Lesson 5

SEMICONDUCTORS

By the end of the lesson the learner should be able to:

(i) Explain the formation of semiconductors diode
(ii) Describe diode biasing with the aid of static V-I characteristics
(iii) Describe the different types of diodes
(iv) Describe the application of diodes

The TWO most common semiconductor materials are Germanium (Chimney sooth) and Silicon (sand on the beach) and they are very common in nature. In their pure state – Intrinsic, they are still not good for electronic use. To make them useful, small ratio of impurities are added to the semiconductor. To get the N-type semiconductor, an atom from a substance with 5 valence electrons (penta-valence) is added to the semicondtor. To get the P-type semiconductor an impurity substance with a valence electron of 3 (trivalent) is added to the semiconductor material. When impurities are added, it becomes Extrinsic.

Junction Diode Symbol and Static I-V Characteristics.

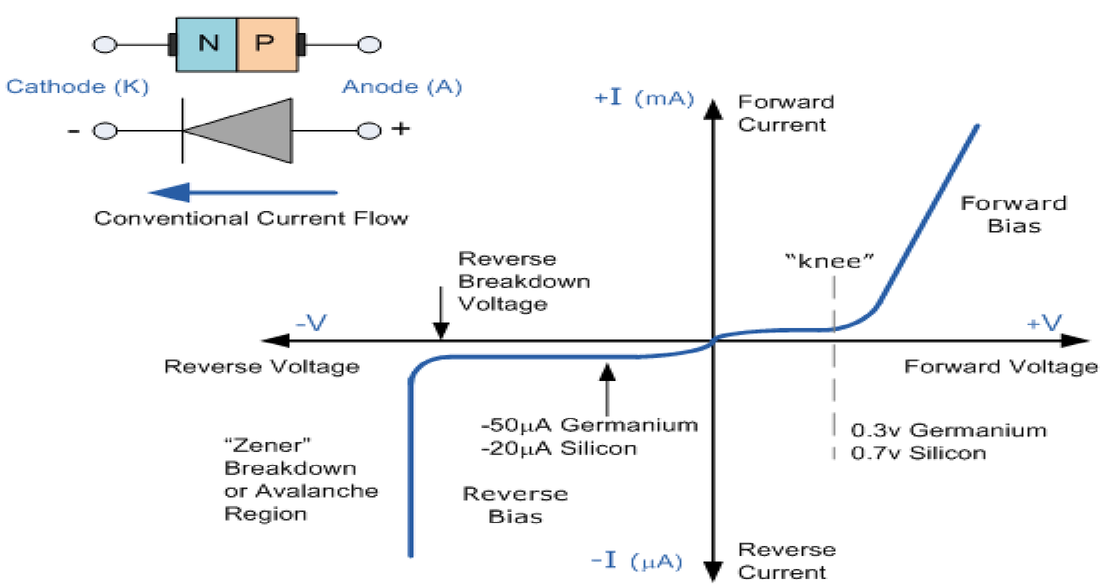


Fig 5.1 Junction Diode Symbol and Static I-V Characteristics

But before we can use the PN junction as a practical device or as a rectifying device we need to firstly bias the junction by connecting a voltage potential across it. On the voltage axis above, "Reverse Bias" refers to an external voltage potential which increases the potential barrier. An external voltage which decreases the potential barrier is said to act in the "Forward Bias" direction.

There are two operating regions and three possible "biasing" conditions for the standard Junction Diode and these are:

(i) Zero bias - No external voltage potential is applied to the PN-junction.
(ii) Reverse Bias - The voltage potential is connected negative, (-ve) to the P-type material and positive, (+ve) to the N-type material across the diode which has the effect of Increasing the PN-junction depletion layer width.
(iii) Forward Bias - The voltage potential is connected positive, (+ve) to the P-type material and negative, (-ve) to the N-type material across the diode which has the effect of Decreasing the PN-junction depletion layer width.

(i) Zero Biased Junction Diode

When a diode is connected in a Zero Bias condition, no external potential energy is applied to the PN junction. However if the diodes terminals are shorted together, a few holes (majority carriers) in the P-type material with enough energy to overcome the potential barrier will move across the junction against this barrier potential. This is known as the "Forward Current" and is referenced as IF

Likewise, holes generated in the N-type material (minority carriers), find this situation favourable and move across the junction in the opposite direction. This is known as the "Reverse Current" and is referenced as IR. This transfer of electrons and holes back and forth across the PN junction is known as diffusion, as shown below.

Zero Biased Junction Diode

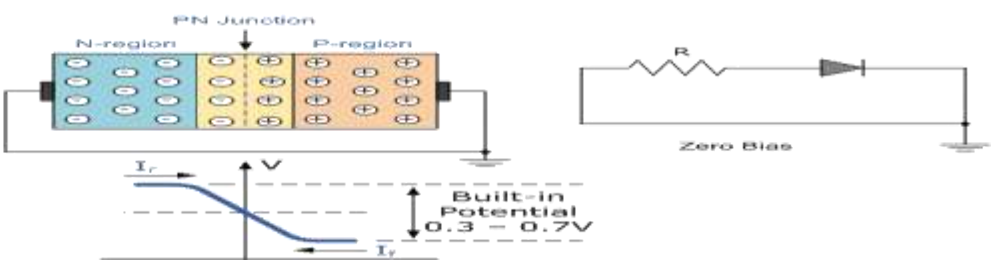


Fig 5.2 Zero biased junction diode

The potential barrier that now exists discourages the diffusion of any more majority carriers across the junction. However, the potential barrier helps minority carriers (few free electrons in the P-region and few holes in the N-region) to drift across the junction. Then an "Equilibrium" or balance will be established when the majority carriers are equal and both moving in opposite directions, so that the net result is zero current flowing in the circuit. When this occurs the junction is said to be in a state of "Dynamic Equilibrium".

The minority carriers are constantly generated due to thermal energy so this state of equilibrium can be broken by raising the temperature of the PN junction causing an increase in the generation of minority carriers, thereby resulting in an increase in leakage current but an electric current cannot flow since no circuit has been connected to the PN junction.

Reverse Biased Junction Diode

When a diode is connected in a Reverse Bias condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material. The positive voltage applied to the N-type material 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. The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

Reverse Biased Junction Diode showing an Increase in the Depletion Layer

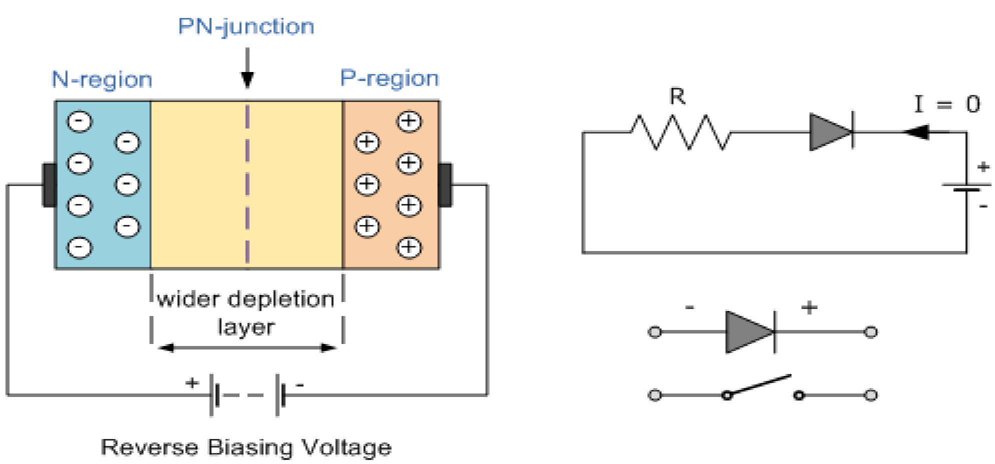


Fig 5.3 Reverse biased junction diode

This condition represents a high resistance value 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 which can be measured in microamperes, (μA). One final point, if the reverse bias voltage Vr applied to the diode is increased to a sufficiently high enough value, it will cause the PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current, and this shown as a step downward slope in the reverse static characteristics curve below.

Reverse Characteristics Curve for a Junction Diode

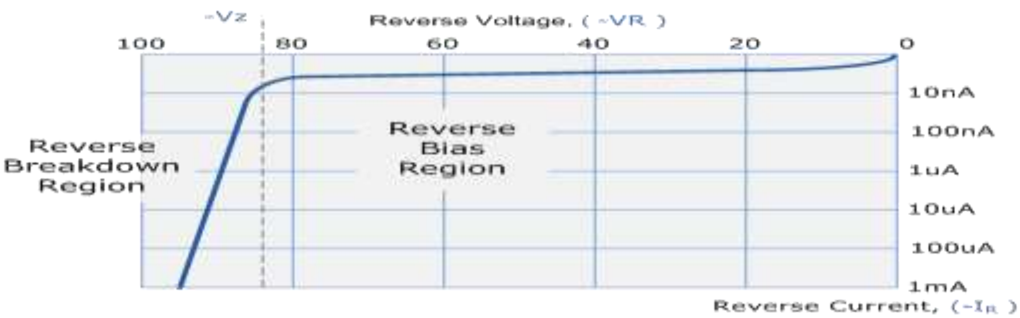


Fig 5.4 Reverse Characteristics Curve for a Junction Diode

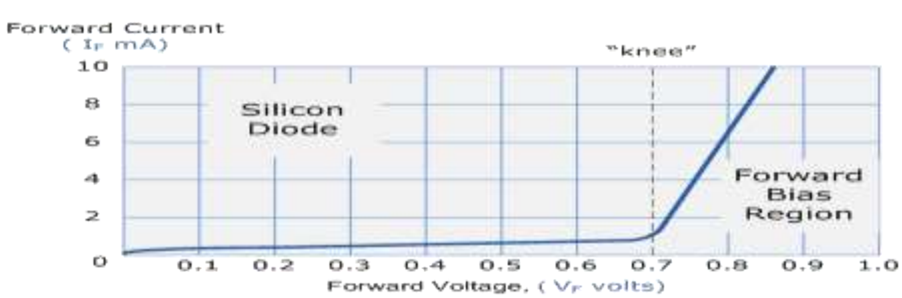
Sometimes this avalanche effect has practical applications in voltage stabilization circuits where a series limiting resistor is used with the diode to limit

This reverse breakdown current to a preset maximum value thereby producing a fixed voltage output across the diode. These types of diodes are commonly known as Zener Diodes.

Forward Biased Junction Diode

When a diode is connected in a Forward Bias condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow. 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. This results in a characteristics curve of zero current flowing up to this voltage point, called the "knee" on the static curves and then a high current flow through the diode with little increase in the external voltage as shown below.

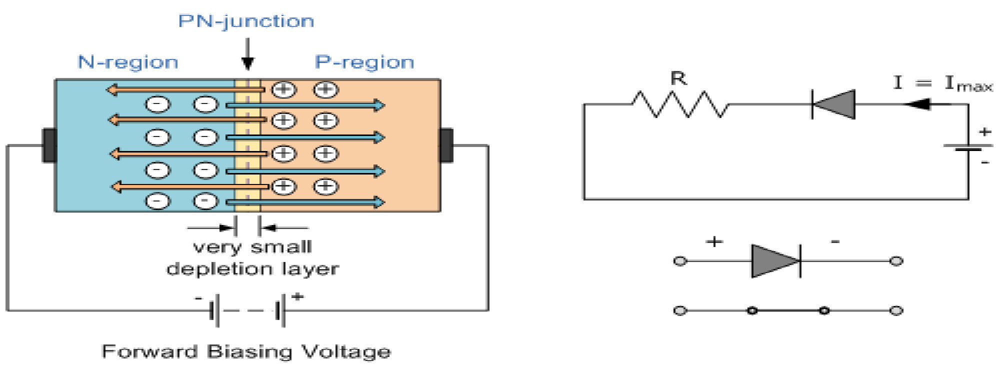
Forward Characteristics Curve for a Junction Diode



5.5 Forward bias characteristics of a diode

The application of a forward biasing voltage on the junction diode results in the depletion layer becoming very thin and narrow which represents a low impedance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the "knee" point.

Forward Biased Junction Diode showing a Reduction in the Depletion Layer



5.6 Forward bias overcoming depletion layer

This condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.7v for silicon junction diodes. Since the diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.

Junction Diode Summary

The PN junction region of a Junction Diode has the following important characteristics:

(i) Semiconductors contain two types of mobile charge carriers, Holes and Electrons.
(ii) The holes are positively charged while the electrons negatively charged.
(iii) A semiconductor may be doped with donor impurities such as Antimony (N-type doping), so that it contains mobile charges which are primarily electrons.
(iv) A semiconductor may be doped with acceptor impurities such as Boron (P-type doping), so that it contains mobile charges which are mainly holes.

(v) The junction region itself has no charge carriers and is known as the depletion region.
(vi) The junction (depletion) region has a physical thickness that varies with the applied voltage.
(vii) When a diode is Zero Biased no external energy source is applied and a natural Potential Barrier is developed across a depletion layer which is approximately 0.5 to 0.7v for silicon diodes and approximately 0.3 of a volt for germanium diodes.
(viii) When a junction diode is Forward Biased the thickness of the depletion region reduces and the diode acts like a short circuit allowing full current to flow.
(ix) When a junction diode is Reverse Biased the thickness of the depletion region increases and the diode acts like an open circuit blocking any current flow.

Types of diodes

Avalanche diode: The avalanche diode by its very nature is operated in reverse bias. It uses the avalanche effect for its operation. In general the avalanche diode is used for photo-detection where the avalanche process enables high levels of sensitivity to be obtained, even if there are higher levels of associated noise.

LASER diode: This type of diode is not the same as the ordinary light emitting diode because it produces coherent light. LASER diodes are widely used in many applications from DVD and CD drives to LASER light pointers for presentations. Although LASER diodes are much cheaper than other forms of LASER generator, they are considerably more expensive than LEDs. They also have a limited life.

Light Emitting Diodes: The Light Emitting Diode or LED is one of the most popular types of diode. When forward biased with current flowing through the junction, light is produced. The diodes use component semiconductors, and can produce a variety of colours, although the original colour was red. There are also very many new LED developments that are changing the way displays can be used and manufactured. High output LEDs and OLEDs are two examples.

Photodiode: The photo-diode is used for detecting light. It is found that when light strikes a PN junction it can create electrons and holes. Typically photo-diodes are operated under reverse bias conditions where even small amounts of current flow resulting from the light can be easily detected. Photo-diodes can also be used to generate electricity. For some applications, PIN diodes work very well as photodetectors.

PIN diode: This type of diode is typified by its construction. It has the standard P type and N-type areas, but between them there is an area of pure) semiconductor which has no doping (Intrinsic). The area of the intrinsic semiconductor has the effect of increasing the area of the depletion region which can be useful for switching applications as well as for use in photodiodes, etc.

Point contact diode: This type of diode is one of the most basic forms of diode in terms of its construction but it performs in the same way as a PN junction diode. This type of diode consists of a piece of N-type semiconductor, onto which a sharp point of a specific type of metal wire (group III metal) is placed. As this physical junction is formed, some of the metal from the wire migrates into the semiconductor and produces a PN junction. Point contact diodes have a very low level of capacitance because the resulting junction is very small. As such this type of diode is ideal for many radio frequency (RF) applications. The downside of the small junction is that they cannot carry high levels of current but they have the advantage that they are very cheap to manufacture, although their performance is not particularly repeatable.

PN Junction: The standard PN junction may be thought of as the normal or standard type of diode in use today. These diodes can come as small signal types for use in radio frequency, or other low current applications which may be termed as signal diodes. Other types may be intended for high current and high voltage applications and are normally termed rectifier diodes.

Rectifier diode: This definition refers to diodes that are used in power supplies for rectifying alternating power inputs. The diodes are generally PN junction diodes, although Schottky diodes may be used if low voltage drops are needed. They are able to rectify current levels that may range from an amp upwards.

Schottky diodes: This type of diode has a lower forward voltage drop than ordinary silicon PN junction diodes. At low currents the drop may be somewhere between 0.15 and 0.4 volts as opposed to 0.6 volts for a silicon diode. To achieve this performance they are constructed in a different way to normal diodes having a metal to semiconductor contact. They are widely used as clamping diodes, in RF applications, and also for rectifier applications.

Signal diode: This form of diode is used for small signal applications where small values of current are drawn. Diodes with the description of signal diode are generally the standard PN junction diode types.

Step recovery diode: A form of microwave diode used for generating and shaping pulses at very high frequencies. These diodes rely on a very fast turn off characteristic of the diode for their operation.

Tunnel diode: Although not widely used today, the tunnel diode was used for microwave applications where its performance exceeded that of other devices of the day.

Varactor diode or varicap diode: This type of diode is used in many radio frequency (RF) applications. The diode has a reverse bias placed upon it and this varies the width of the depletion layer according to the voltage placed across the diode. In this configuration the varactor or varicap diode acts like a capacitor with the depletion region being the insulating dielectric and the capacitor plates formed by the extent of the conduction regions. The capacitance can be varied by changing the bias on the diode as this will vary the width of the depletion region which will accordingly change the capacitance.

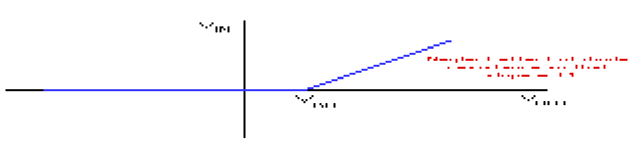
Zener diode: The Zener diode is a very useful type of diode as it provides a stable reference voltage. As a result it is used in vast quantities. It is run under reverse bias conditions and it is found that when a certain voltage is reached it breaks down. If the current is limited through a resistor, it enables a stable voltage to be produced. This type of diode is therefore widely used to provide a reference voltage in power supplies. Two types of reverse breakdown are apparent in these diodes: Zener breakdown and Impact Ionization. However the name Zener diode is used for the reference diodes regardless of the form of breakdown that is employed.

Summary

Semiconductor diodes are widely used throughout all areas of the electronics industry from electronics design through to production and repair. The semiconductor diode is very versatile, and there are very many variants and different types of diode that enable all the variety of different applications to be met. The different diode types of diodes include those for small signal applications, high current and voltage as well as different types of diodes for light emission and detection as well as types for low forward voltage drops, and types to give variable capacitance. In addition to this there are a number of diode types that are used for microwave applications. From this it can be seen that the semiconductor diode is a particularly versatile form of electronics component that can be used in many areas of electronics

Diode Applications

5.7 Diode Transfer Characteristic



Rectification ("frequency shifting")

Typical power supply applications

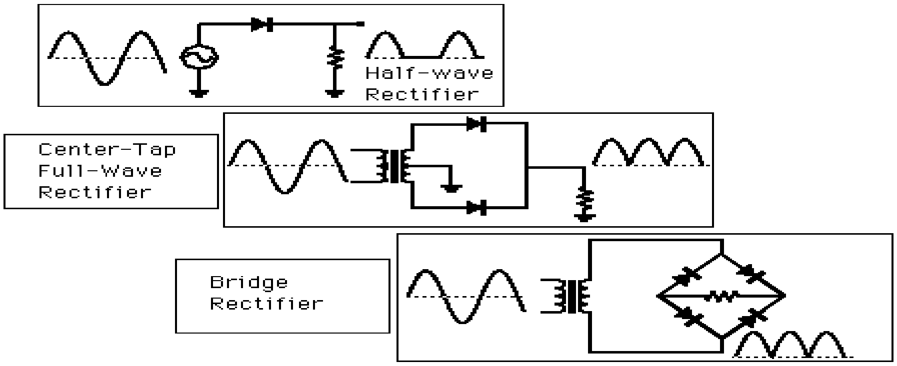


Fig 5.8 power supply applications

Half-Wave Rectification

"Figure shows a half-wave rectifier circuit. The signal is exactly the top half of the input voltage signal, and for an ideal diode does not depend at all on the size of the load resistor.

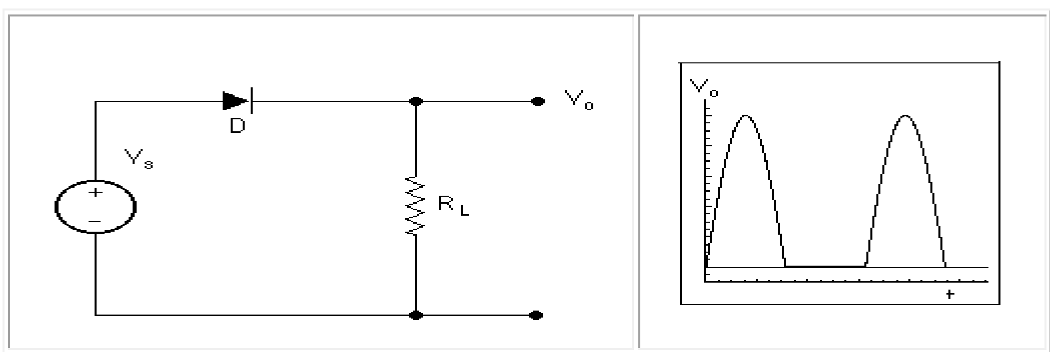


Fig 5.9 Half Wave Rectification

The rectified signal is now a combination of an AC signal and a DC component. Generally, it is the DC part of a rectified signal that is of interest, and the un-welcomed AC component is described as ripple. It is desirable to move the ripple to high frequencies where it is easier to remove by a low-pass filter.

"When diodes are used in small-signal applications - a few volts - their behaviour is not closely approximated by the ideal model because of the PN turn-on voltage. The equivalent circuit model can be used to evaluate the detailed action of the rectifier under these conditions. During the part of the wave when the input is positive but less than the PN turn-on voltage, the model predicts no loop current and the output signal voltage is therefore zero. When the input exceeds this voltage, the output signal becomes proportional to, or about 0.6 V lower than the source voltage."

Half-wave rectifier with filter capacitor or peak detector

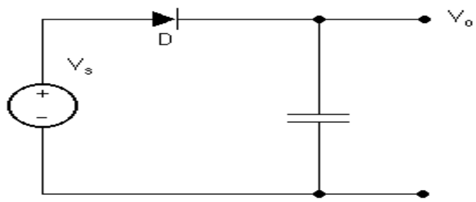


Fig 5.10 Half-wave rectifier with filter capacitor or peak detector

When a signal drives an open-ended capacitor the average voltage level on the output terminal of the capacitor is determined by the initial charge on that terminal and may therefore be quite unpredictable. Thus it is necessary to connect the output to ground or some other reference voltage via a large resistor. This action drains any excess charge and results in an average or DC output voltage of zero.

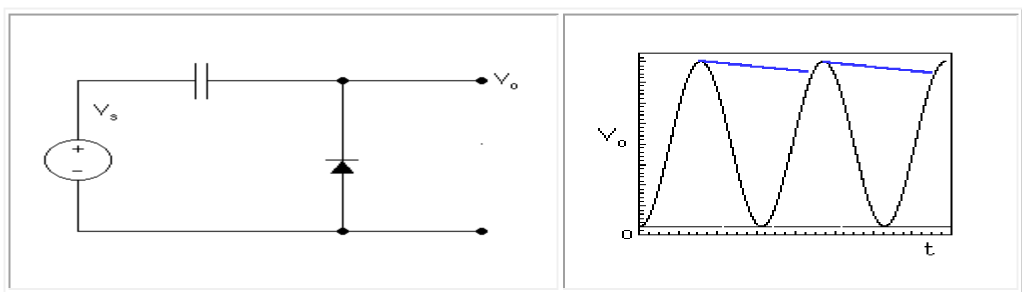


Fig 5.11 Smoothing Capacitor

Full-Wave Rectification

Version 1 - Center-Tap Full-Wave Rectifier

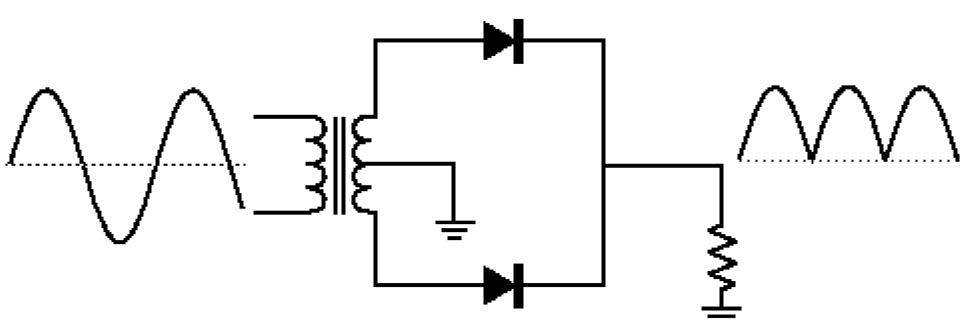


Fig 5.12 Center-Tap Full-Wave Rectifier

Version 2 - Bridge Full-Wave Rectifier

"The diode bridge circuit shown above is a full-wave rectifier. The diodes act to route the current from both halves of the AC wave through the load resistor in the same direction, and the voltage developed across the load resistor becomes the rectified output signal. The diode bridge is a commonly used circuit and is available as a four-terminal component in a number of different power and voltage ratings."

A simple alternative method of establishing a DC reference for the output voltage is by using a diode clamp. By conducting whenever the voltage at the output terminal of the capacitor goes negative, this circuit builds up an average charge on the terminal that is sufficient to prevent the output from ever going negative.

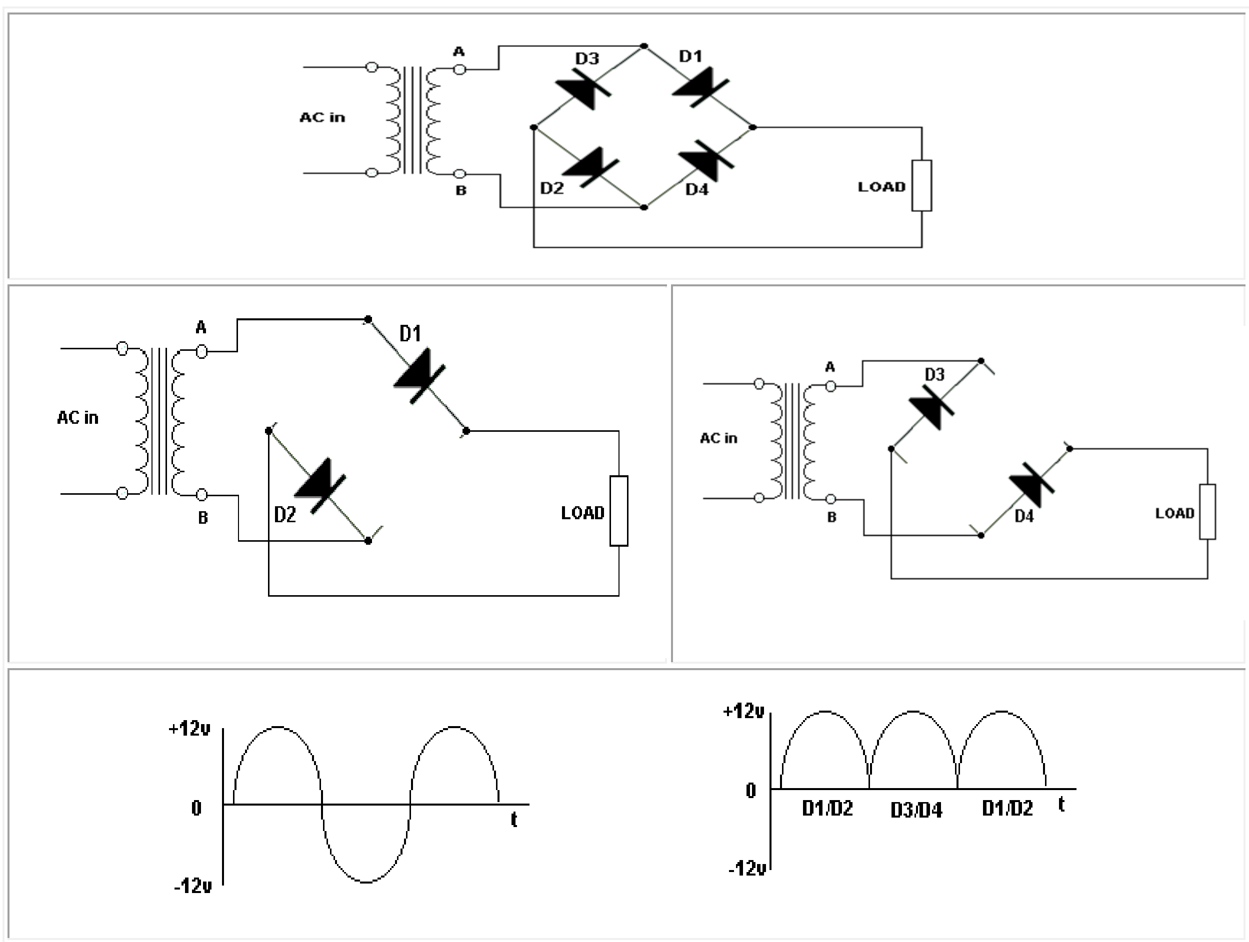


Fig 5.13 Bridge Rectifier

A Variety of Other Applications:

Clipper Circuits

A Clipper circuit is a circuit that **rejects the part** of the input wave specified while **allowing the remaining** portion. The portion of the wave above or below the cut off voltage determined is clipped off or cut off.

The clipping circuits consist of linear and non-linear elements like resistors and diodes but not energy storage elements like capacitors. These clipping circuits have many applications as they are advantageous.

- The clipping circuits eliminate the unwanted noise present in the amplitudes.
- These can work as square wave converters, as they can convert sine waves into square waves by clipping.
- The amplitude of the desired wave can be maintained at a constant level.

Among the Diode Clippers, the two main types are **positive** and **negative clippers**.

Positive Series Clipper

A Clipper circuit in which the diode is connected in series to the input signal and that attenuates the positive portions of the waveform, is termed as **Positive Series Clipper**. The following figure represents the circuit diagram for positive series clipper.

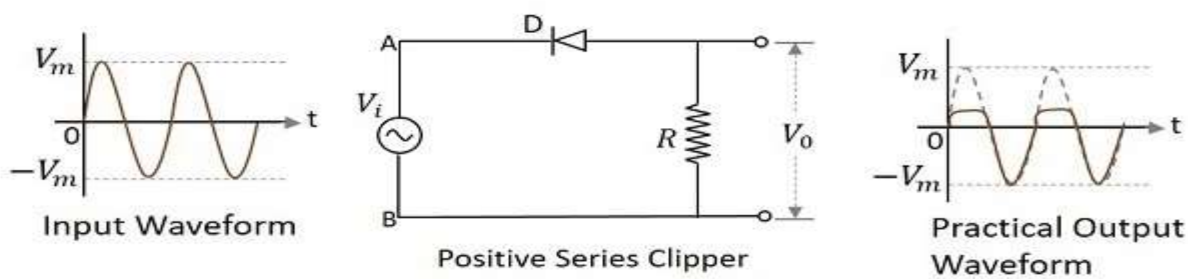


Fig 5.14 Positive Clipper

Positive Cycle of the Input − When the input voltage is applied, the positive cycle of the input makes the point A in the circuit positive with respect to the point B. This makes the diode reverse biased and hence it behaves like an open switch. Thus the voltage across the load resistor becomes zero as no current flows through it and hence

Vo will be zero.

Positive Series Clipper with positive Vr

A Clipper circuit in which the diode is connected in series to the input signal and biased with positive reference voltage Vr and that attenuates the positive portions of the waveform, is termed as **Positive Series Clipper with positive** Vr.

The following figure represents the circuit diagram for positive series clipper when the reference voltage applied is positive.

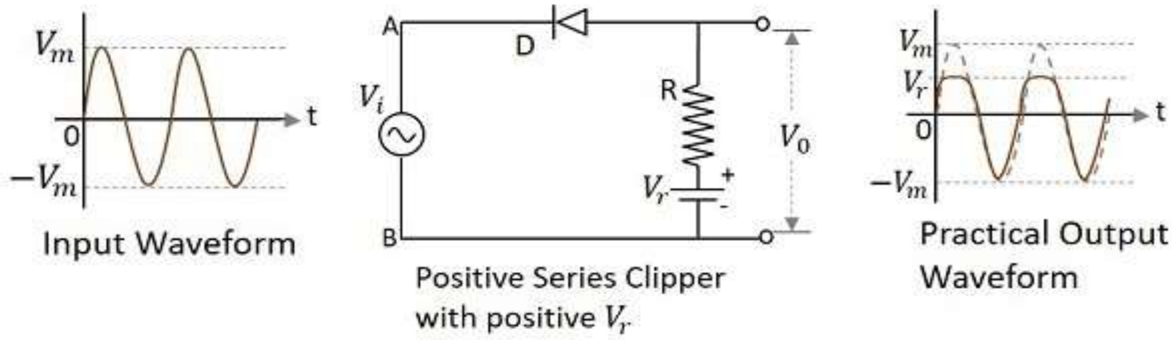


Fig 5.15 Positive Clipper with a reference voltage

During the positive cycle of the input the diode gets reverse biased and the reference voltage appears at the output. During its negative cycle, the diode gets forward biased and conducts like a closed switch. Hence the output waveform appears as shown in the above figure.

- Clamp

Clamper Circuit

A Clamper circuit can be defined as the circuit that consists of a diode, a resistor and a capacitor that shifts the waveform to a desired DC level without changing the actual appearance of the applied signal.

Positive Clamper Circuit

A Clamping circuit restores the DC level. When a negative peak of the signal is raised above to the zero level, then the signal is said to be **positively clamped**.

A Positive Clamper circuit is one that consists of a diode, a resistor and a capacitor and that shifts the output signal to the positive portion of the input signal. The figure 5.16 below explains the construction of a positive clamper circuit.

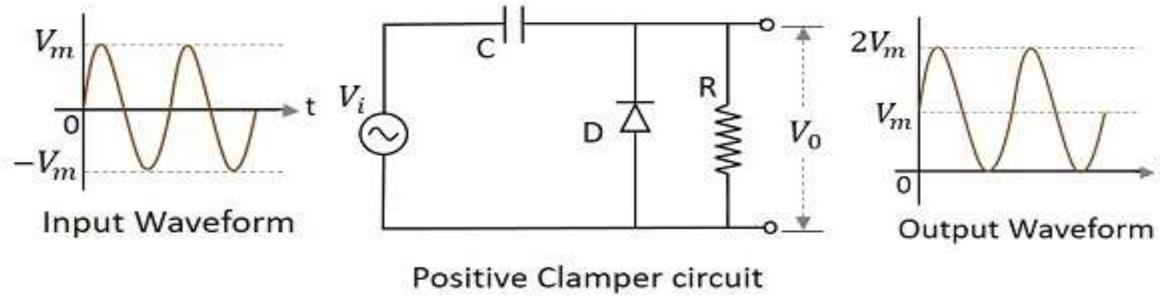


Fig 5.16 Positive Clamp

Initially when the input is given, the capacitor is not yet charged and the diode is reverse biased. The output is not considered at this point of time. During the negative half cycle, at the peak value, the capacitor gets charged with negative on one plate and positive on the other. The capacitor is now charged to its peak value Vm. The diode is forward biased and conducts heavily.

During the next positive half cycle, the capacitor is charged to positive Vm while the diode gets reverse biased and gets open circuited. The output of the circuit at this moment will be

$$V0=Vi+Vm$$

Hence the signal is positively clamped as shown in the above figure Fig 5.16. The output signal changes according to the changes in the input, but shifts the level according to the charge on the capacitor, as it adds the input voltage.

Positive Clamper with Positive V_r

A Positive clamper circuit if biased with some positive reference voltage, that voltage will be added to the output to raise the clamped level. Using this, the circuit of the positive clamper with positive reference voltage is constructed as below.

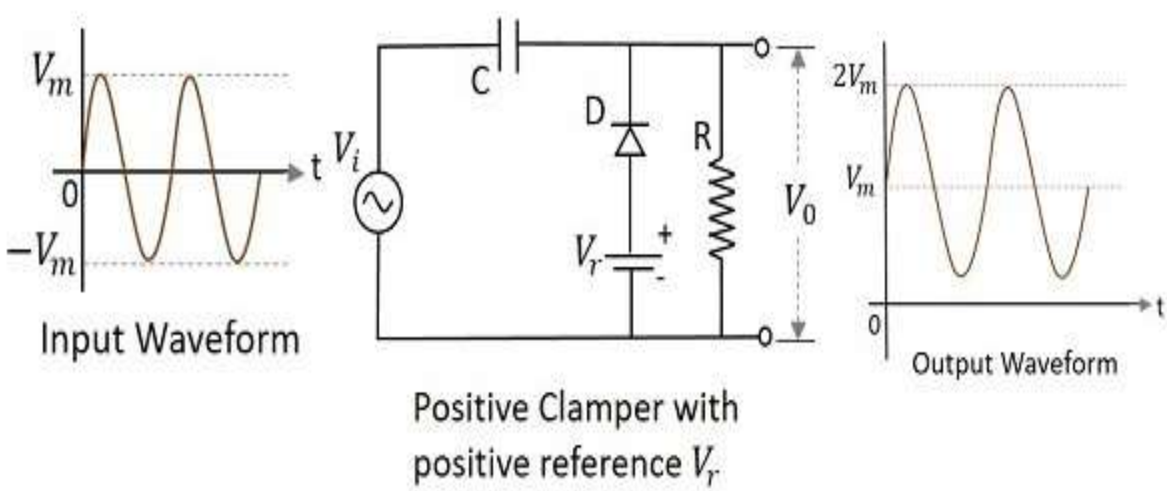


Fig 5.17 Positive Clamp with a bias

During the positive half cycle, the reference voltage is applied through the diode at the output and as the input voltage increases, the cathode voltage of the diode increase with respect to the anode voltage and hence it stops conducting. During the negative half cycle, the diode gets forward biased and starts conducting. The voltage across the capacitor and the reference voltage together maintain the output voltage level.

Applications of Clippers and Clamps.

There are many applications for both Clippers and Clampers such as

Clippers

- Used for the generation and shaping of waveforms
- Used for the protection of circuits from spikes
- Used for amplitude restorers
- Used as voltage limiters
- Used in television circuits
- Used in FM transmitters

Clampers

- Used as direct current restorers
- Used to remove distortions
- Used as voltage multipliers
- Used for the protection of amplifiers
- Used as test equipment
- Used as base-line stabilizer

Diode Logic

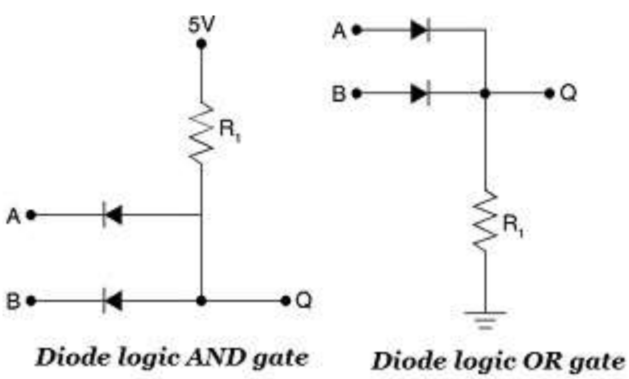


Fig 5.18 Diode logic gates

To the right (above) you see a basic Diode Logic OR gate. We'll assume that a logic 1 is represented by +5 volts, and a logic 0 is represented by ground, or zero volts. In this figure Fig 5.18, if both inputs are left unconnected or are both at logic 0, output Z will also be held at zero volts by the resistor, and will thus be a logic 0 as well. However, if either input is raised to +5 volts, its diode will become forward biased and will therefore conduct. This in turn will force the output up to logic 1. If both inputs are logic 1, the output will still be logic 1. Hence, this gate correctly performs a logical OR function.

To the left (above) is the equivalent AND gate. We use the same logic levels, but the diodes are reversed and the resistor is set to pull the output voltage up to a logic 1 state. For this example, +V = +5 volts, although other voltages can just as easily be used. Now, if both inputs are unconnected or if they are both at logic 1, output Z will be at logic 1. If either input is grounded (logic 0), that diode will conduct and will pull the output down to logic 0 as well. Both inputs must be logic 1 in order for the output to be logic 1, so this circuit performs the logical AND function."

https://www.tutorialspoint.com/electronic_circuits/electronic_clamper_circuits.htm