Number of holes (concentration) in p-type

and $n_n \cong N_D$ while in p-type
$n_p << p_p$ and $p_p \cong N_A$

Hence, conductivity can be calculated as,

$$\sigma_n = N_D \mu_n q \text{ and } \sigma_p = N_A \mu_p q$$

- Mass-action law $np = n_i^2$

$$\text{In } n\text{-type, } n_n p_n = n_i^2, \text{ hence } p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D}$$

$$\text{In } p\text{-type, } p_p n_p = n_i^2, \text{ hence } n_p = \frac{n_i^2}{p_p} = \frac{n_i^2}{N_A}$$

Diffusion Current

Diffusion is defined as the migration of charge carriers from higher concentration to lower concentration. Due to this non-uniform concentration, there can exist a current called **diffusion current**. The diffusion current depends on concentration gradient $\frac{dp}{dx}$ or $\frac{dn}{dx}$.

Diffusion Current Density

The diffusion current density is given by,

$$\text{In } p\text{-type, } J_p = -qD_p \frac{dp}{dx}$$

$$\text{In } n\text{-type, } J_n = -qD_n \frac{dn}{dx}$$

D_p and D_n are called **diffusion constants**.

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Drift Current

In open circuit, continuously graded semiconductor diffusion current exists. But net current is zero. So there exist drift current in opposite direction of diffusion current to cancel it.

Note To have drift current exists a potential internally generated. This indicates that non-uniform doping of bar, results in the induced voltage.

Einstein's Relation

In a semicondutor, this relation gives the relationship between diffusion constant, mobility and thermal voltage.

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = KT$$

$V_T = KT$ and is 26 mV at 27°C

Potential Difference and Junction Potential

The potential difference between any two points of non-uniformly doped bar depends on concentration at those two points given by

$$V_{21} = V_T \ln \frac{p_1}{p_2}, V_{21} = V_T \ln \frac{n_2}{n_1}$$

where, V_{21} = The potential difference between points 1 and 2

V_T = Thermal voltage

V_j = Junction potential

The expression for the junction potential is given by

$$V_J = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

For germanium, $V_J = 0.2$ to 0.3 V

For silicon, $V_J = 0.6$ to 0.7 V

Fermi Level

Fermi energy is defined as the energy possessed by the fastest moving electron at 0 K.

Fermi-Dirac Function

The Fermi-Dirac function of a metal or semiconductor is given by

$$F(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

Fermi Level in *n*-type Semiconductor

$$E_C - E_F = kT \log_e \frac{N_C}{N_D}$$

where, E_c = Maximum energy of conduction band
E_V = Maximum energy of valence band
E_F = Fermi energy in eV.

$$E_C - E_F = kT \log_e \frac{N_C}{N_D}$$

Fermi Level in *p*-type Semiconductor

$$E_F = E_V + kT \log_e \frac{N_V}{N_A}$$

where, N_A = Concentration of acceptor ions
N_D = Concentration of donor ions
N_C = Material constant and can be considered as a function of temperature

$$N_V = 2\left[\frac{2\pi - kTm_r}{h^2}\right]^{3/2}$$

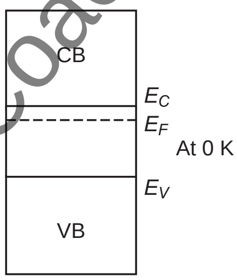
$$N_C = 2\left[\frac{2\pi\, kTm_n}{h^2}\right]$$

$k = 1.81 \times 10^{-23}$ J/K

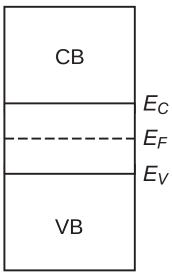
m = Mass of electron

m_n = Effective mass of electron

h = Planck constant $= 6.625 \times 10^{-34}$ J-s



Fermi level for *n*-type



Fermi level for *p*-type

Key Points

- It *p*-type and *n*-type materials are combined chemically it results into *p*-*n* junction.
- At junction there is step change in the concentration of charge carriers.
- The region near the junction gets depleted off the free charged particles hence called as **depletion region**.
- The potential gets developed near the junction due to change in concentrations of carriers called potential barrier or cut-in voltage or junction potential or height of potential barrier. It has fixed polarity.
- The width of depletion region depends on the doping of both sides. The depletion region penetrates more on the lightly doped side.

Vacuum Diode

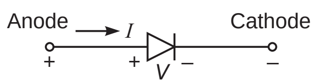
The thermionic vacuum diode has a plate and either a directly or an indirectly heated cathode. It is bulky when compared with the selenium diode or the ultra compact semiconductor diode. An ideal diode is a two terminals polarity sensitive device that has zero resistance when it is forward biased and infinite resistance when reverse biased.

A vacuum diode's characteristics follow child's three halves power law, $I = KV^{3/2}$ while current increases exponentially with voltage in a semiconductor diode.

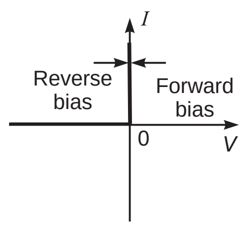
Ideal Diode

An ideal diode may be considered as most fundamental non-linear element. Silicon and germanium diodes exhibit a cut-in voltage of 0.6 V and 0.2 V respectively in their characteristic curves and thus approximate closely the ideal diode in this respect. The Peak Inverse Voltage (PIV) is the highest reverse voltage a diode can withstand before breaking down and permitting current to flow in the reverse direction.

The **static** and **dynamic resistances** of a diode may be determined from the characteristic curves and represent the DC and AC opposition to current flow offered by the diode. An equivalent circuit of a diode is a linearisation of the diode's characteristic curve and typically consists of an ideal diode in series with a battery (representing the cut-in voltage) and a resistance equal to the dynamic resistance of the diode over its linear portion.



Ideal diode symbol



V-I characteristic of ideal diode

Note A diode in a series circuit with an AC voltage applied will cause half-wave rectification.

Semiconductor Diode

The two types of material *n*-type and *p*-type are chemically combined to form a *p*-*n* junction. A region near the junction is without any free charge particles called **depletion region**.

Note The characteristics of an ideal diode are those of a switch that can conduct current in only one direction.

Biasing of a Diode

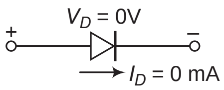
The electric field across the junction has a fixed polarity called **barrier potential** or height of the barrier. A popular semiconductor device is formed using a *p-n* junction called ***p-n* junction diode**.

No Applied Bias ($V_D = 0V$)

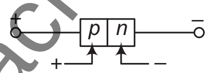
In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero.

Forward Bias ($V_D > 0V$)

In forward biased condition, majority carrier carry the current, when applied voltage approaches barrier potential. The depletion region reduces as forward bias increases.



Diode in forward bias

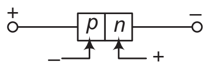


Symbol of forward bias mode

Reverse Bias ($V_D < 0V$)

On the other hand in reverse biased condition, the depletion region widens and minority carriers carry the current called **reverse saturation current** denoted as I_0.

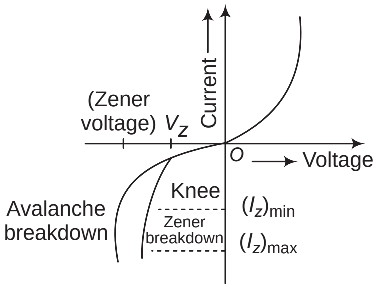
Diode in reverse bias



Symbol of reverse bias mode

Breakdown in Diode

If reverse biased voltage increases, at a particular voltage breakdown occurs due to accelerated minority charge particles. This is called **avalanche effect**. For a heavily doped diode, electric field across the depletion region is so intense to pull the electrons out of valence bands. This effect is called **zener effect**.



Breakdown *V-I* characteristics

Some Important Currents in Diode *w.r.t.* FB

In forward biased condition, *the diode current has four components*.

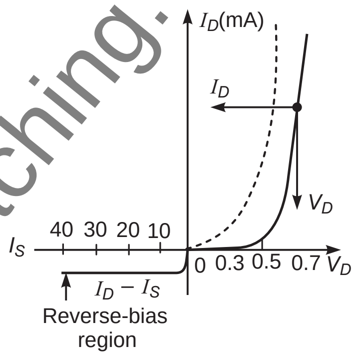
I_{pp} = current due to holes in p side
I_{nn} = current due to electrons in n side
I_{pn} = current due to holes in n side
I_{np} = current due to electrons in p side

All are functions of distance from the junction. At the junction, at $x = 0$ the total current I is,

$$I = I_{pn}(0) + I_{np}(0)$$

Voltage-Current Characteristics

The proportion of current due to electrons and holes varies with the distance inside the diode but sum of the currents carried by electrons and holes at any point inside the diode is always constant, equal to total forward diode current. The graph of current against voltage applied to a diode is called *V-I* characteristics.



V-I characteristics of diode

In forward biased region, when applied voltage exceeds cut-in voltage, heavy conduction starts. Cut-in voltage is denoted as V_c and is 0.2 for Ge and 0.6 for Si diode. The reverse saturation current I_0 is almost constant in reverse biased region and is dependent on temperature.

Static and Dynamic Resistance

The static resistance is simply the ratio of DC voltage across the diode to the DC current flowing through it.

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

While the dynamic resistance is AC resistance and defined as ratio of incremental change in voltage to the corresponding change in current.

$$r = \text{dynamic resistance} = \frac{\Delta V_d}{\Delta I_d}$$

$$r = \frac{1}{\text{Slope of } V\text{-}I \text{ characteristics}}$$

The V- I characteristics is given by the equation

$$I = I_0 (e^{V/nV_T} - 1)$$

when $V > 0,\ I_I = I_0 e^{V/nT}$

when $V < 0,\ I_s = -I_0$

This is called **current equation of a diode**. From this, dynamic resistance can be determined as,

$$r = \frac{1}{\text{Slope of graph}} = \frac{1}{\left\{\frac{dI}{dV}\right\}} = \frac{nV_T}{I_0 e^{V/nV_T}}$$

- For forward biased, V must be considered positive while for the reverse biased, V must be considered negative. This dependence of I_0 on temperature is given by

$$I_0 = KT^M e^{-V_{G0}/nV_T}$$

where, $m = 2$ for Ge, 1.5 for Si

and $V_{G_0} = 0.785$ V for Ge, 1.21 V for Si

- The change in voltage with respect to temperature required to keep diode current constant is given by,

$$\frac{dV}{dt} = \frac{V - (V_{G_0} + mnV_T)}{T}$$

where, $n = 1$ for Ge; $n = 2$ for Si

- It is -2.10 mV/°C for Ge and -2.3 m for Si. Practically, considered as 2.5 mV/°C for any diode. While change in I_0 will respect to temperature is given by,

$$\frac{d\,\text{In}\,(I_0)}{dT} = \frac{m}{T} + \frac{V_{G_0}}{nTV_T}$$

- It is 11% per °C for Ge while 8% per °C for Si. Practically, it is considered as after every 10°C rise in temperature, diode reverse saturation current doubles while it rises by 7% per °C rise in temperature for any diode. From this it can be written as

$$(I_0)_2 = (1.07)^{\Delta T}\ (I_0)_1$$

where, $(I_0)_2$ = Reverse saturation current at T_2

$(I_0)_1$ = Reverse saturation current at T_1

$\Delta T = T_2 - T_1$

Transition and Diffusion Capacitance

In reverse biased condition, due to change with respect to voltage there exists a capacitive effect called as **transition capacitance** denoted as C_T.

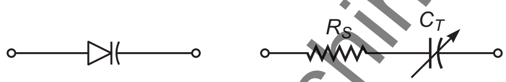
It is given by $$C_T = \frac{\varepsilon A}{W} = \frac{\varepsilon_0 \varepsilon_r A}{W}$$

where, W = width of the carrier. W is related to barrier potential V_B by the relation, barrier potential, $V_B = \frac{1}{2}\frac{qN_A}{\varepsilon}W^2$

ε_0 and ε_r are the permittivity and relative permittivity respectively.

Hence, $$W \propto \sqrt{V_B} \text{ while } C_T \propto \frac{1}{W}$$

On the other hand, in forward biased condition also there exists a capacitive effect called as **diffusion capacitance** denoted as C_D.



(a) Circuit symbol (b) Equivalent circuit

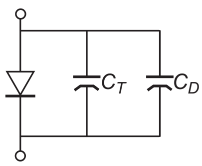
$$C_D = \frac{tI}{nV_T}$$

where, t = mean life time for holes; $C_D >> C_T$

Varactor Diode

The rate of change of stored charge with applied voltage is defined as diffusion capacitance and is denoted by C_D.

Diffusion capacitance, $$C_D = \frac{dQ}{dV}$$



Varactor diode

Note In the reverse bias region, we have the transition while in forward bias region we have difussion capacitance.

The transition capacitance effect is made purposely dominant in practice, to use the diodes in tuning circuits. Such diodes are called as **varactor diodes**.

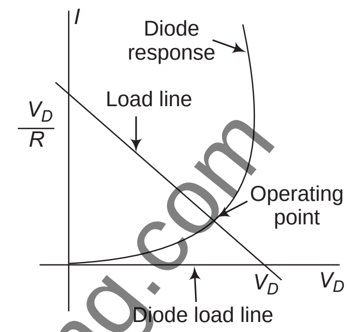
Reverse Recovery Time

The diode is used as an electronic switch in many circuits. Diode cannot be reversed instantaneously. The diode requires a time to reverses a time to reverse called as its **reverse recovery time** (t_{rr}) which is made up of storage time (t_s) and transition time (t_t).

Note In analyzing practical circuits, diode is replaced by a battery or voltage equal to cut-in voltage in series with it a forward resistance if given. This is called **equivalent mode of a diode**.

Operating Point in a Diode

The determination of current flowing in a series circuit containing a diode, resistor R_L and DC applied voltage V is made by drawing a load line on the static characteristic curve of the diode. One end of the load line is at $V_D = V$, $I = 0$, the other at $V_D = 0$, $I = \frac{V}{R_L}$. The intersection of the load line with the curve gives the **Q-point.**



V-I characteristics

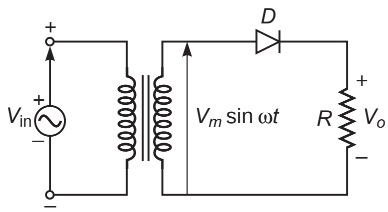
When an alternating voltage is applied to a series diode resistor circuit, a dynamic curve may be constructed to give the output current waveform for the load resistor for which the curve was drawn.

Applications of Diode

The diode can be used as a **rectifier**. A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as **rectification**.

Half-Wave Rectifier

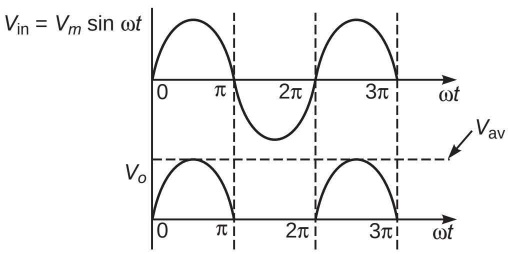
- In positive half cycle, diode D conduct and V_0 is same as V_i.
- In negative half cycle diode D does not conduct so that the voltage V_0 output is zero.



Half-wave rectifier circuit

$V_{av} = 0.318 V_m$

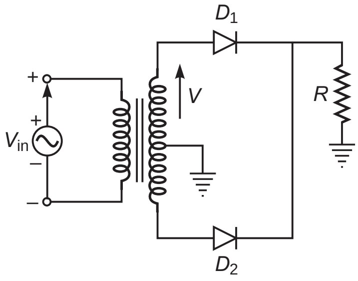
$I_{av} = V_m / \pi R$



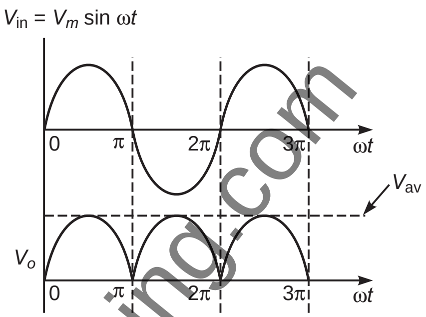
Waveform of half-wave rectifier

Full-Wave Rectifier

- In positive half cycle diode D_1 conduct but D_2 will be off and V_0 is same as V_i.
- In negative half cycle diode D_2 conduct but D_1 will be off so that the output voltage V_o is inverted of V_i (*i.e.,* half cycle)



Full wave-rectifier circuit



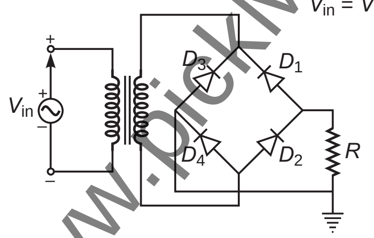
Waveform of full-wave rectifier

$$V_{av} = 2V_m / \pi \; ; \; I_{av} = \frac{2V_m}{\pi R}$$

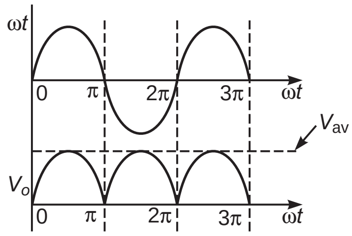
where V_m = maximum value of voltage

Bridge Rectifier

The single-phase full-wave bridge rectifier is shown in figure.



Bridge rectifier circuit



Waveform of bridge rectifier

In the positive half cycle, D_1 and D_4 are forward biased and D_2 and D_3 are reverse biased. In the negative half cycle, D_2 and D_3 are forward biased, D_1 and D_4 are reverse biased. The output voltage waveform is shown in figure, it is same as full-wave rectifier but the advantage is that PIV rating of diodes are V_m and only single secondary transformer is required.

Ripple Factor

The ripple factor is the measure of the purity of DC output of a rectifier and is defined as

$$\text{Ripple factor} = \frac{\text{rms value of the AC output voltage}}{\text{Average DC output voltage}} = \sqrt{V_o^2 + \sum_{n=1}^{\infty} V_n^2}$$

$$\text{Therefore, ripple factor} = \frac{\sqrt{V_{\text{rms}}^2 - V_o^2}}{V_o} = \sqrt{\left(\frac{V_{\text{rms}}}{V_o}\right)^2 - 1}$$

Key Points

- A half-wave rectifier is characterised by an excessive ripple, low values of ratio of rectification and transformer utilisation factor and DC saturation of the transformer core.
- The centre tapped and bridge type full-wave rectifiers improve on the half-wave characteristics but the three phase, full-wave rectifier is even better.

Basic Parameters used in Rectifying Circuits

The basic parameters used in rectifying circuits are given below

- **Ratio of rectification** $= \dfrac{\text{DC power delivered to the load}}{\text{AC input power from transformer secondary}}$

  and is a figure of merit (a measure of efficiency) to compare rectifiers.
- **Transformer utilisation factor**

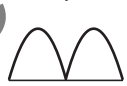
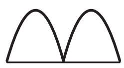
  $$= \frac{\text{DC power delivered to the load}}{\text{AC rating of transformer secondary}}$$

  and is used to determine the necessary rating of a transformer for a given DC load.

  % Voltage regulation $= \dfrac{V_{\text{no load}} - V_{\text{full load}}}{V_{\text{full load}}} \times 100\%$

  and is an indication of how the output voltage of a power supply varies with load.
- The internal resistance of a power supply, $R_{\text{int}} = \dfrac{V_{\text{NL}} - V_{\text{FL}}}{I_l}$, is due to the resistance of the diodes and transformer winding. Where V_{NL} and V_{FL} are voltage during no load and full load respectively.

Comparison of Rectifier Circuits with Resistive Load

Characteristics Parameters	Half-Wave	Full-Wave	Bridge	Three Phase Full-Wave
Secondary voltage line to line $(V_m = \sqrt{2}V)$	V	$2V$	V	V
Number of diodes	1	2	4	6
Peak inverse voltage	V_m	$2V_m$	V_m	V_m
No load DC output V_{DC}	$\frac{V_m}{\pi} =$ 0.318 V_m	$\frac{2V_m}{\pi} =$ 0.636 V_m	$\frac{2V_m}{\pi} =$ 0.636 V_m	$\frac{3V_m}{\pi} =$ 0.955 V_m
Ripple factor	1.21	0.482	0.482	0.055
Ratio of rectification	0.406	0.812	0.812	0.995
Transformer utiliation factor	0.287	0.693	0.812	0.955
DC power available from a 1 kVA Transformer watts	287	693	812	955
Ripple frequency	f	$2f$	$2f$	$6f$
Output waveform of voltage and current				

Note The reading of an AC voltmeter depends upon the type of meter and the waveform across which it is connected.

Filter Circuits for Power Supplies

Electronic filters are electronic circuits which perform signal processing functions, specifically to remove unwanted frequency components from the signal, to enhance wanted ones, or both. *Electronic filters can be classified as*

- passive or active
- analog or digital
- high-pass, low-pass, bandpass, band-reject (band-reject; notch), or all-pass.
- discrete-time (sampled) or continuous-time
- linear or non-linear
- Infinite Impulse Response (IIR type) of Finite Impulse Response (FIR type)

The ripple factor may be determined experimentally by observing the output voltage on an oscilloscope and determining the peak to peak value of the ripple voltage. This is converted to an rms value assuming it to be a sinusoid except in the case of a capacitor filter, in which the ripple will be more triangular and has an rms value of $\frac{V_{r,p-p}}{2\sqrt{3}}$.

Key Points

- An inductor filter has a ripple that increases with load resistance and consequently is used only with relatively high load currents.
- The ratio of this rms value to the DC average of the wave is the ripple factor.

Summary of Filter Information (Full-Wave Rectifier)

Parameters	Type of Filter				
	None	L	C	L-Section	π-Section
V_{DC}, no load	$0.636\,V_m$	$0.636\,V_m$	V_m	$V_m(N_O R_b)$	V_m
V_{DC}, load I_{DC}	$0.636\,V_m$	$0.636\,V_m$	$V_m - \frac{4170\,I_{DC}}{C}$	$0.636\,V_m$	$V_m - \frac{4170 I_{DC}}{C}$
Ripple factor r	0.48	$\frac{R_L}{1600L}$	$\frac{2410}{CR_L}$	$\frac{0.83}{LC}$	$\frac{3330}{C_1C_2LR_L}$
Peak inverse	$2\,V_m$	$2\,V_m$	$2\,V_m$	$2\,V_m$	$2\,V_m$

C is in microfarad, L in henry, R_L in ohm, V_m in volt and I_{DC} in ampere.

The ripple from a capacitor filter decreases as the load resistance increases and provides effective filtering only for light loads of 50 mA and

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less. The capacitor filter provides poor voltage regulation because of the increase in ripple with load current causing a decrease in average voltage.

When the ripple from a capacitor filter is known to be high, in the region of 30%, a more accurate determination of ripple may be made using

$$r = \frac{2410}{2\,CR_L} \text{ instead of } r = \frac{2410}{CR_L}.$$

A capacitor filter is characterised by the high peak current that the diodes must handle due to the capacitor recharging in a very short interval and this current increases with the value of C.

Key Points

- A diode's peak inverse voltage in a half-wave rectifier employing a capacitor filter is $2V_m$.
- L-C filter's ripple factor is independent of load provided a critical inductance, $L_C \geq \frac{R_L}{900}$ is used at all times.
- The use of a bleeder resistor or swinging choke will help to maintain good voltage regulation in an L-C filter.
- Use of an L-C filter makes the selection of filtering components very flexible and requires less capacitance than in a capacitor filter for a given amount of ripple. It also reduces the peak diode current requirement and is generally preferred for load currents in excess of 50 mA.
- Multiple L-C sections or the use of a C-L-C filter improve the filtering process and in some cases the inductor may be replaced by a resistor for light loads.

Clippers

Clipping circuits are used to select that portion of the input wave which lies above or below some reference levels.

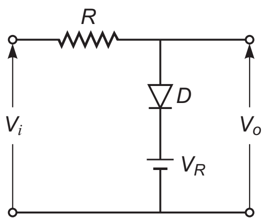
Some of the clipper circuits are discussed below.

Clipper Circuit 1

The circuit shown in figure, clips the input signal above a reference voltage (V_R).

If $V_i < V_R$, diode is reversed biased and does not conduct. Therefore, $V_o = V_i$.

If $V_i > V_R$, diode is forward biased, then $V_o = V_R$.



Clipper circuit 1

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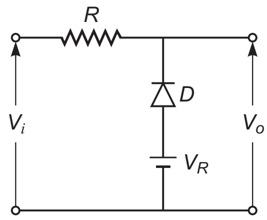
Clipper Circuit 2

The clipper circuit shown in figure clips the input signal below reference voltage V_R.

If $V_i > V_R$, diode is reverse biased so, $V_o = V_i$.

If $V_i < V_R$, diode is forward biased so, $V_o = V_R$.



Clipper circuit 2

Clipper Circuit 3

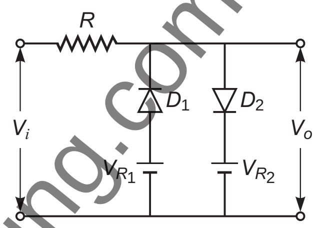
To clip the input signal between two independent levels ($V_{R_1} < V_{R_2}$), the clipper circuit is shown in figure.

The diodes D_1 and D_2 are assumed ideal diodes.

when $\quad V_i \le V_{R_1}, V_o = V_{R_1}$

and $\quad V_i \ge V_{R_2}, V_o = V_{R_2}$

and $\quad V_{R_1} < V_i < V_{R_2}, V_o = V_i$



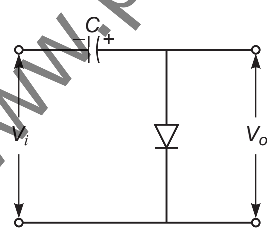
Clipper circuit 3

Clamper Circuits

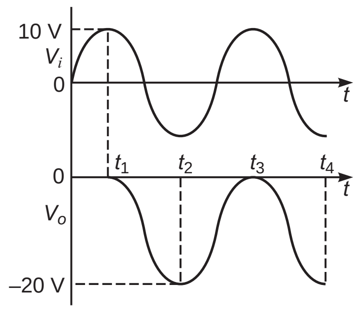
Clamping is a process of introducing a DC level into a signal. For example, if the input voltage swings from –10 V and +10 V, a positive DC clamper, which introduces +10 V in the input will produce the output that swings ideally from 0 V to +20 V. The complete waveform is lifted up by +10 V.

Negative Diode Clamper

A negative diode clamper is shown in figure below which introduces a negative DC voltage equal to peak value of input in the input signal



Negative diode clamper circuit

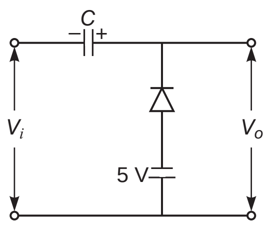


Input and output waveform of negative diode clamper

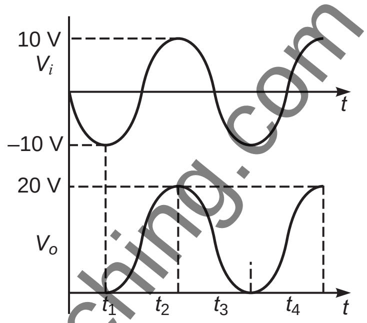
Positive Clamper

The positive clamper circuit is shown in figure, which introduces positive DC voltage equal to the peak of input signal. The operation of the circuit is same as of negative clamper.

During first negative half cycle as V_i rises from 0 to –10 V, the diode conducts. The capacitor charges during this period to 10 V, with the polarity shown.



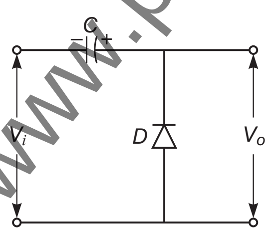
Positive clamper circuit



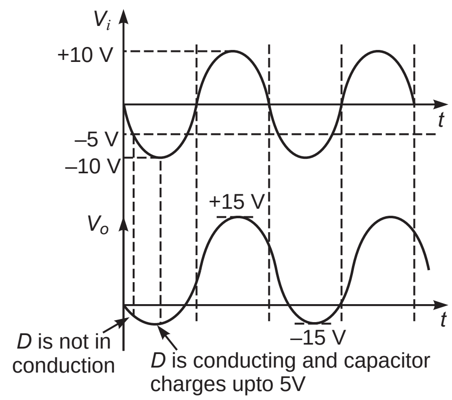
Input and output waveform of positive clamper circuit

After that V_i starts to drop which means the anode of D is negative relative to cathode, ($V_D = V_i - V_C$) thus, reverse biasing of diode and preventing the capacitor from discharging.

In the negative half cycle, when the voltage exceed from 5 V then D conducts. During input voltage variation from – 5 V to – 10 V, the capacitor charges upto 5 V with the polarity shown in figure. After that D becomes reverse biased and open circuited. Then complete AC signal is shifted upward by 5 V.



Positive clamper circuit

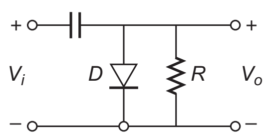


Input and output voltage waveform of positive clamper

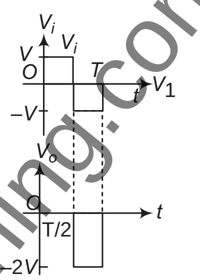
Voltage Doublers

Figure shows the circuit of voltage doubler. The circuit provides a DC voltage, which is double the peak input voltage.

A half-wave or cascade voltage doubler is a diode clamper circuit followed by a rectifier and filter, producing a DC output voltage of $-2V_m$ to $+2V_m$ depending upon diode polarities. The half-wave voltage doubler may be used to provide a high DC output voltage (typically 3 kV) or to convert AC into DC in a VTVM application.

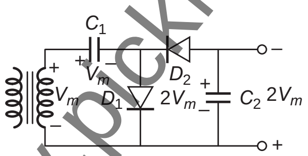


Voltage doubler circuit

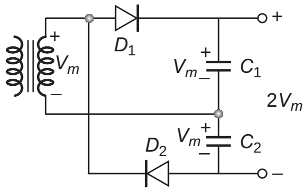


Input and output waveform of voltage doubler

A full-wave voltage doubler uses two diodes to charge two series connected capacitors to a total output voltage of $2V_m$, with a ripple frequency twice that of the input. The full-wave voltage doubler, which does not relay upon a clamping and rectifying action, can be used to provide two DC output voltages of opposite polarity with respect to ground and equal to $\pm V_m$.

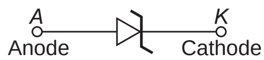


(a) Half-wave voltage doubler



(b) Full-wave voltage doubler

Zener Diode

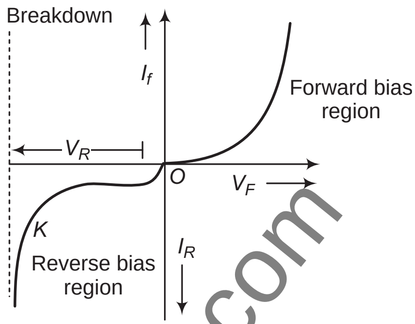


Zener diode symbol

A zener diode is a *p-n* junction operated in the reverse biased mode to take advantage of its sharply defined breakdown voltage. The zener voltage V_Z is specified at some test value of current I_{ZT}, at which the diode will exhibit some dynamic impedance $Z_T = \dfrac{\Delta V_Z}{\Delta I_Z}$ which depends upon the zener voltage of the diode and the level of zener current.

Operation

A zener diode may be used to regulate the load voltage at the value V_Z by acting as a **bypass value** to counteract line voltage or load current variations. Diodes having a breakdown voltage below about 6V rely on the true zener effect (high electric field moves electrons from bonds), while the avalanche effect is responsible for reverse current above 6 V. Zener diodes have a temperature coefficient, α_Z which generally is negative for V_Z below about 6 V but positive above 6V, and is expressed in per cent of V_Z per °C, with the change in zener voltage given by the equation.

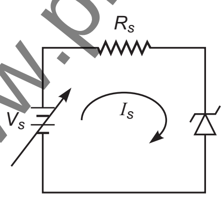


Zener diode characteristics

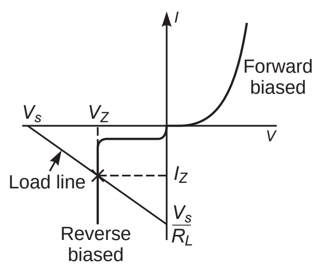
$$\Delta V_Z = V_Z \times \frac{\alpha_Z}{100} \times \Delta T$$

Zener Regulator

When zener diode is forward biased, it works as a diode and drop across it is 0.7 V. When it works in breakdown region, the voltage across it is constant (V_Z) and the current through diode is decided by the external resistance. Thus, zener diode can be used as a voltage regulator in the configuration shown in figure. The load line of the circuit is given by $V_s = I_s R_s + V_Z$.



Zener diode as regulator



V-I characteristics of zener diode

To operate the zener in breakdown region V_s should always be greater than V_Z. R_s is used to limit the current.

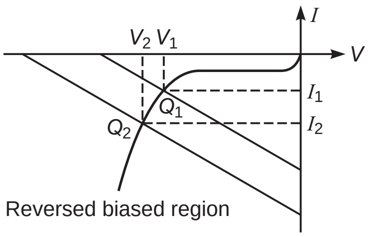
The Zener on state resistance produces more IR drop as the current increases. As the voltage varies form V_1 to V_2 the operating point shifts from Q_1 to Q_2.

The voltage at Q_1 is $V_1 = I_1 R_Z + V_Z$

and at Q_2, $V_2 = I_2 R_Z + V_Z$

Thus, change in voltage is

$V_2 - V_1 = (I_2 - I_1)R_Z$; $\Delta V_Z = \Delta I_Z R_Z$



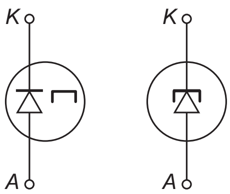
Operating point in *V-I* characteristics of zener diode

Key Points

- Reference zener diodes are available with α_Z as low as 0.0005%/°C.
- The admission of a small amount of mercury gas increases the current capability of a hot cathode gas filled tube.
- A cold cathode or glow discharge diode may be used as a DC voltage regulator in a similar manner to a zener diode.

Tunnel Diode

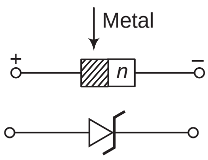
A tunnel diode's characteristics exhibit a **negative resistance region** and it may be used as an **ultra-fast switching device** or in ultra-high frequency oscillators.



Tunnel diode symbol

Schottky Diode

The charge storage problem of a p-n junction diode can be eliminated or minimize in a Schottky diode. This diode is also known as hot carrier diode, hot electron diode or **ESBAR diode** (epitaxial Schottky barrier). In this diode, the barrier potential is set with a contact between a metal and a semiconductor. The rectifying action depends upon the flow of electrons.



Schottky diode symbol

Thermistors

Thermistors are semiconductors which have a high negative temperature coefficient in the order of –4%/° C and may be used for temperature measurement and control. Thermistors may also be used in the self heated mode where they are sensitive to the rate of heat removal and have applications such as flow measurement devices or voltage regulators for DC or AC.

Thermistors symbol