Conduction in semiconductors

1. Conductor, insulator and semiconductor:

Insulator *has a very poor electrical conductivity such as plastic and wood. It has a very high energy band gap (~6 eV) which separates the filled valance band and the conduction band.*

The energy which supplies to the electrons from an applied field is too small to the assist the electron to travel through the wide band gap, therefore, the conduction in impossible.

Conductor *has an excellent electrical conductivity such as metals. It has a very small or even no band gap between valance and conduction band.*

Applying a field will assist the electrons to pass through the gap and the conduction occurs.

Semiconductor *has a band gap which is relatively small (1-2 eV) such as silicon. Such energies (1-2 eV) which is required to excite the electron from the valance band to the conduction band cannot be acquired from the applied field; therefore, the valance band remains full and the conduction band empty.*

- *These materials are insulators at low temperatures.*
- *The conductivity of the semiconductor is increased by increasing the temperature or by doping.*

The band gap can be calculated according to the following equation:

$$\lambda = \frac{12,400}{E_2 - E_1} \qquad (1)$$

The lowest energy state (E_1) is called ***normal or ground state*** *and other levels are called* ***excited levels (E_2)***.

As the electron is given more and more energy, it moves into the stationary states which are farther and farther away from the nucleus. *When its energy is large enough it will be detached out of the field of influence of ion*, this energy is called ***ionization energy***; is represented as the highest state in the energy level diagram.

Conduction in semiconductors

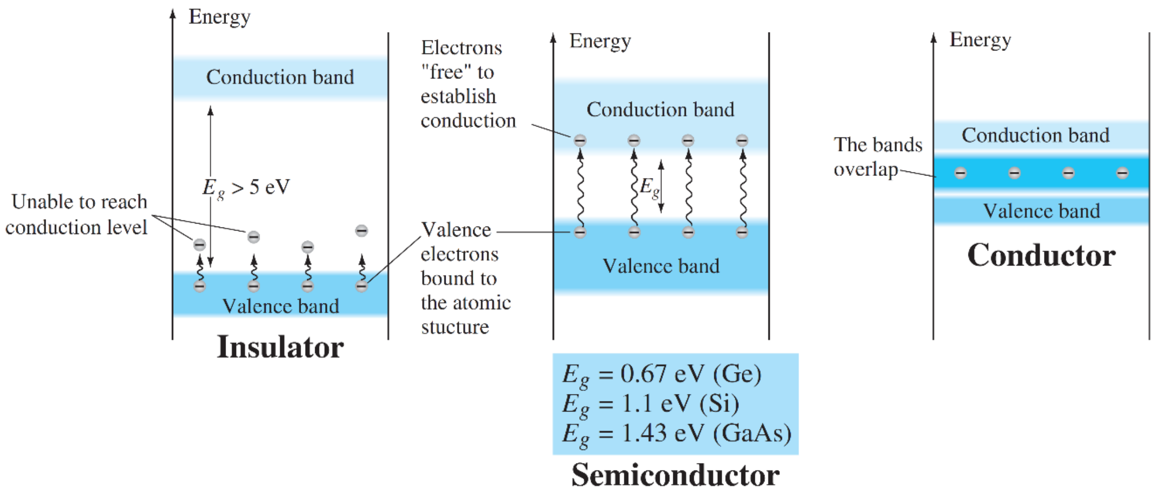


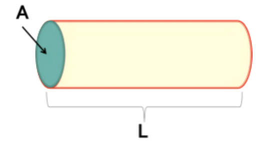
Figure 1 Conduction and valence bands of an insulator, a semiconductor, and a conductor.

Conduction in semiconductors

2. Mobility and conductivity:

$$\text{conductivity } (\sigma) = \frac{1}{\text{resistivity } (\rho)} \qquad (2)$$

Where, σ is the conductivity, and ρ is the resistivity. In general, for a conductor wire with cross section area (A) and length (L), the resistivity or specific resistivity (R) is:



$$R = \rho\frac{L}{A} \qquad (3)$$

$$\rho = \frac{AR}{L} \qquad (4)$$

$$\because \; R = \frac{V}{I} \qquad (5)$$

$$\because \; J = \frac{I}{A} \qquad (6)$$

$$\therefore \sigma = \frac{1}{\rho} = \frac{L}{AR} = \frac{L}{A(\frac{V}{I})} \qquad (7)$$

$$\because \; E = \frac{V}{L} \qquad (8)$$

$$\therefore \sigma = \frac{J}{E} \quad \text{or} \quad J = \sigma E \qquad (9)$$

Where J is the current density per unite area, which is *the resulted current from the movement of number of charges (n) a cross section of A in one second*. Then if we suggest that the average speed (u) of these charges, we obtain:

$$J = qnu \qquad (10)$$

$$\therefore \sigma = \frac{J}{E} = \frac{qnu}{E} \qquad (11)$$

Where $\frac{u}{E}$ is the charge mobility (μ).

For electrons is μ_e.

$$\mu_e = \frac{u}{E} \qquad (12)$$

$$\sigma_e = qn\mu_e \qquad (13)$$

σ_e is the electron conductivity. And for holes:

$$\sigma_p = qp\mu_p \qquad (14)$$

The total mobility is the average of both hole and electron mobilities:

$$\sigma = qn\mu_n + qp\mu_p \qquad (15)$$

For intrinsic semiconductor n=p=n$_i$

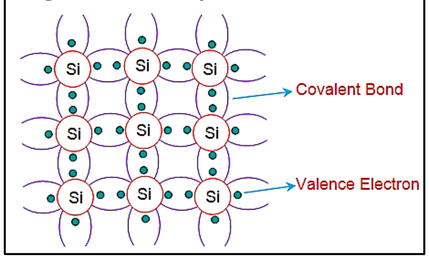
$$\sigma_i = qn_i(\mu_n + \mu_p) \qquad (16)$$

Conduction in semiconductors

3. Intrinsic and Extrinsic semiconductor:

The intrinsic (pure) semiconductor has charge mobility between insulators and conductors, that's why they called it SEMICONDUCTOR, such as Ge and Si which has 4 valence electrons in the outer orbital each.

Figure 1; 2D crystal lattice of Si

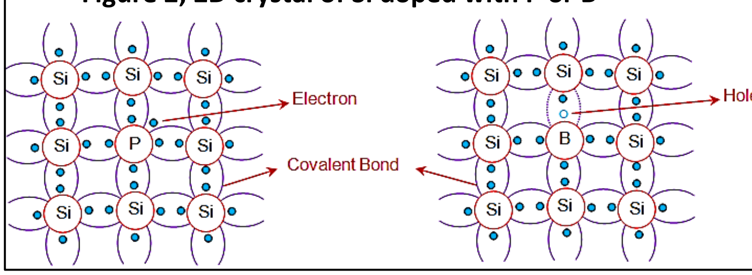


Semiconductor has lower conductivity than conductors, *because the density of charges is lower in semiconductor than in conductor*.

The Si and Ge atoms are arranged in 3D atomic structure, every two atoms have covalent band between them (see Fig.1 for 2D atomic structure); each atom has 4 neighboring atoms.

This covalent bond can be broken by applying external energy such as light or heat. Every free electron generated and leaves behind a hole; the electron-hole pair is then generated.

Figure 2; 2D crystal of Si doped with P or B



For the electron density in intrinsic semiconductor, (i) is used, so electron density in such semiconductor is (n_i) is equal to the hole density (P_i).

Adding impurities to the intrinsic semiconductor assists in increasing the density of the free electrons or holes in the semiconductor. The impurities used are even 3 or 5 covalent elements which have 3 valence electrons (such as B) or 5 valence electrons (such as P) in the outer orbit (see Fig.2).

4. n-type and p-type semiconductors:

When Si doped with elements with 5 electrons in the outer orbit (such as P), and because the Si has only 4 electrons in the outer orbit, therefore, a free electron will exist in the atom and the semiconductor is n-type. While with 3 electrons elements, a free hole will exhibit and the semiconductor is p-type (Si will be doped with very few impurities).

Conduction in semiconductors

The number of free electron (holes) in such case is equal to the number of impurities in the atom; adding few impurities will results in higher density of electrons.

In n-type semiconductor, *electrons are the majority (n_n) and holes (pn) are the minority charge carriers*; whereas, in **p-type semiconductor**, *holes are the majority (p_p) and electrons (n_p) are the minority charge carriers*. Where:

For n-type $$n_n p_n = n_i^2 \quad (16)$$

For p-type $$p_p n_p = n_i^2 \quad (17)$$

Because the density of free electrons is equal to the doped atoms, therefore:

$$\mathrm{n} = \mathrm{N_d} \quad (18)$$

$$\mathrm{p} = \mathrm{N}_a \quad (19)$$

Where N_d is the density of donors' impurities and N_a is the density of acceptor's impurities.

For n-type semiconductor, equ.12 becomes:

$$\sigma_e = qN_d\mu_e \quad (20)$$

For p-type semiconductor, equ.13 becomes:

$$\sigma_p = qN_a\mu_p \quad (21)$$

The conductivity of the semiconductor is based on N_d and N_a, where q is constant and μ_e and μ_p is fixed for each semiconductor.

5. Basic electronic components

Electronic components are the basic building blocks of an electronic circuit. They are very small with two or more terminals. Usually they classified into two types, passive and active components.

Conduction in semiconductors

When a group of electronic components is connected together in an electronic board such as printed circuit board (PCB), a useful electronic circuit is formed. Each electronic component in a circuit performs a particular task.

- ***Passive component:*** *is the electronic component, which consumes energy in the form of voltage from the source, but does not produce or supply energy*

Passive components cannot control the flow of electrons or electric current through a circuit, but they limit it. They cannot amplify or increase the power of an electrical signal.

Passive components temporarily **store the electrical energy** in the form of **static electric field or magnetic field**.

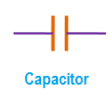
The different types of passive components include resistors, capacitors, and inductors.

Resistor*: is an electronic component that limits the electric current or the flow of electrons to a certain level. It consists of two terminals*.

Q, How much electric current does a resistor reduce or limits is depends on the resistance value of a resistor?

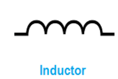
The high resistance value reduces large amount of electric current whereas the low resistance value reduces less.

Capacitor: *is the most widely used electronic components after the resistors. It temporarily stores the electrical energy in the form of static electric field.*



Capacitors consist of: two parallel electrical conductors separated by a non-conductive or insulating material called dielectric. Dielectric materials do not allow the electricity to flow through them.

Inductor*: is a passive two terminal electronic component that temporarily stores the electrical energy in the form of a magnetic field.*



Conduction in semiconductors

Inductors consist of: coil of copper wires or electrical conductive wires. When the electric current is passed through the coil, a magnetic field is produced and stored in the coil of copper wires.

- ***Active component:*** *is the electronic component, which consumes energy in the form of voltage or current and produces or supplies energy in the form of electric current or voltage is called active component*.

An active component not only controls the flow of electrons or electric current, but also amplifies or increases the power of electronic signal. It depends on the external source of energy or voltage to perform a specific operation.

The different types of active components include diodes, transistors, and integrated circuits (IC).

Diode: *is a semiconductor component that allows most of the electric current or flows of electrons in one direction (forward direction) while blocks most of the electric current in opposite direction (reverse direction).*

Transistor: *is a semiconductor component that amplifies or increases the electronic signals. They are made from semiconductor materials such as silicon and germanium.*

Integrated circuit: *is a small semiconductor chip on which millions of electronic components such as capacitors, resistors, and transistors are fabricated. It can function as a microprocessor, amplifier, and counter.*

The cost of Integrated circuit is low compared to the discrete components *because in integrated circuit all the components are fabricated on a single chip.*

Conduction in semiconductors

Home work:

Example.1; (a) Find the resistivity of the intrinsic germanium crystal at 3000K. (b) What will be the resistivity of this germanium crystal if the donor impurity of 1 atom per10^8 germanium atoms is introduced?
Where n_i = 2.5 x10^{19} atoms/m^3, μ_n = 0.38 m^2/Volt-sec, μ_p = 0.18 m^2/Volt-sec, Atomic conc. of Ge = 4.4x10^{28} atoms/m^3.
Solution:
(a)

$$\sigma_i = qn_i(\mu_n + \mu_p)$$

$$=1.6\text{x}10^{-19}\text{x}2.5\text{ x}10^{19}\ (0.38+0.18) = 2.24\Omega/\text{m}$$

The resistivity of the intrinsic germanium is given by:

$$\rho = \frac{1}{\sigma} = \frac{1}{2.24} = 0.45\Omega/\text{m}$$

(b)

$$\text{N}_d = \frac{4.4 \times 10^{28}}{10^8} = 4.4 \times 10^{20}$$

$$\sigma_n = qN_d\mu_n$$

$$=1.6 \times 10^{-19} \times 4.4 \times 10^{20} \times 0.38 = 26.752\Omega/\text{m}$$

$$\rho_n = \frac{1}{\sigma_n} = \frac{1}{26.752} = 0.037\Omega/\text{m}$$

Example.2; (a) Pure germanium crystal has the resistivity of 0.45 Ω-m. How much donor impurities should be added to Ge crystal so that its resistivity decreases to 10% of the original value? (b) Find the values of n and p in this n-type Ge crystal. Where μ_n= 0.38 m^2/Volt-sec, n_i = 2.5 x10^{19} atoms/m^3

Example.3; n-type Ge crystal is 0.02m long and has a cross section of 0.0002m x 0.0002m. A current of 10mA flows through the crystal, when a 2Volt battery is applied across it. Find (a) doping concentration N_d where (μ_n = 0.38 m^2/volt-sec)

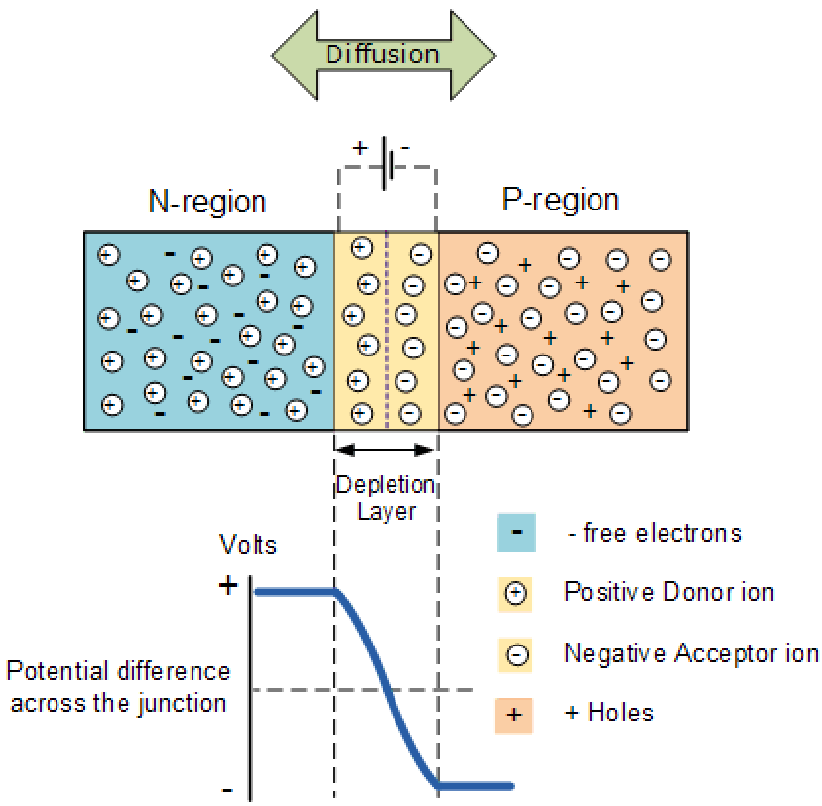
PN junction

PN junction

When the N-type and P-type semiconductors are joined together, a very large density gradient exists between both sides of the PN junction. Some of the free electrons in n-type begin to migrate across the junction to fill up the holes in the P-type producing negative ions. This charge transfer of electrons and holes across the PN junction is known as ***diffusion***.

This process continues until a state of equilibrium occurs producing a "potential barrier" around the junction *as the donor atoms repel the holes and the acceptor atoms repel the electrons, therefore, no free charge carriers can rest in a position where there is a potential barrier*.

Space charge region: *because there is a density gradient across the junction, holes will initially diffuse from p-type region to n-type region and the electrons diffuse vice-versa creating a space charge region (depletion region) as in the following figure.*



PN junction

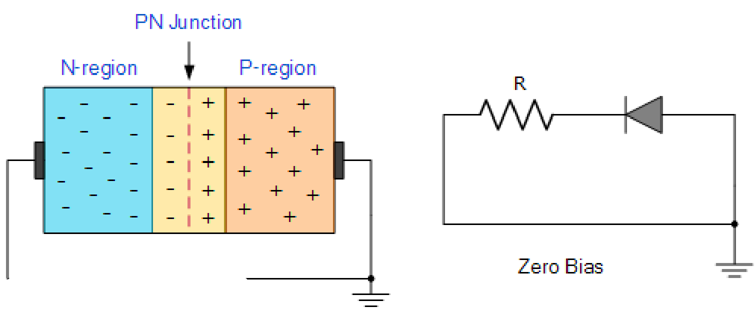
PN junction under zero bias:

In n-type $D_n \geq D_p$

In p-type $D_p \geq D_n$

The density of electrons in the n-type (D_n)

The density of holes in the p-type (D_p)



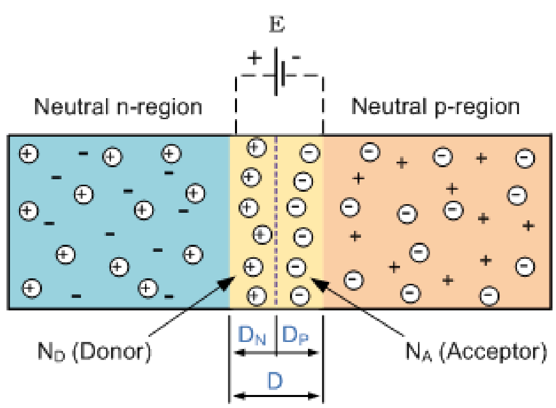
Due to the density difference, the diffusion of both charge carriers in both directions is demonstrated. This diffusion is exhibited gradually due to the following diffusion equation:

$$I_{ed} = qD_n \frac{dn}{dx} \qquad (22)$$

$$I_{pd} = qD_p \frac{dp}{dx} \qquad (23)$$

I_{ed} is the diffusion current of electrons

I_{pd} is the diffusion current of holes



PN junction

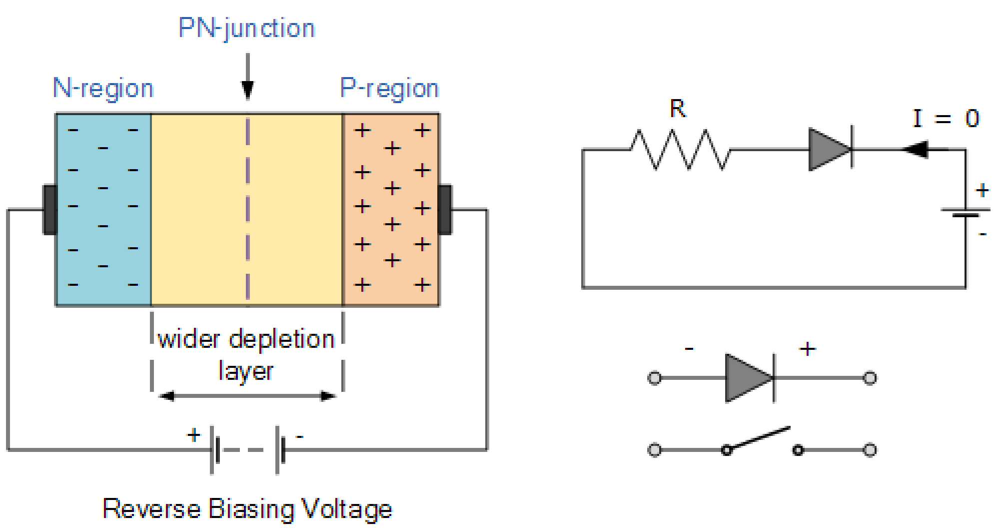
PN junction under bias:

Reverse Biased PN Junction Diode

When a diode is connected in a **Reverse Bias**, *a positive terminal is applied to the N-type and a negative terminal is applied to the P-type.*

The positive terminal attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.

This condition represents a high resistance (or high potential barrier) to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small leakage current does flow through the junction called (***reverse saturation current***).

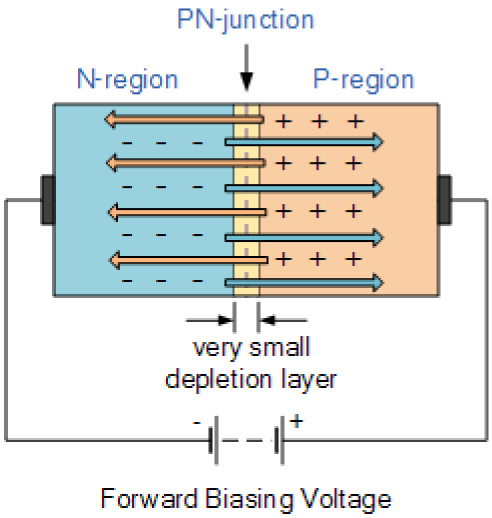


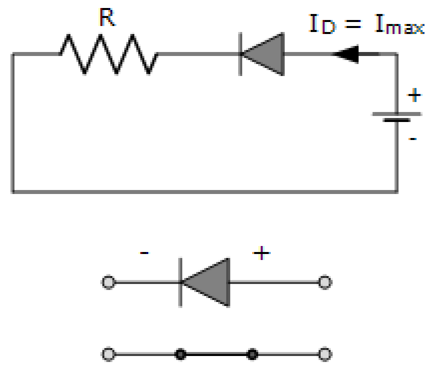
Forward Biased PN Junction Diode

When a diode is connected in a **Forward Bias**, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. The external voltage becomes greater than the potential barrier and current flows.

This is because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage.

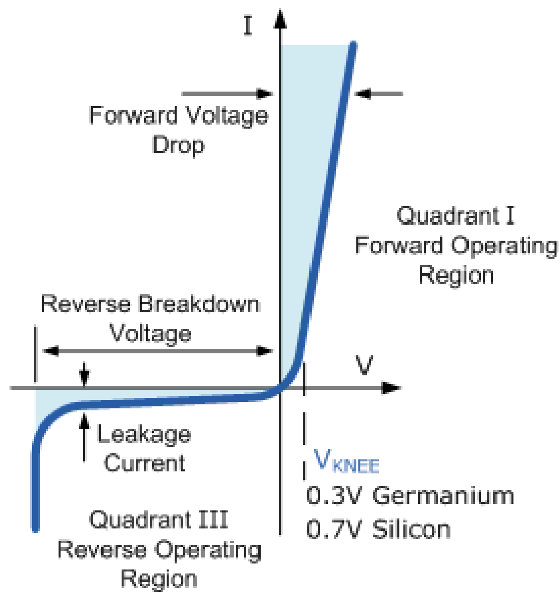
PN junction





2.1. The diode I-V curve:

When a variable voltage is applied to the diode, the current passing through the diode will vary as shown in the figure.



The current increase slightly at the beginning, then it increases rapidly when the knee voltage exceeds (V_K) which almost equal to the potential barrier.

Under reverse bias, there will be a small current consisting of minority carriers current and surface leakage current. When the reverse bias exceeds the breakdown voltage (V_B), the current will increase rapidly causing damage in the diode.

In conclusion, the diode can rectify the alternative current, i.e., the diode passes the current in one direction, so it is called **rectifier diode**.

I-V characteristics of the junction diode may also be expressed in the following equation:

$$I = I_s\left[e^{qV/nKT} - 1\right] \qquad (24)$$

Where I_s is the reverse saturation, K is the Boltzmann constant ($1.38x10^{-23}$ J/K), q is the electron charge ($1.6x10^{-19}$ Coulomb),T is the absolute temperature in kelvins = 273 + the temperature in °C, n is ideality factor, it value depends on the material of the diode and the quality of the junction.

The term (KT / q) has the dimension of voltage known as ***thermal energy*** is denoted by V_T. The value of V_T at room temperature (T = 300 K) is 0.026 Volt = 26 mV. Then:

$$\mathrm{I} = \mathrm{I_s}\left[\mathrm{e}^{\mathrm{V}/\mathrm{nV_T}} - 1\right] \qquad (25)$$

When the diode is forward biased and V > V_T, the value of (V / V_T) >> 1, the equation (25) may be approximated as:

$$\mathrm{I} = \mathrm{I_s}\left[\mathrm{e}^{\mathrm{V}/\mathrm{nV_T}}\right] \qquad (26)$$

Example.1

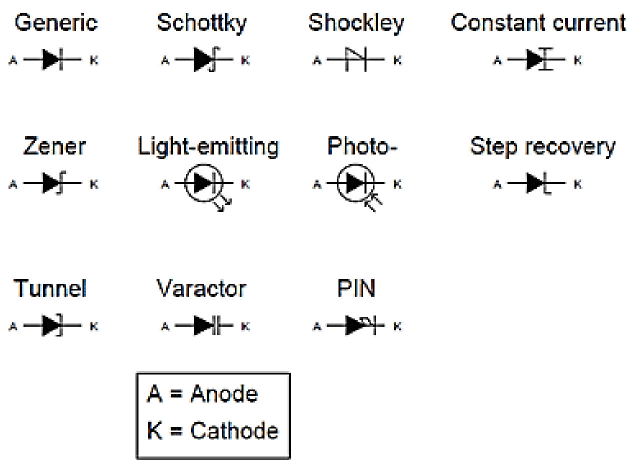
At a temperature of 27°C, determine the thermal voltage V_T.

T= 273 + 27 = 300 K

$$V_T = \frac{kT_K}{q} = \frac{(1.38 * 10^{-23})(300)}{1.6 * 10^{-19}} = 26\,mV$$

2.2. Special diodes:

There are several special diodes, this section includes: light emitted diode (LED), photodiode, Schottky diode and Zener diode.



Light emitting diode (LED): Under forward bias, the electrons in the conduction band cross the junction and fall in a hole, when this occurs, energy is emitted. This energy is released as a heat in a rectifier diode, but in LED such energy is radiated as light.

The advantages of LED over the ordinary lamps are the long life time, small voltage and high speed switching (few ns).

Photodiode: *When light falls on the junction of a reverse bias diode, electron-hole pair will be generated inside the depletion region and move under the influence of the reverse voltage causing a passage of current. This current increases with increasing the light intensity as the production of the carrier is increased.*

Schottky diode: This diode consists of a metal like Au, Al, Ag or Pt on one side and doped semiconductor on the other side. This kind of diode is unipolar device because the electrons are the majority carriers at both sides of the junction.

PN junction

Schottky diode is a metal-semiconductor junction diode that has less forward voltage drop than the P-N junction diode and can be used in high-speed switching applications.

The junction between the metal and the semiconductor is known as a metal-semiconductor junction or M-S junction; this creates a barrier or depletion layer known as a **Schottky barrier***, the electrons have to overcome this potential energy barrier to flow across the diode.*

Schottky diode is very useful in high-speed switching power circuits and computers, why?

1- *Can switch on and off much faster than the p-n junction diode.*
2- *Produces less unwanted noise than p-n junction diode.*

Zener diode: *If reverse biased voltage applied to the p-n junction diode is highly increased, a sudden rise in current occurs. At this point, a small increase in voltage will rapidly increases the electric current. This sudden rise in electric current causes a junction breakdown called* ***zener or avalanche breakdown***.

Zener diode *is a special type of device designed to operate in the zener breakdown region. It acts like normal p-n junction diode under forward biased condition; it allows large amount of electric current and blocks only a small amount of electric current.* The breakdown voltage of a zener diode is carefully set by controlling the doping level during manufacture.

Zener diodes are the basic building blocks of electronic circuits. They are widely used in all kinds of electronic equipment. Zener diodes are mainly used to protect electronic circuits from over voltage.

Home Work

Example.2: The saturation current density of a PN junction Ge diode is 220mA/m^2 at 300^{o}K. Find the voltage that would have to be applied to cause a forward current density of (i) 103A/m^2 and (ii) 104A/m^2 to flow.

$$I = I_s\left[e^{V/nV_T}\right]$$

$$I = I_s\left[e^{V/nV_T}\right] = I_s\left[e^{11600\times V/300}\right]$$

n = 1 for Ge , VT = (T/11600) and T = 300

$$\frac{I}{I_s} = e^{38.67\times V}$$

(i) In case of I=103A/m^2 and I_s= 220mA/m^2=0.22A/m^2

$$\frac{103}{0.22} = e^{38.67\times V}$$

V=0.217Volt

(ii) In case of I=103A/m^2 and I_s= 220mA/m^2=0.22A/m^2

$$\frac{104}{0.22} = e^{38.67\times V}$$

V=0.277Volt

Example.3: A silicon diode operates at a forward voltage of 0.4 Volt. Calculate the factor by which the current is multiplied when the temperature is increased from 27^{o}C to 125^{o}C.

Diode application

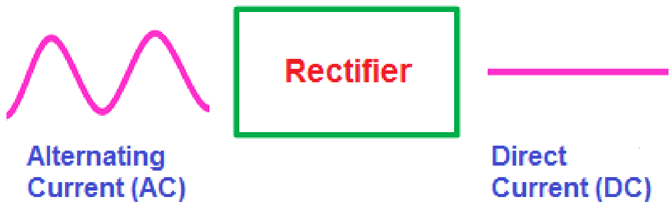
Introduction:

In a large number of electronic circuits, DC voltage is required for operation. The AC voltage or AC current can be easily converted into DC voltage or DC current by using a device called ***PN junction diode***.

One of the most important applications of a PN junction diode is *the rectification of Alternating Current (AC) into Direct Current (DC)*.

A PN junction diode *allows electric current in only forward bias condition and blocks electric current in reverse bias condition*. This unique property of the diode allows it to acts like a **rectifier**.

A rectifier *is an electrical device that converts an Alternating Current (AC) into a Direct Current (DC) by using one or more PN junction diodes*.



How does the rectifier work?

The **DC voltage source**, it works based on the polarity of the connected weather it is positive or negative, the DC current is represented by a straight horizontal line as shown in Figure 1.

While the **AC voltage source** (voltage or current), it is often represented by a sinusoidal (sin) waveform. In the sinusoidal waveform, the upper half cycle represents the positive half cycle and the lower half cycle represents the negative half cycle as shown in Figure 1.

Diode application

- ***The positive half cycle of the AC voltage is analogous to the forward bias DC voltage & the negative half cycle of the AC voltage is analogous to the reverse bias DC voltage.***

When AC (voltage or current) is applied across the PN junction diode:

During the positive half cycle: Diode is forward biased and allows electric current through it.

During the negative half cycle: Diode is reversed biased and does not allow electric current through it.

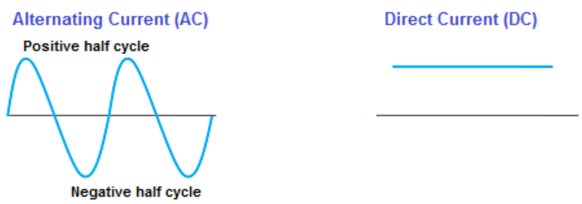


Figure 1

- In fact, the DC current produced by a basic rectifier (half wave rectifier) **is not a pure DC current**; it is a ***pulsating*** DC current with value changes over a short period.
- The pulsating DC current always flows in one direction like the pure DC current. The electric current produced by batteries, power supplies, and solar panels is a pure DC current.

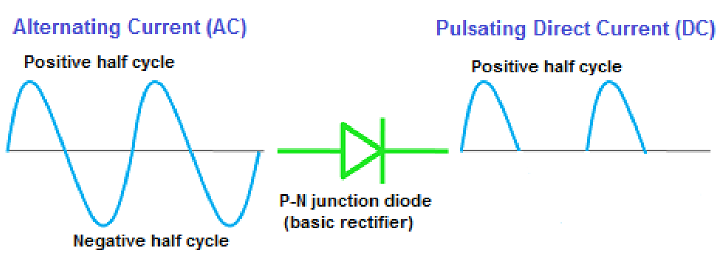


Figure 2

Diode application

Types of rectifiers

Rectifiers are mainly converted the Alternating Current (AC) into Direct Current (DC). They are classified to Half-wave rectifier (HWR), Full-wave rectifier (FWR) and Bridge rectifier.

Half wave rectifier (HWR): *is a type of rectifier which converts half of the AC input signal (positive half cycle) into pulsating DC output signal and the remaining half signal (negative half cycle) is blocked or lost. In half wave rectifier circuit, we use only a single diode.*

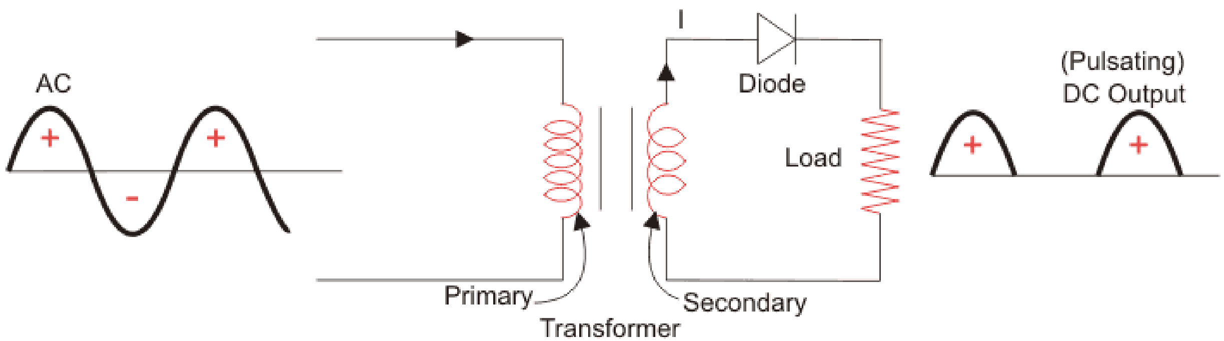


Figure - 3

Working Principle of HWR:

Applying a high AC voltage to the primary side of the transformer and we will get a low voltage at the secondary side which will be applied to the diode.

During the positive half cycle: *the diode is forward biased and the current flows through the diode.*

During the negative half cycle: *the diode is reversed biased and the flow of current is blocked.*

Characteristics of HWR:

Ripple Factor (γ): The outputs of HWR consist of both AC and DC components. The AC components are undesirable to us and will cause pulsations in the output. *This unwanted AC component is called* ***Ripple****.*

The smoothness of the output DC signal is measured by using a factor known as ***ripple factor****.*

The output DC signal with very fewer ripples is considered as the smooth DC signal while the output DC signal with high ripples is considered as the high pulsating DC signal.

Ripple factor is mathematically defined as *the ratio of ripple voltage to the pure DC voltage and given by:*

$$\gamma = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

Note*: To construct a good rectifier, minimum ripple factor is better, can use capacitors or inductors to reduce the ripples in the circuit.*

Rectifier Efficiency (η): it determines how efficiently the rectifier converts AC into DC. High **η** indicates a most reliable rectifier while the low **η** indicates a poor rectifier. **η** is defined as the ratio of the DC output power to the AC input power.

$$\eta = \frac{DC_{\ out\ power}}{AC_{\ input\ power}} = \frac{P_{DC}}{P_{AC}}$$

Peak Inverse Voltage (PIV): *is the maximum voltage that the diode should withstand during reverse bias condition. If a voltage is applied more than the PIV, the diode will be destroyed*.

Diode application

Applications of HWR: HWR is not much used compared to FWR, but for some special purpose it can be used:

- For rectification purpose
- For signal demodulation purpose
- For signal peak detection

Advantages of HWR: It is cheaper to setup and construct, due to the less number of components used.

Disadvantage of HWR:

- Wasted half-cycle through it and leads to power loss.
- Produces low output voltage.
- The output current is not purely DC and there are a lot of ripples in it.

Full wave rectifier (FWR): *is a type of rectifier which converts the full AC input signal (positive half cycle and negative half cycle) to pulsating DC output signal. Unlike HWR, the input signal is not wasted in full wave rectifier. The efficiency of FWR is high as compared to HWR.*

In order to overcome the disadvantages of HWR, scientists developed a new type of rectifier known as ***center tapped full wave rectifier (CT-FWR)*** *as shown in Figure 4.*

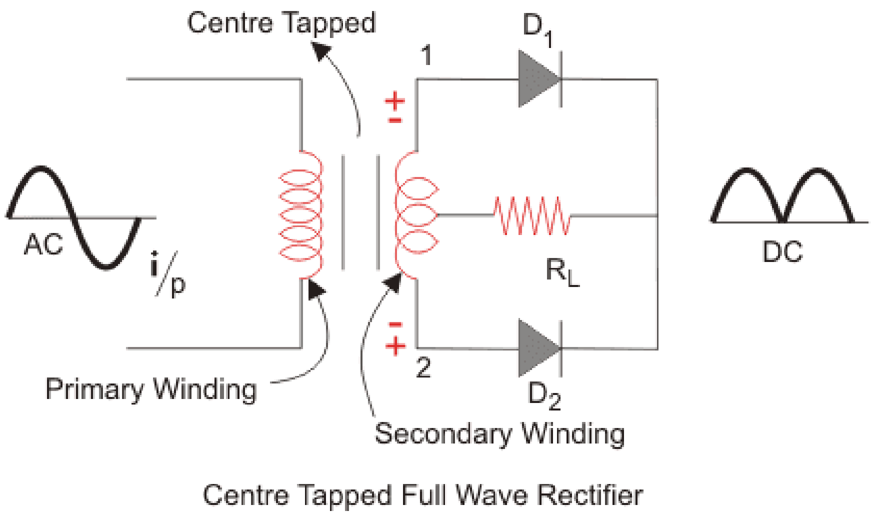


Figure 4

The main advantage of CT-FWR:

- *It allows electric current during both positive and negative half cycles of the input AC signal. As a result, the DC output of CT-FWR is double of that of HWR.*
- *DC output contains very fewer ripples. So the output is smoother than HWR.*

However, CT-FWR **has one drawback** that *is the center-tapped transformer used in it is very expensive and occupies large space.* **To cut this extra cost**, *scientists developed a new type of rectifier known as a bridge rectifier.*

The rectifier efficiency of a bridge rectifier is almost equal to CT-FWR. *The only advantage of bridge rectifier over center tapped full wave rectifier is the reduction in cost. In bridge rectifier, instead of using the center-tapped transformer, four diodes are used.*

Diode application

Bridge rectifier: *is a type of full wave rectifier which uses four or more diodes in a bridge circuit configuration to efficiently convert the Alternating Current (AC) into Direct Current (DC)* Figure 5.

Bridge rectifier: is made up of four diodes namely D1, D2, D3, D4 and load resistor RL. The four diodes are connected in a closed loop (Bridge) configuration to efficiently convert AC into DC.

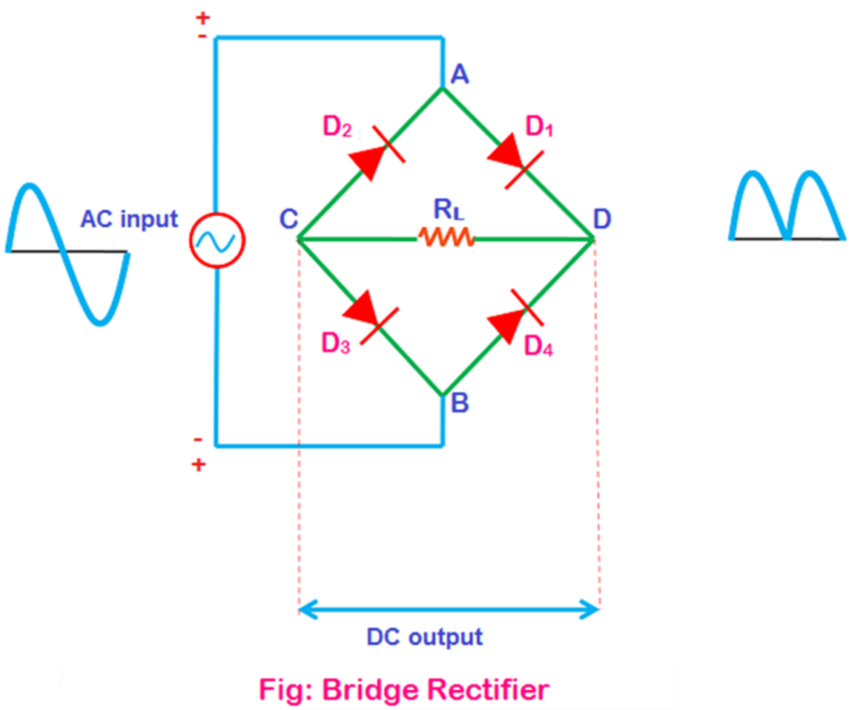


Figure 5

How does it work?

- Input AC signal across terminals A and B.
- The output DC signal is across the load resistor (R_L) which is connected between the terminals C and D.
- The four diodes D_1, D_2, $D_3$and D_4 are arranged in series.

Diode application

During the positive half cycle:

Terminal A becomes positive while the terminal B becomes negative.

D_1 and D_3 forward biased and D_2 and D_4 reverse biased.

The current flow direction during the positive half cycle is shown in the figure A.

During the negative half cycle:

Terminal B becomes positive while the terminal A becomes negative.

D_2 and D_4 forward biased and D_1 and D_3 reverse biased.

The current flow direction during negative half cycle is shown in the figure B.

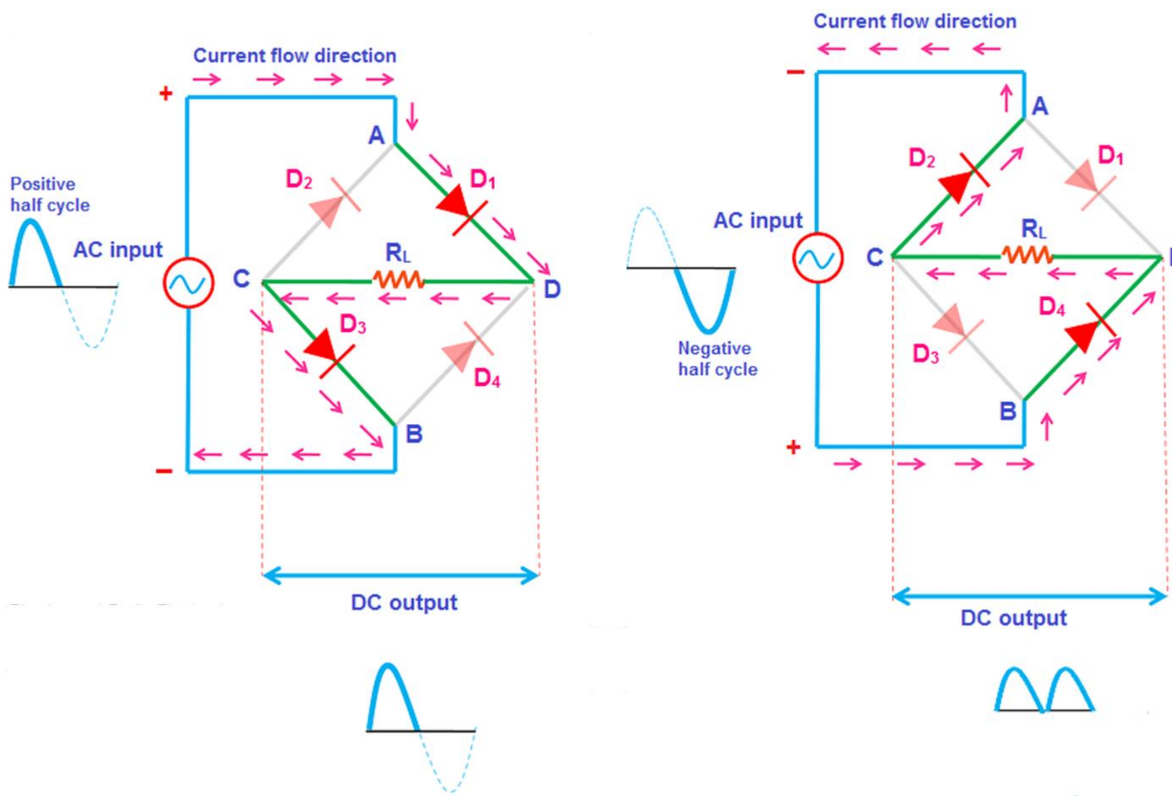


Fig A: Bridge rectifier during positive half cycle

Fig B: Bridge rectifier during negative half cycle

Figure 6

Because the direction of current flow across load resistor R_L is same during the positive half cycle and negative half cycle. *Therefore, the polarity of the output DC signal is same for both positive and negative half cycles.*

Diode application

The output DC signal polarity may be either completely positive or negative. In our case, it is completely positive. If the direction of diodes is reversed then we get a complete negative DC voltage.

Thus, a bridge rectifier allows electric current during both positive and negative half cycles of the input AC signal. The output waveforms of the bridge rectifier is shown in the below figure.

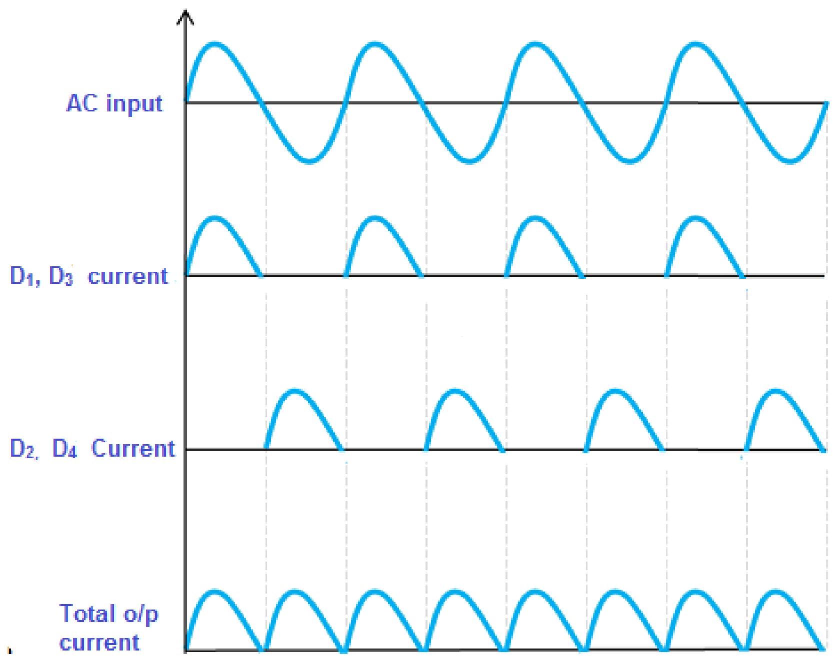


Figure 7

Clipper circuits

Electronic devices are very sensitive to voltage. If a large amplitude voltage is applied, it may permanently destroy the device, so, *clipper circuits* is used to protect the electronic devices.

*A **clipper** is a device that uses diodes to clip a portion of the input signal without distorting the remaining part of the waveform*.

The clipper circuit **does not** contain energy storage elements such as capacitor but contains both linear and no-linear elements. The linear elements used in the clippers include resistors and the non-linear elements used in the clippers include diodes or transistors.

One of the basic clipping devices is *the half wave rectifier*. A half wave rectifier removes either the positive half cycle or negative half cycle of the input AC signal and allows the remaining half cycle of the input AC signal.

Clipper circuits are extensively used in digital computers, radars, television receivers, radio receivers and other electronic systems for removing unwanted portion of the input AC signal.

Types of clippers

1- Series clippers, where the diode is connected in series with the output load resistance.
2- Shunt (Parallel) clippers, where the diode is connected in parallel with the output load resistance
3- Dual (combination) clippers, which combine both clippers.

Series positive clipper without bias

Fig.1 shows a series positive clipper the arrowhead of the diode is pointing towards the input, where the vertical line in the diode symbol represents the cathode (n-side) and the opposite end represents the anode (p-side). Then diode D is connected in series with the output load resistance R_L

During the positive half cycle:

The input voltage (Vi) terminal A is positive (connected to n-side) and terminal B is negative (connected to p-side) of the diode

Then the diode is said to be reverse biased (open circuit)

Therefore, no current flows through the diode (I=0)

Due to Ohms' law (V=IR), therefore, (Vo=0).

So the positive half cycle is blocked or removed at the output.

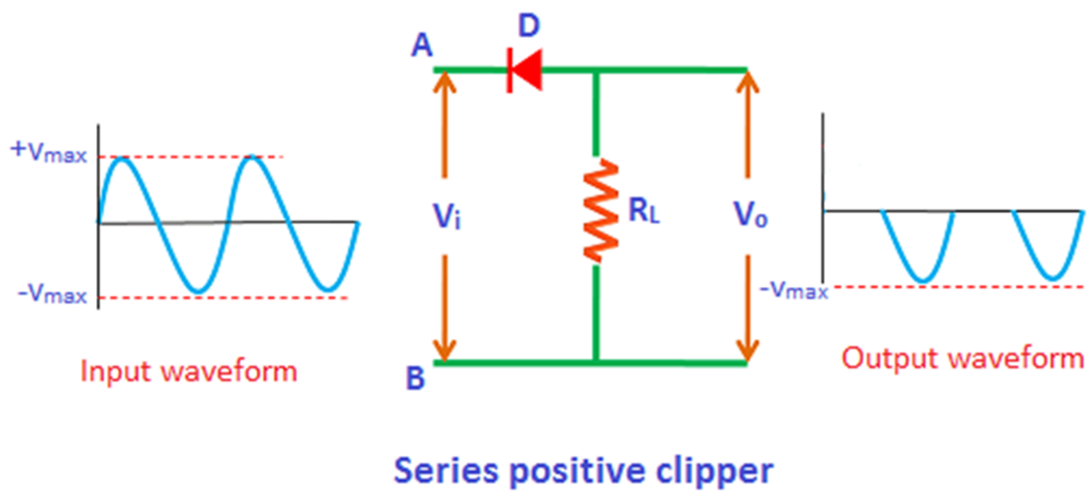


Figure 1

During the negative half cycle:

Terminal A is negative (connected to n-side) and terminal B is positive (connected to p-side).

Then the diode is said to be forward biased, so, the current flows through the diode (short circuit)

Therefore, the negative half cycle is allowed at the output.

Series Negative clipper with bias

Sometimes it is desired to shift and remove a portion of input waveform. In such cases, the biased clippers are used.

The construction of the series clipper with bias is almost similar to the series clipper. The only difference is an extra element called **battery** is used in series positive clipper with bias.

Series Negative clipper with positive bias

The positive terminal of the battery is connected to p-side of the diode and the negative terminal of the battery is connected to n-side of the diode. Therefore, the diode is forward biased by the battery voltage V_B. however, the voltage was supplied from the AC voltage source v_i.

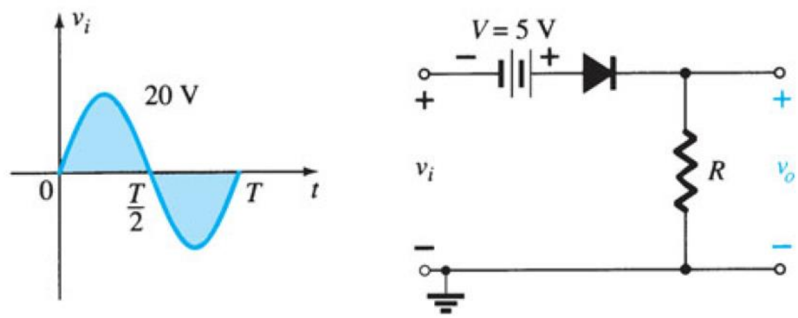


Figure 2

Initially, $v_i = 0$, The diode is forward biased by the battery (V_B) and allows electric current through it and the signal appears at the output at all its positive cycle.

The clipping (removal of a signal) takes place during the negative half cycle only when $V_B + v_i < 0$. Figure 3 shows the circuit representation in while the diode in forward bias condition and the output resultant signal form clipper.

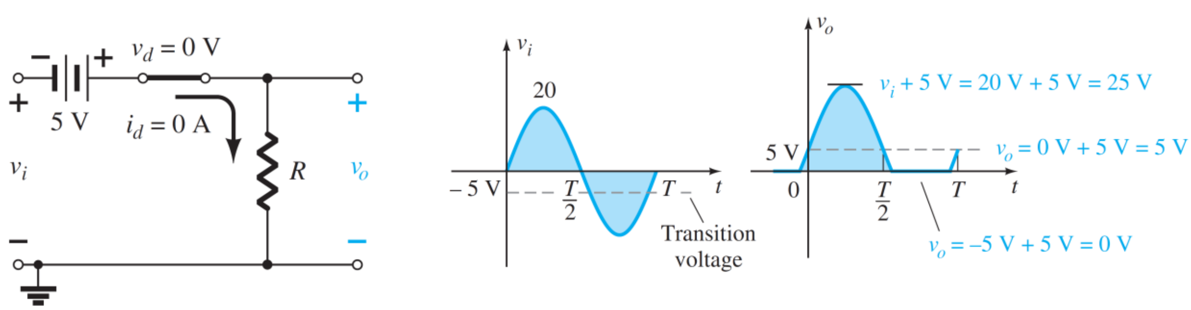


Figure 3

Series* Negative *clipper with negative bias

In this type of clipper, the battery is connected in reverse polarity to the diode (as shown in Fig. 4),

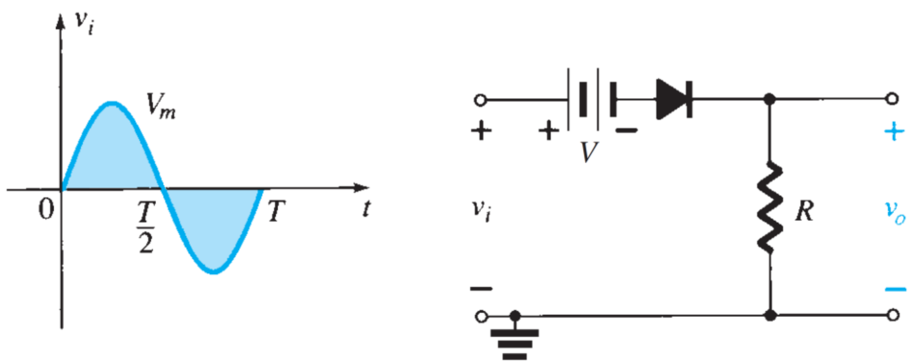


Figure 4

During the positive half cycle of the input signal, the diode is reverse biased by battery voltage (V_B).

Initially, V_B dominates v_i. So the diode remains under reverse bias until $V_B < v_i$, Then, the diode is forward biased by v_i and the signal appears at the output (v_0).

During the negative half cycle, the diode is reverse biased by both V_i and V_B. So no signal appears at the output during the negative half cycle. Therefore, the complete negative half cycle is removed.

The circuit configuration of the clipper in Figure 4 and the output signal is given in Figure 5.

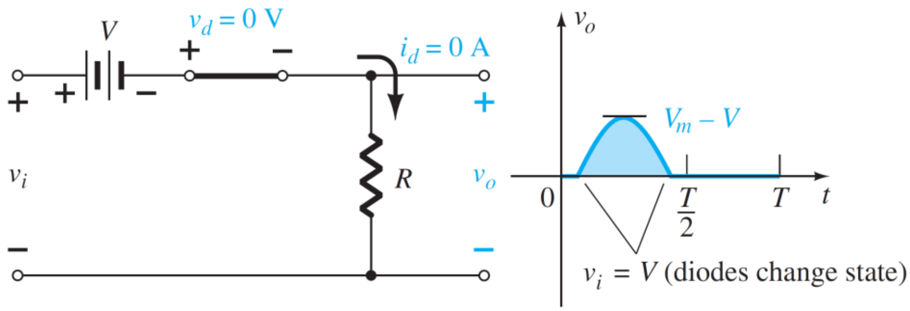


Figure 5

Notes:

1. Take careful note of where the output voltage is defined, which will help to draw and obtain the output signal.
2. In the case of series biased add the DC voltage to the input signal and determined the output as no-biased clipper.

Example 1// Find the output voltage for the network examined in Figure 2 if the applied signal is the square wave of Figure 6.

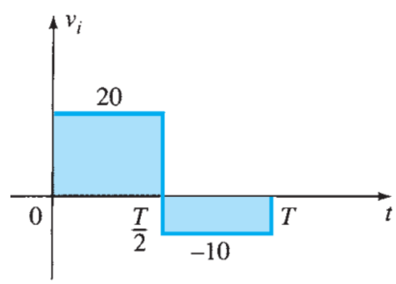


Figure 6

Sol/ For v_i = 20 V (in the positive cycle) the network of Fig. 6 results. The diode is in the short-circuit state, and v_o = 20 V + 5 V = 25 V. For negative part of the signal when v_i = - 10 V, the diode will be in reverse biased off states. The circuit configuration and the output as shown in Figure 7.

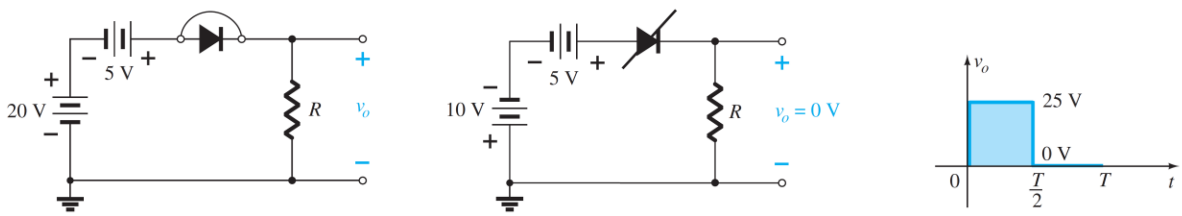


Figure 7

Example 2 // Determine the output waveform for the sinusoidal input in Figure 8. (assume V_m = 20 V, Battery voltage V_B = 5 and the diode is Si)

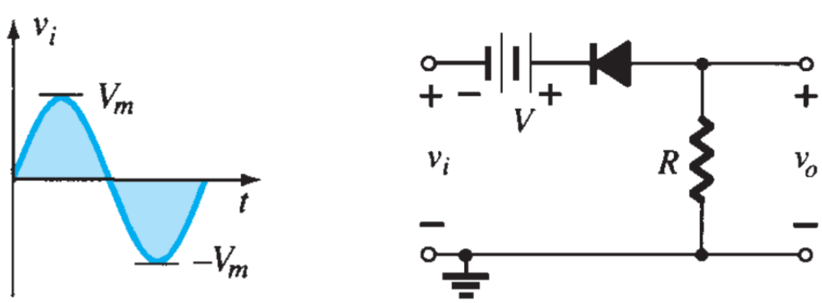


Figure 8

Step 1: find the type of the clipper (in this example the circuit is positive clipper)

Step 2: the bias whether is positive or negative (its positive in this case)

Step 3: add the bias voltage to the input waveform and remove the positive part of the signal. The output signal is shown in Figure 9.

The minimum output voltage = - V_m + V_B = - 20 + 5 + 0.7 = - 14.3 V

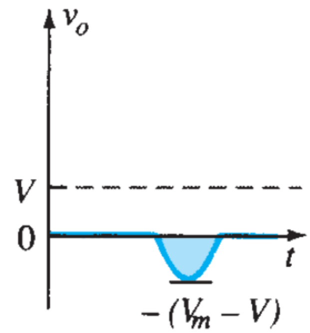


Figure 9

1.1.1. Shunt (Parallel) positive clipper

In shunt (parallel) clipper, the diode is connected in parallel with the output load resistance. The operating principles of the shunt clipper are nearly opposite to the series clipper. Figure 1 shows parallel positive clipper.

The series clipper passes the input signal to the output load when the diode is forward biased and blocks the input signal when the diode is reverse biased. The shunt clipper on the other hand passes the input signal to the output load when the diode is reverse biased and blocks the input signal when the diode is forward biased.

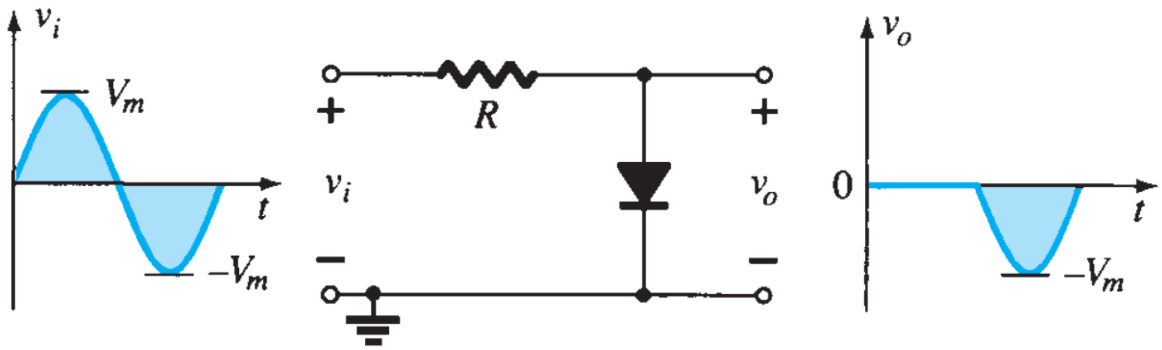


Figure 1

In shunt positive clipper, during the positive half cycle the diode is forward biased and hence no output is generated. On the other hand, during the negative half cycle the diode is reverse biased and hence the entire negative half cycle appears at the output.

6.1.2. Shunt positive clipper with bias

6.1.2.1. Shunt positive clipper with positive bias

During the positive half cycle, the diode is forward biased by the input supply voltage V_i and reverse biased by the battery voltage V_B. However, initially, the input supply voltage V_i is less than the battery voltage V_B. Hence, the battery voltage V_B makes the diode to be reversed biased. Therefore, the signal appears at the output. However, when the input supply voltage V_i becomes greater than the battery voltage V_B, the diode D is forward biased by the input supply voltage V_i. As a result, no signal appears at the output.

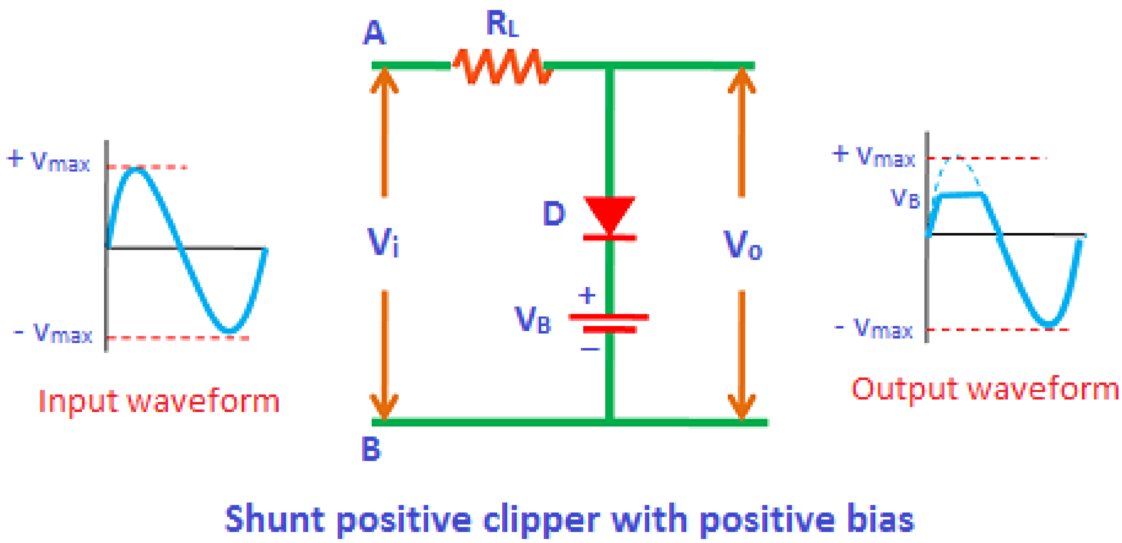


Figure 2

During the negative half cycle, the diode is reverse biased by both input supply voltage and battery voltage. So it doesn't matter whether the input supply voltage is greater or lesser than the battery voltage, the diode always remains reverse biased. As a result, a complete negative half cycle appears at the output.

6.1.2.2. Shunt positive clipper with negative bias

During the positive half cycle, the diode is forward biased by both input supply voltage V_i and battery voltage V_B. Therefore, no signal appears at the output during the positive half cycle.

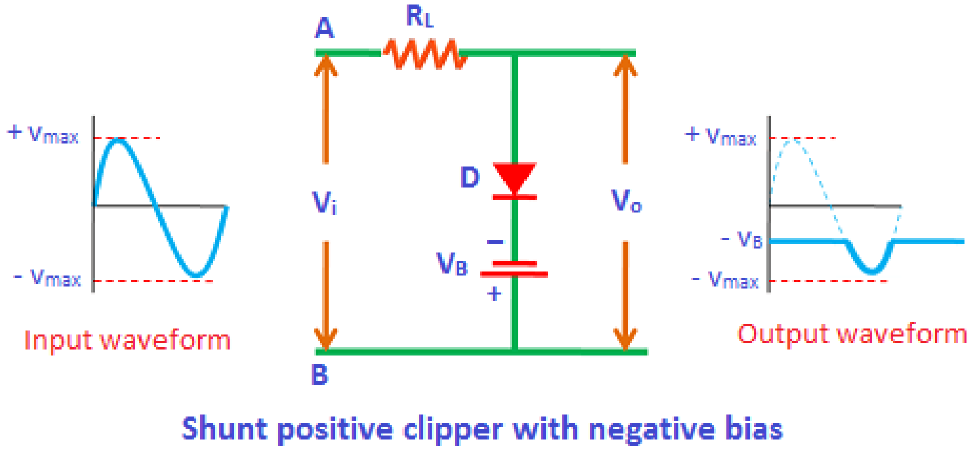


Figure 3

During the negative half cycle, the diode is reverse biased by the input supply voltage and forward biased by the battery voltage. However, initially, the input supply voltage V_i is less than the battery voltage V_B. So the battery voltage makes the diode to be forward biased. As a result, no signal appears at the output. However, when the input supply voltage V_i becomes greater than the battery voltage V_B, the diode is reverse biased by the input supply voltage V_i. As a result, the signal appears at the output.

6.2. Dual (combination) clipper

Sometimes it is desired to remove a small portion of both positive and negative half cycles. In such cases, the dual clippers are used.

The dual clippers are made by combining the biased shunt positive clipper and biased shunt negative clipper.

Let us consider a dual clipper circuit in which a sinusoidal ac voltage is applied to the input terminals of the circuit.

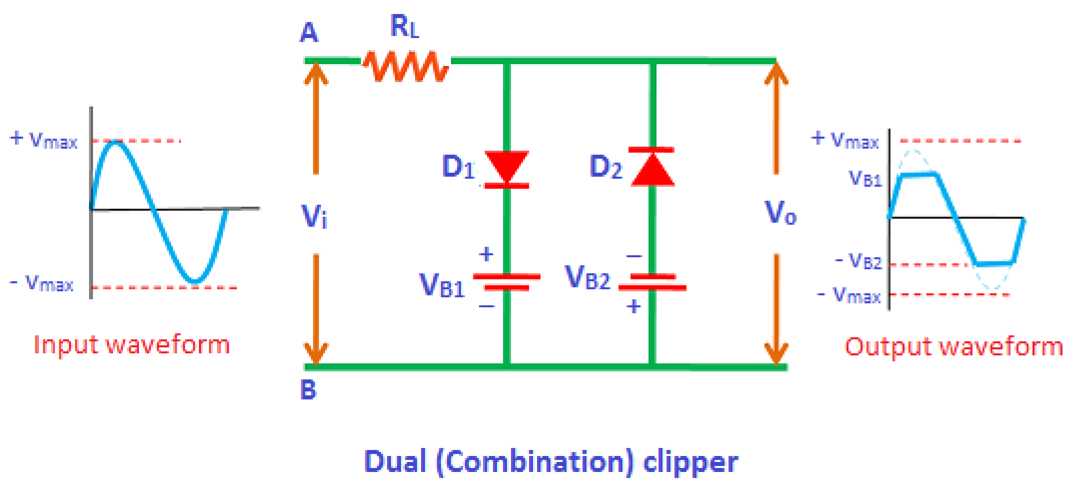


Figure 4

During the positive half cycle, the diode D_1 is forward biased by the input supply voltage $V_i$and reverse biased by the battery voltage V_{B1}. On the other hand, the diode D_2 is reverse biased by both input supply voltage V_i and battery voltage $V_{B2.}$

Initially, the input supply voltage is less than the battery voltage. So the diode D_1 is reverse biased by the battery voltage V_{B1}. Similarly, the diode D_2 is reverse biased by the battery voltage V_{B2}. As a result, the signal appears at the output. However, when the input supply voltage V_i becomes greater than the battery voltage V_{B1}, the diode D_1 is forward biased by the input supply voltage. As a result, no signal appears at the output.

During the negative half cycle, the diode D_1 is reverse biased by both input supply voltage V_i and battery voltage V_{B1}. On the other hand, the diode D_2 is forward biased by the input supply voltage V_i and reverse biased by the battery voltage V_{B2}.

Initially, the battery voltage is greater than the input supply voltage. Therefore, the diode $D_1$and diode D_2 are reverse biased by the battery voltage. As a result, the signal appears at the output.

When the input supply voltage becomes greater than the battery voltage V_{B2}, the diode D_2 is forward biased. As a result, no signal appears at the output.

6.3. Applications of clippers

- Clippers are commonly used in power supplies.
- Used in TV transmitters and Receivers
- They are employed for different wave generation such as square, rectangular, or trapezoidal waves.
- Series clippers are used as noise limiters in FM transmitters.

Notes:

1. Take careful note of where the output voltage is defined, which will help to draw and obtain the output signal.
2. For parallel clipper circuits, in the negative bias case the clipping happened after $V_B < v_i$.
3. In the case of positive bias case $v_0 = V_B$ and v_i will appear at the output only $V_B < v_i$.

Ex 1// Determine v_0 for the network of Figure 4. The used diode is silicon with $V_K = 0.7$ V.

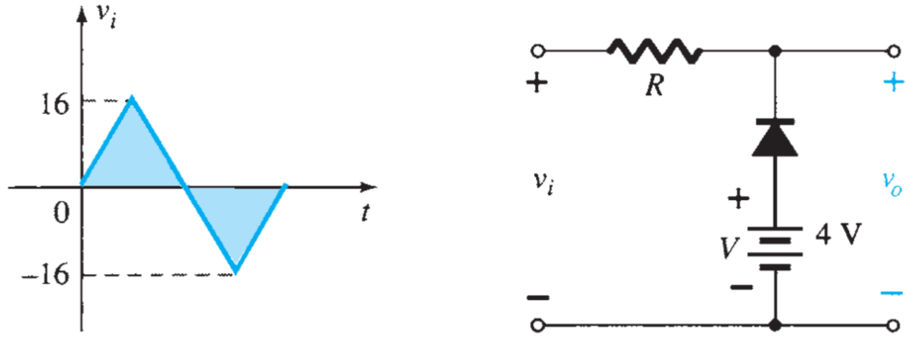


Figure 4

Sol// Step 1: In this example the output is defined across the series combination of the 4 V battery and the diode, not across the resistor R.

Step 2: Define the clipper, in the example the clipper is negative which lead to remove the negative part of the signal.

Step 3: Find the effect of the bias, to understand the effect of the bias, redraw the circuit while the diode in short circuit as shown in Figure 5.

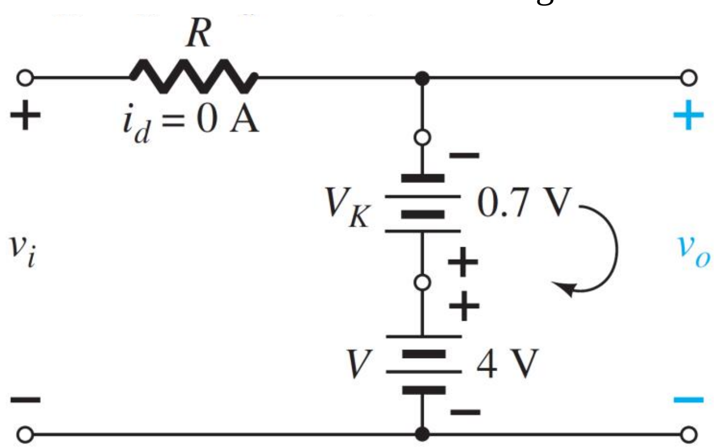


Figure 5

In the positive part of the input wave form the diode will be forward bias till

$V - V_K < v_i$

For the negative part of the part of the signal the diode will be forward biased and the output voltage can be calculated by applying KVL

$v_0 - V + V_K = 0$, $v_0 = 4 - 0.7 = 3.3$ V

The output waveform will be as shown in Figure 6.

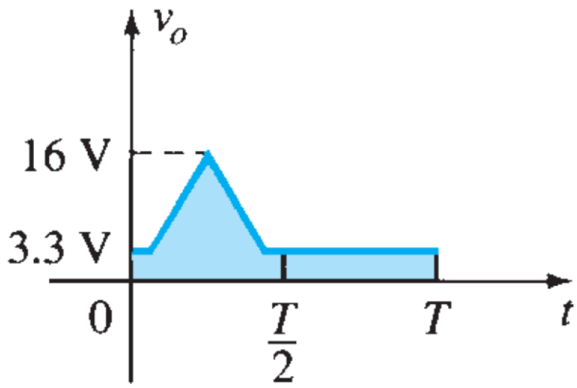


Figure 6

Ex 2 // Determine v_o for the network of Figure 7 for the input shown.

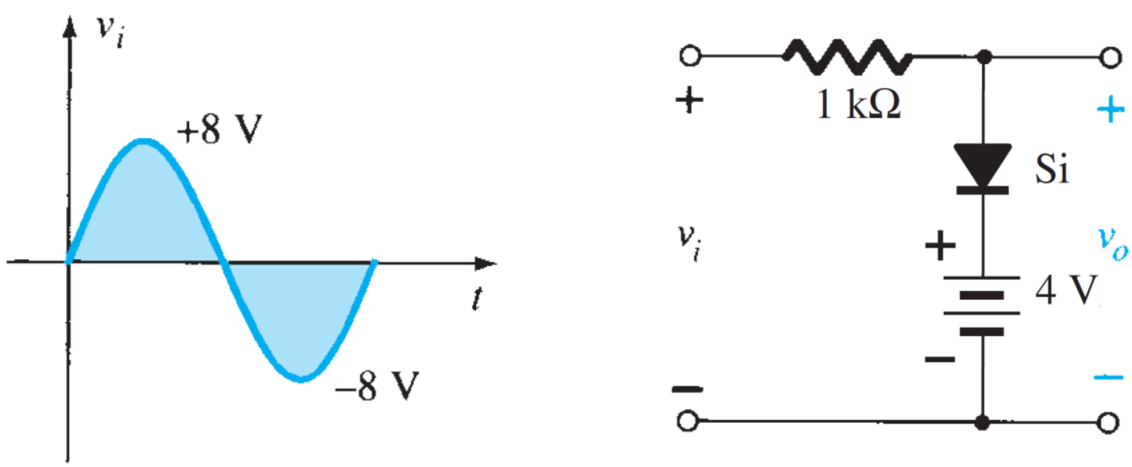


Figure 7

Sol// Step 1: Identify the type of clipper, in this case its positive clipper.

Step 2: The effect of the battery bias which is positive bias in this case.

Step 3: The positive part will appear at the output till $v_i < V + V_K$, $v_i < 4.7$, while all the negative part will appear at the output, the resultant v_0 is redrawn as shown in Figure 8.

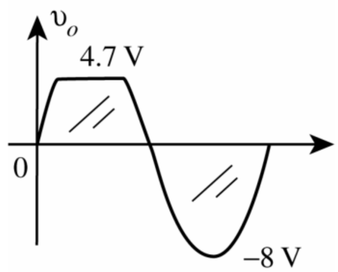


Figure 8

Clamper Circuits

The construction of the clamper circuit is almost similar to the clipper circuit. The only difference is the clamper circuit contains an extra element called capacitor. A capacitor is used to provide a dc offset (dc level) from the stored charge.

A clamper is a circuit constructed of a diode, a resistor, and a capacitor that shifts a waveform to a different dc level without changing the appearance of the applied signal.

The simplest of clamper networks is provided in Figure 1. It is important to note that the capacitor is connected directly between input and output signals and the resistor and the diode are connected in parallel with the output signal.

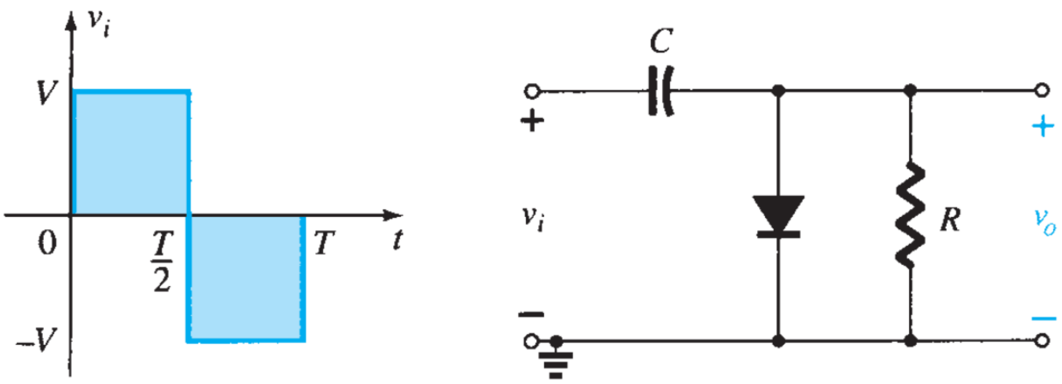
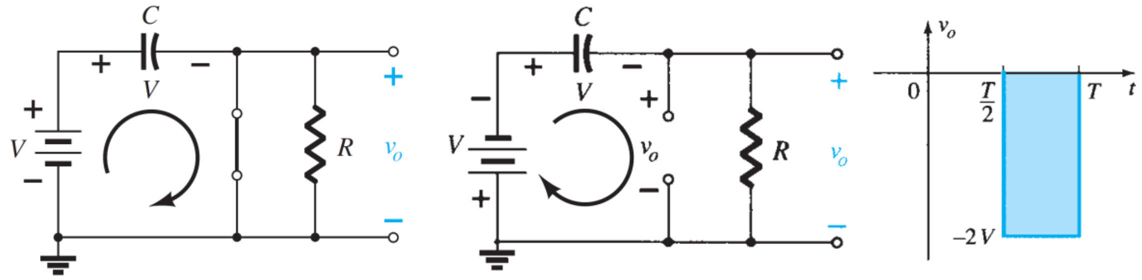


Figure 1

1. Negative clamper

Figure 1 shows negative clamper circuit, the diode will be forward biased for the positive portion of the applied signal. For the interval 0 to T/2 the network will appear as shown in Figure 2a. During this same interval of time, the capacitor will quickly charge to the peak value of V volts as shown in Figure 2a with the inverse polarity (negative) with the input voltage.

When the input switches to the -V state, the network will appear as shown in Figure 2b, with the open-circuit equivalent for the diode determined by the applied signal and stored voltage across the capacitor. The resulting output waveform will equal to the summation of the input voltage and the capacitor voltage as appears in Figure 2c.



(a) (b) (c)

Figure 2

2. Positive clamper

Figure 3 shows positive clamper, during the negative half cycle of the input AC signal, the diode is forward biased and hence no signal appears at the output. In forward biased condition, the diode allows electric current through it. This current will flow to the capacitor and charges it to the peak value of input voltage Vm. The capacitor charged in inverse polarity (positive) with the input voltage.

During the positive half cycle of the input AC signal, the diode is reverse biased and hence the signal appears at the output. Therefore, the input current directly flows towards the output. The voltage appeared at the output is equal to the sum of the voltage stored in the capacitor (Vm) and the input voltage (Vm).

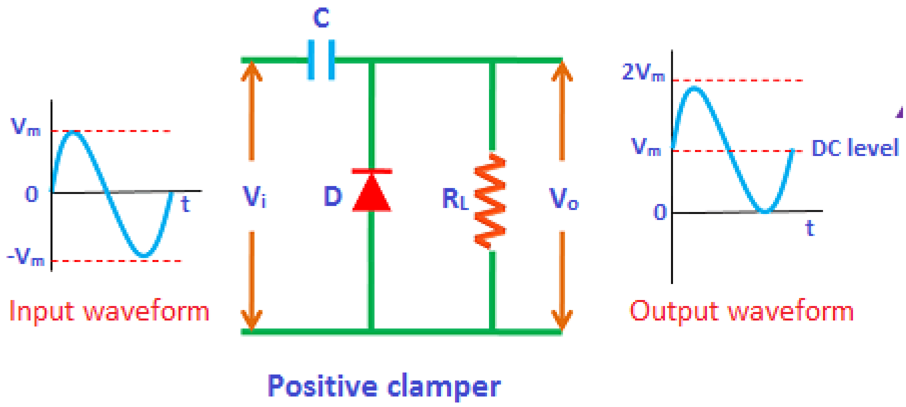


Figure 3

Sometimes an additional shift of DC level is needed. In such cases, biased clampers are used. The working principle of the biased clampers is almost similar to the unbiased clampers. The only difference is an extra element called DC battery is introduced in biased clampers.

Tips will to solve problems related to clamper circuits:

1. Identify which the portion of the input signal that will forward bias the diode.
2. Assume that the capacitor will charge up instantaneously with $V = V_m$ when the diode is in on status.
3. Assume that during the period when the diode is in the "off" state the capacitor will be considered as voltage source with $V = V_m$

Ex 1// Determine v_0 for the network of Figure 4 for the input indicated and using a silicon diode with $V_K = 0.7$ V.

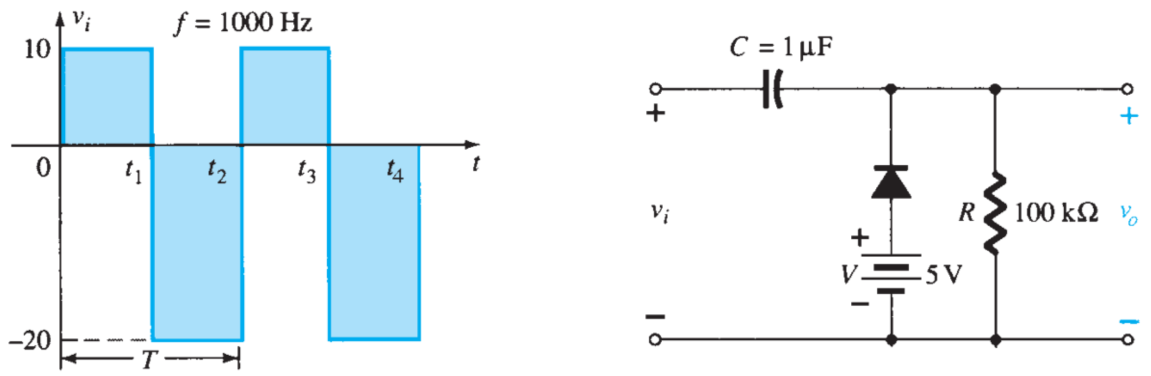
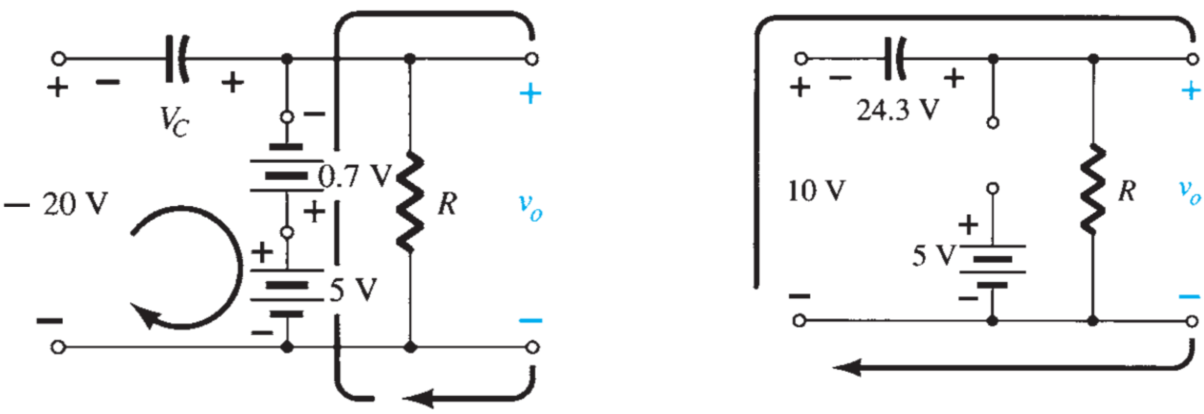


Figure 4

Sol// Step 1: Identify when the diode is in forward biased condition then the circuit will be redrawn as shown in Figure 5a.

Step 2: since the diode will be forward biased from t_1 to t_2



(a) (b)

Figure 5

Step 3: Calculate the v_0 by appling KVL for the output loop

$v_0 + V_K – V_B = 0$, $v_0 = 5 – 0.7 = 4.3$ V

and the capacitor charge voltage will be estimated by taking KVL for the input

$v_i + V_c + V_K - V_B = 0$, $- 20 + 0.7 – 5 + V_c = 0$

$V_c = 24.3$ V

Step 4: Estimate the output for the period from t_2 to t_3, which will be estimated by using Figure 5b. The output voltage will be combination form v_i and V_c

$v_i + V_c - v_0 = 0$, $v_0 = 10 + 24.3 = 34.3$ V

Step 5: redraw the output assume t_0 to t_1 is the charging period of the capacitor. The output signal is redrawn in Figure 6.

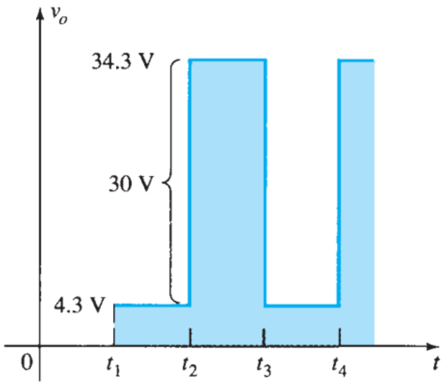


Figure 6

Ex 2// Determine v0 for the network of Figure 7 for the input indicated assume using ideal diode.

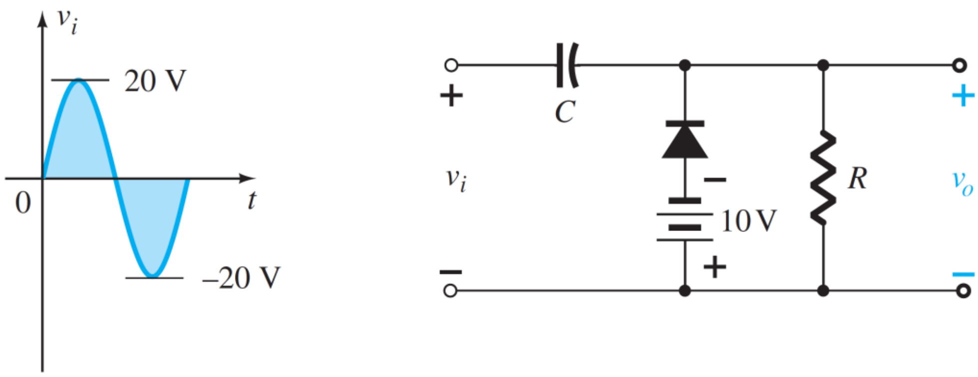


Figure 7

Sol// Step 1: remove the bias battery form the circuit, it will appear the same of clamper which will shift the input up by V_m as shown in Figure 3.

Step 2: add the effect of the bias battery to the circuit which negative bias in this circuit.

Step 3: redraw the input signal with positive shift equal to $V_m - V_B$ as shown in Figure 8.

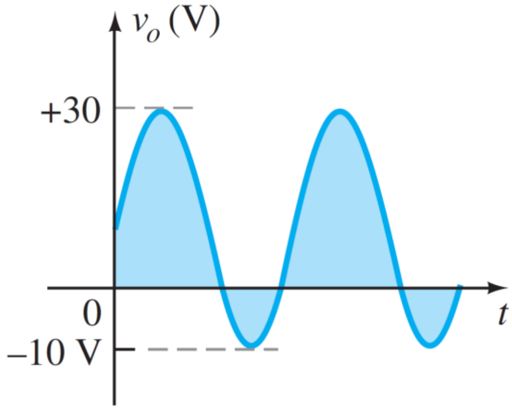


Figure 8