MODULE – VI
Semiconductor devices and applications

Diode, Zener diode and Transistor– conduction due to both charge carriers

MOSFET - conduction due to one charge carrier

PN Junction Diode

Diode is a semiconductor device, which conduct the current in one direction only. Two terminals: **anode** and **cathode**.

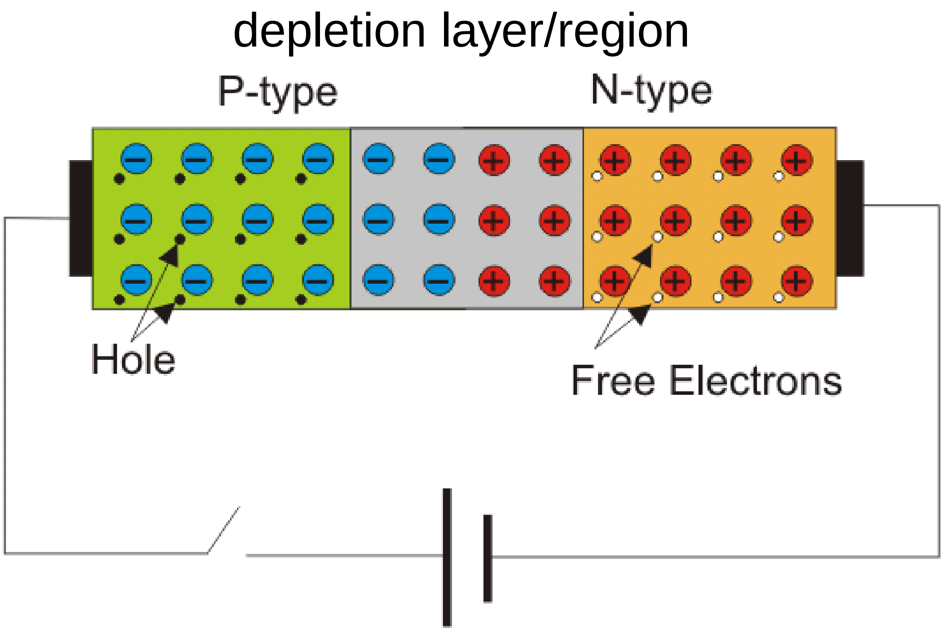
When the positive polarity of supply is connected to the anode – the diode is **forward biased** and it conducts.

When the positive polarity of supply is connected to the cathode – the diode is **reversed biased** and it does not conduct.

If the reverse-biasing voltage is sufficiently large than **breakdown voltage**, the diode is in **reverse-breakdown** region and large current flows though it.

In a piece of semiconductor material, if one half is doped by P-type and the other half is doped by N-type impurity, a PN junction is formed. The plane dividing the two halves or zones is called **PN junction or depletion layer/region.**
The N-type **has high concentration of free electrons** while P-type has high concentration of **holes**. Therefore at the junction there is a tendency for the free electrons to diffuse over to the P-side and holes to the N-side (process called diffusion). The net opposite charge in each layer prevents further diffusion into that layer. Thus a barrier is set up near the junction which prevents further movement of charge carriers. This is called as **potential barrier** (0.3V for germanium and 0.7V for silicon).

Unbiased Diode



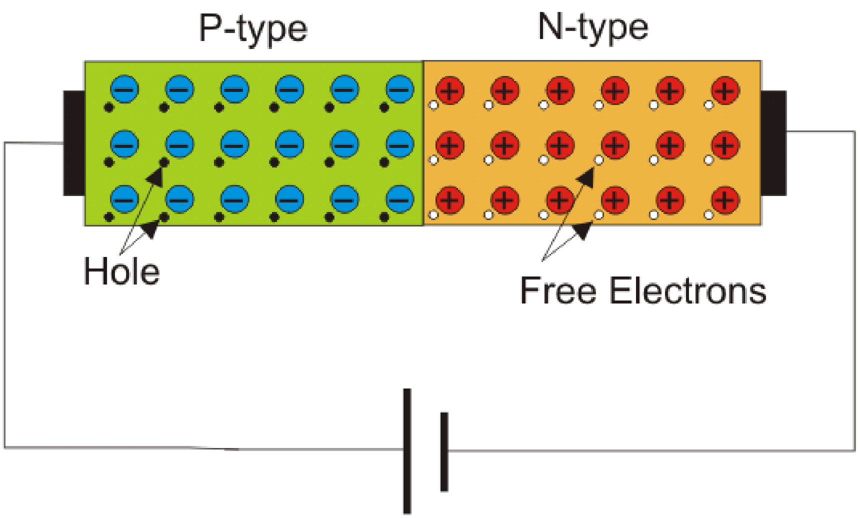
https://www.myelectrical2015.com/2021/04/mobile-charge-carriers-immobile-ions.html

N-side will have a significant number of free electrons, and very few holes (due to thermal excitation) whereas the p side will have a high concentration of holes and very few free electrons. Due to this, a process called diffusion takes place. In this process, free electrons from n side will diffuse (spread) into the p side and recombine with holes present there, leaving positive immobile (not moveable) ions in n side and creating negative immobile ions in the p-type side of the diode.

Due to the presence of these positive and negative ions, a static electric field called as barrier potential is created across the PN junction of the diode. It is called "barrier potential" because it acts as a barrier and opposes the further migration of holes and free electrons across the junction.

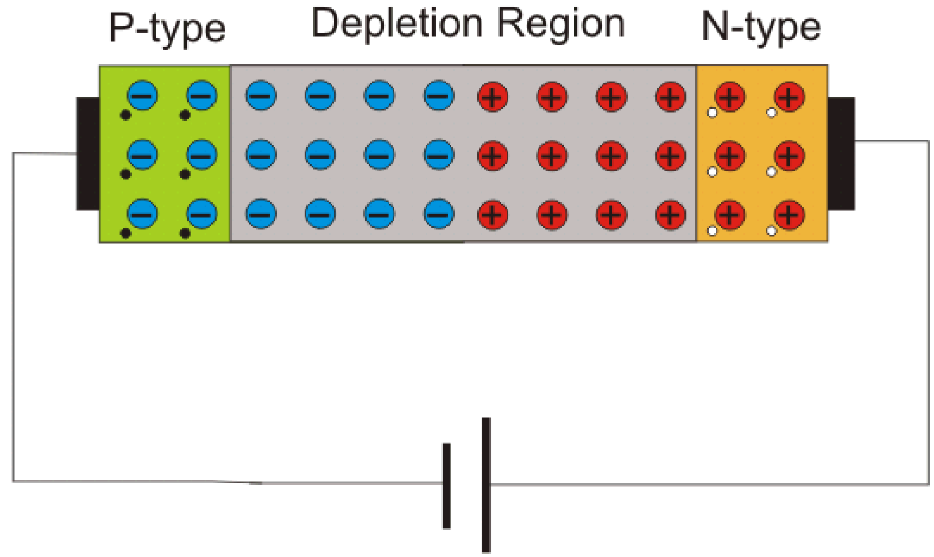
Forward Biased Diode

depletion layer/region

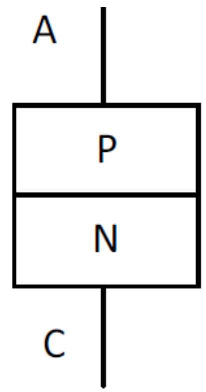


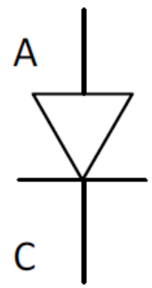
Reverse Biased Diode

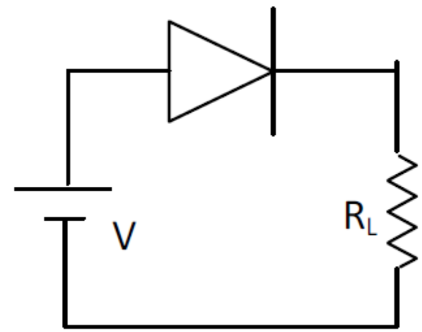
depletion layer/region



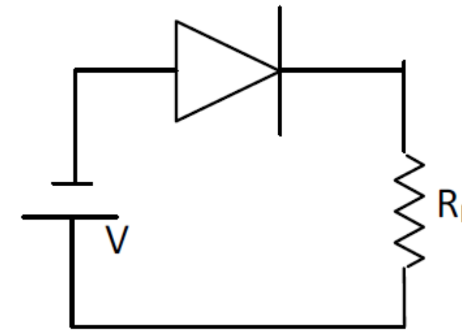
As the magnitude of the reverse voltage increases, the kinetic energy of the minority charge carriers also increase. These fast-moving electrons collide with the other atoms in the device to knock-off some more free electrons from them. The free electrons so released further release much more free electrons from the atoms by breaking the covalent bonds. This process is termed as carrier multiplication and leads to a considerable increase in the flow of current through the p-n junction. The associated phenomenon is called Avalanche Breakdown.



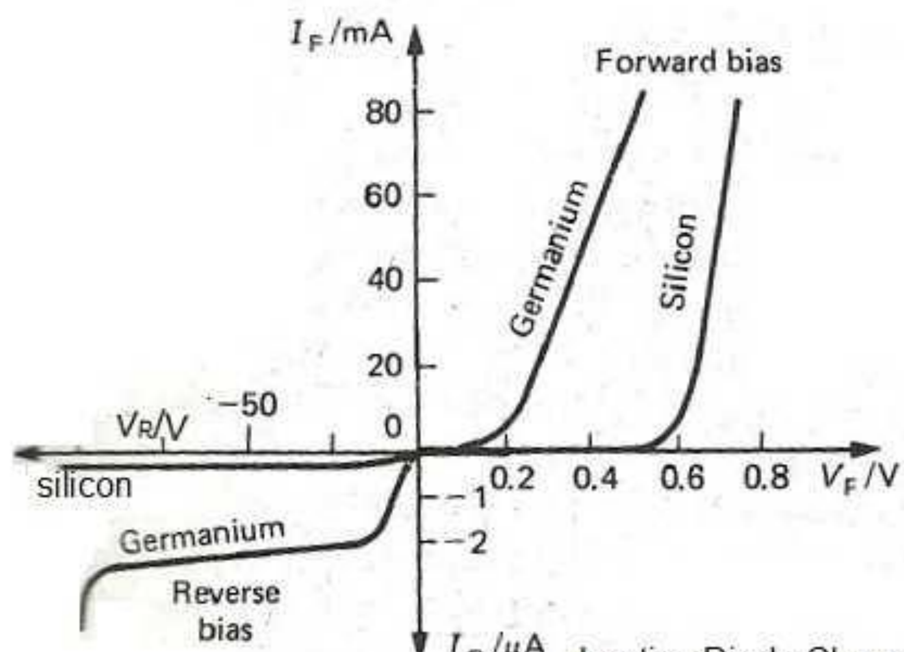




Forward bias



Reverse bias



Junction Diode Characteristics

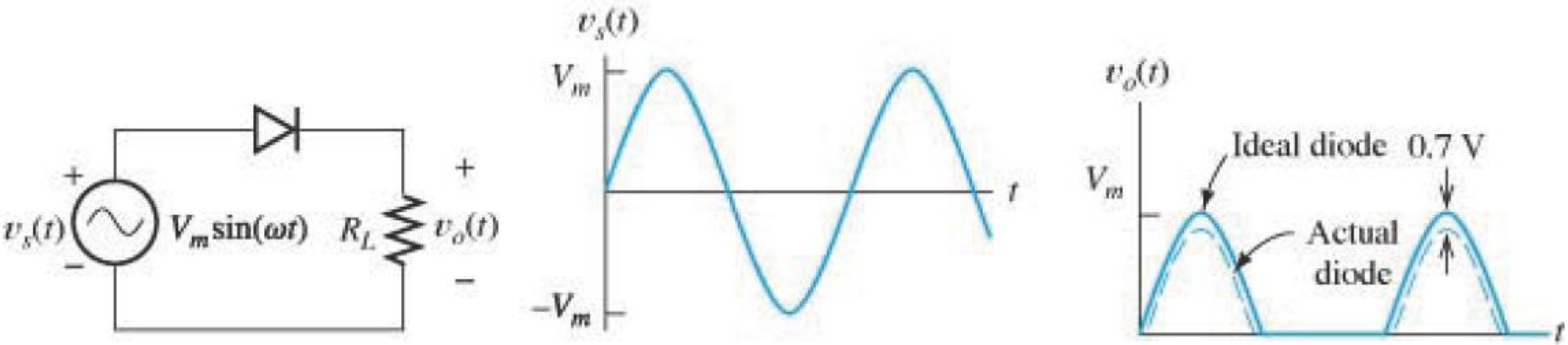
Ideal diode:

- perfect conductor with zero voltage drop (**short circuit**) when the diode is forward biased

- **open circuit**, when the diode is reversed biased.

Applications of Diode

Half - Wave Rectifier Circuits



(a) Circuit diagram (b) Source voltage versus time (c) Load voltage versus time

Applications of Diode

Full - Wave Rectifier Circuits

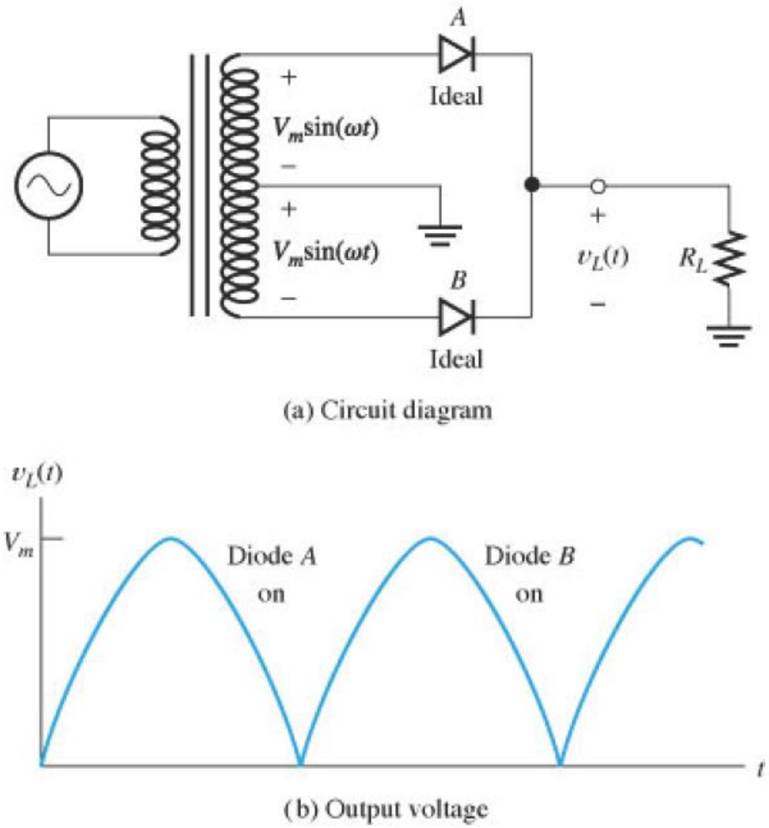


Figure Full-wave rectifier.

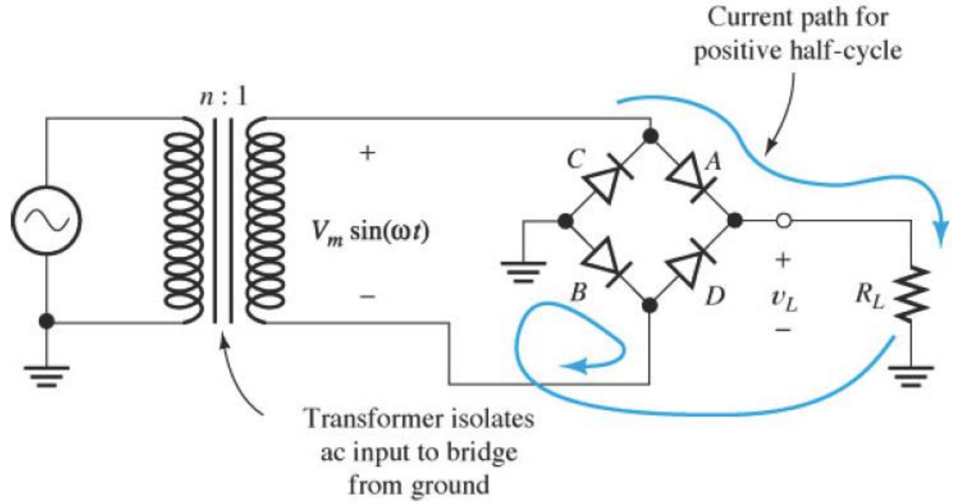
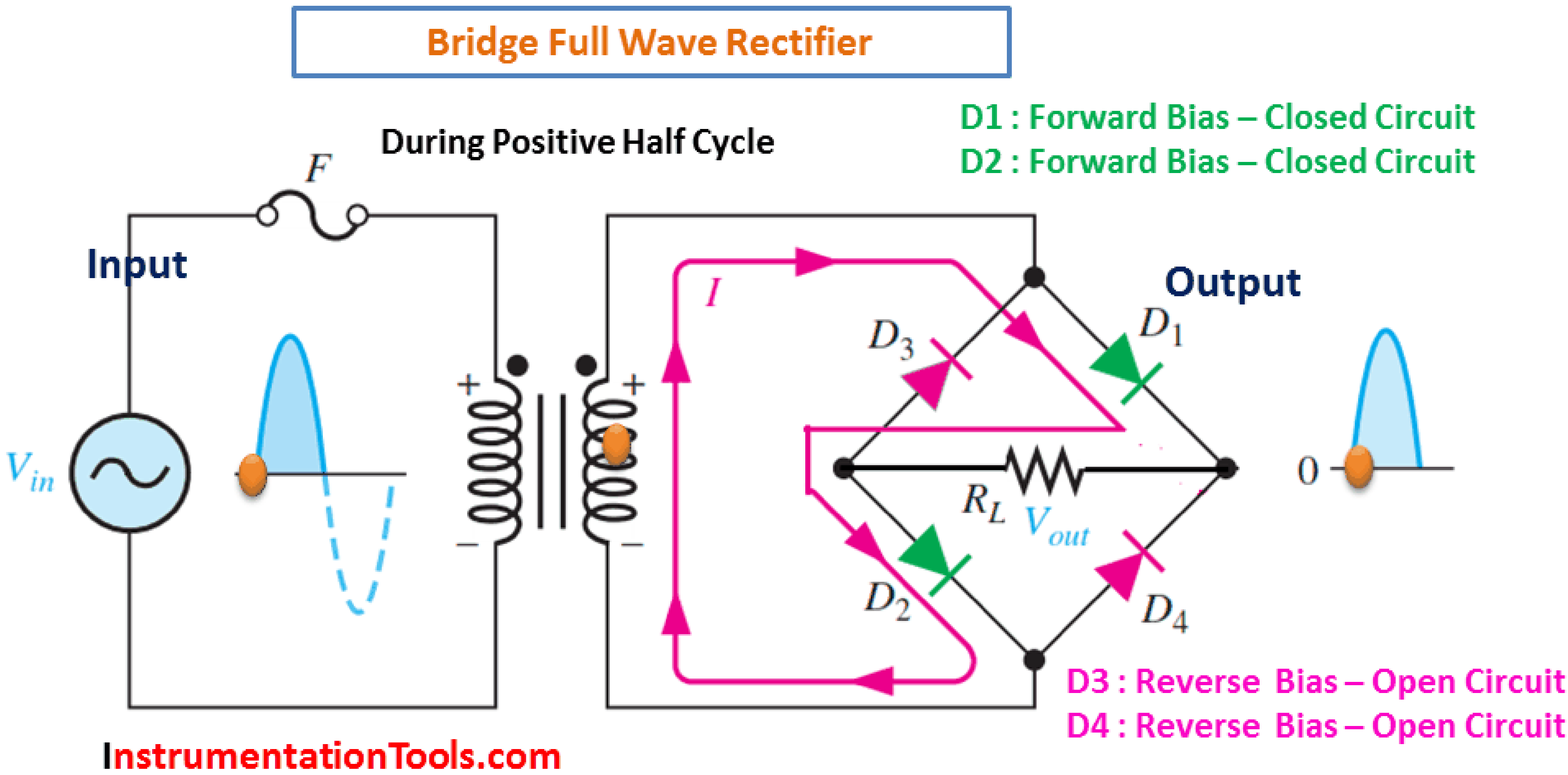


Figure Diode-bridge full-wave rectifier.

The bridge rectifier uses four diodes connected as shown in Figure. When the input cycle is positive as in part (a), diodes D1 and D2 are forward-biased and conduct current in the direction shown. A voltage is developed across RL that looks like the positive half of the input cycle. During this time, diodes D3 and D4 are reverse-biased.

(a) During the positive half-cycle of the input, D1 and D2 are forward-biased and conduct current. D3 and D4 are reverse-biased.
(b) During the negative half-cycle of the input, D3 and D4 are forward-biased and conduct current. D1 and D2 are reverse-biased.

When the input cycle is negative, diodes D3 and D4 are forward-biased and conduct current in the same direction through RL as during the positive half-cycle During the negative half-cycle, D1 and D2 are reverse-biased. A full-wave rectified output voltage appears across RL as a result of this action.

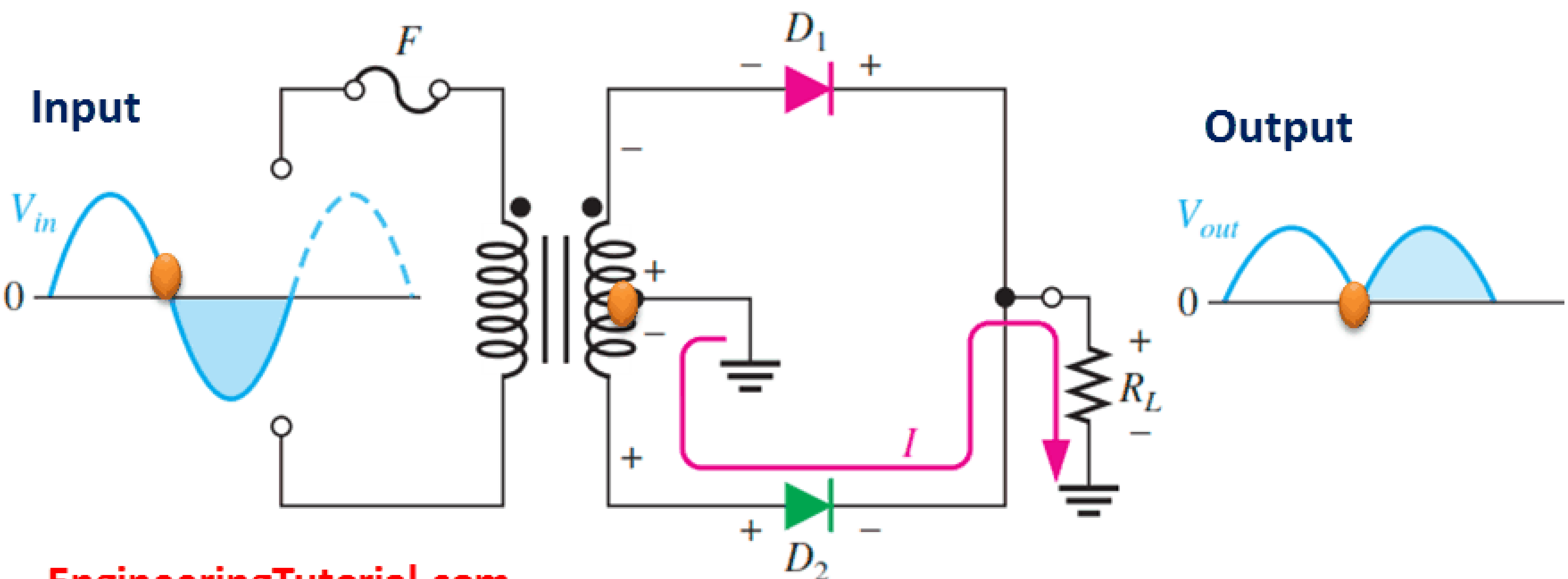


Bridge Full Wave Rectifier
During Positive Half Cycle
D1 : Forward Bias – Closed Circuit
D2 : Forward Bias – Closed Circuit
F
Input
V_{in}
I
D_3
D_1
Output
R_L
V_{out}
D_2
D_4
0
D3 : Reverse Bias – Open Circuit
D4 : Reverse Bias – Open Circuit
InstrumentationTools.com

Center Tapped Full Wave Rectifier

During Negative Half Cycle

D1 : Reverse Bias – Open Circuit

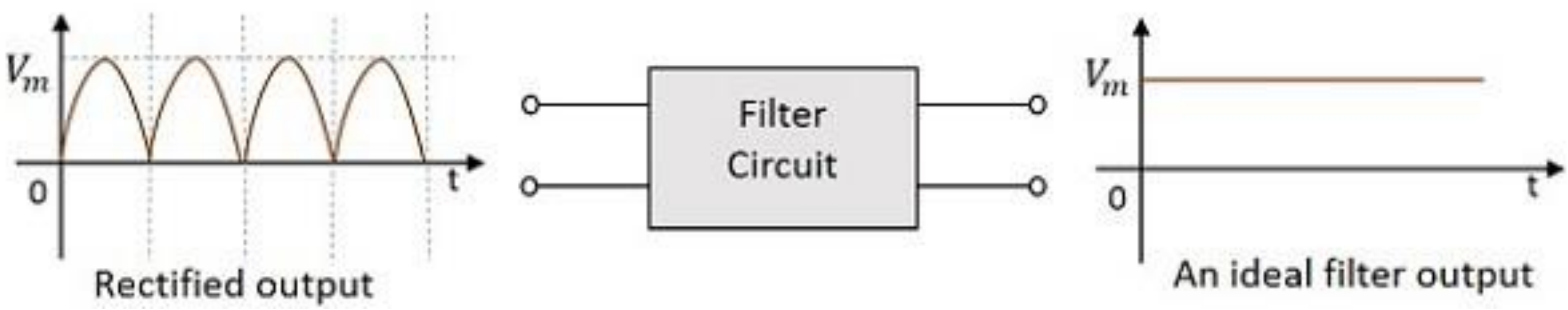


EngineeringTutorial.com

D2 : Forward Bias – Closed Circuit

Why Do We Need Filters?

The **ripple** in the signal denotes the **presence of some AC component**. This ac component has to be completely removed in order to get pure dc output. So, we need a circuit that **smoothens** the rectified output into a pure dc signal.
A **filter circuit** is one which removes the ac component present in the rectified output and allows the dc component to reach the load.
The following figure shows the functionality of a filter circuit.



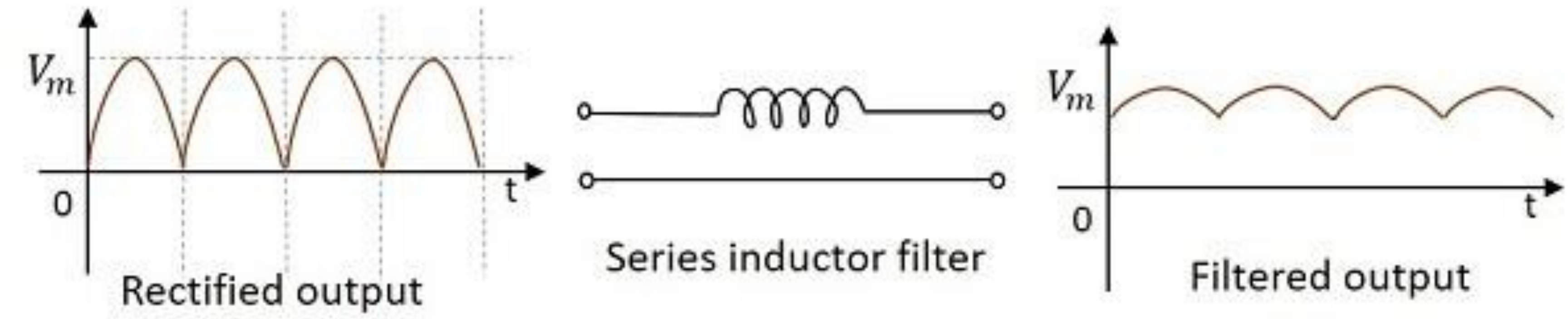
A filter circuit is constructed using two main components, inductor and capacitor.
We have already studied in Basic Electronics tutorial that

- An inductor allows **dc** and blocks **ac**.
- A capacitor allows **ac** and blocks **dc**.

Let us try to construct a few filters, using these two components.

Series Inductor Filter

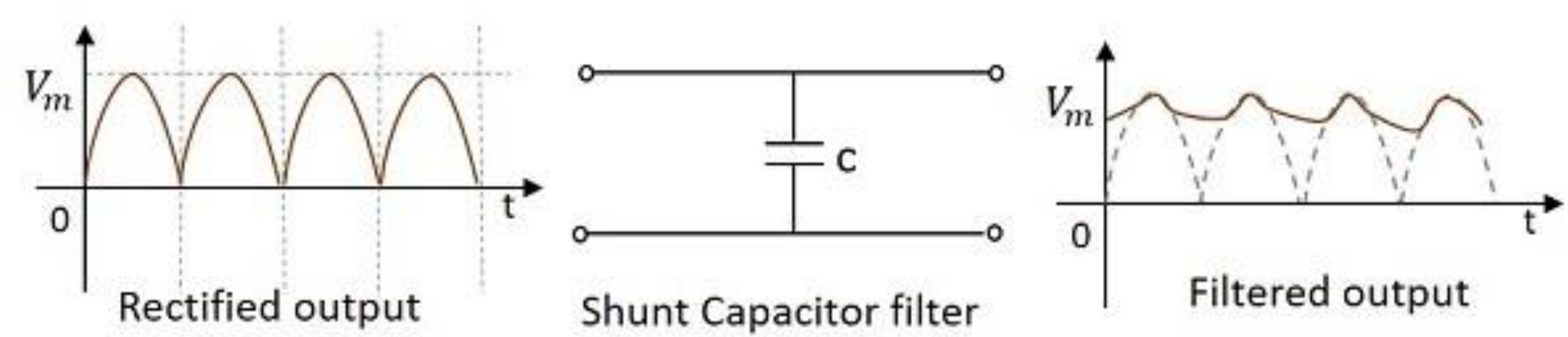
As an inductor allows dc and blocks ac, a filter called **Series Inductor Filter** can be constructed by connecting the inductor in series, between the rectifier and the load. The figure below shows the circuit of a series inductor filter.



The rectified output when passed through this filter, the inductor blocks the ac components that are present in the signal, in order to provide a pure dc. This is a simple primary filter.

Shunt Capacitor Filter

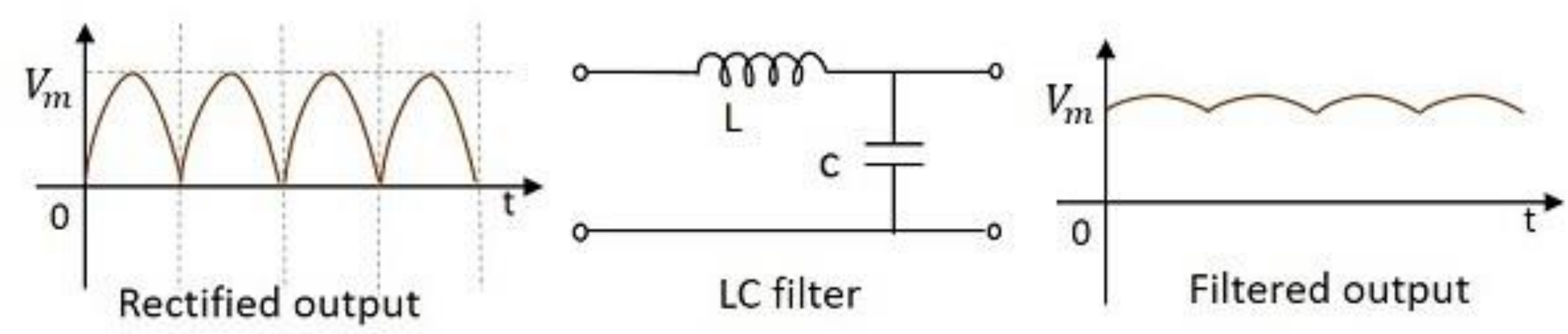
As a capacitor allows ac through it and blocks dc, a filter called **Shunt Capacitor Filter** can be constructed using a capacitor, connected in shunt, as shown in the following figure.



The rectified output when passed through this filter, the ac components present in the signal are grounded through the capacitor which allows ac components. The remaining dc components present in the signal are collected at the output. The above filter types discussed are constructed using an inductor or a capacitor. Now, let’s try to use both of them to make a better filter. These are combinational filters.

L-C Filter

A filter circuit can be constructed using both inductor and capacitor in order to obtain a better output where the efficiencies of both inductor and capacitor can be used. The figure below shows the circuit diagram of a LC filter.



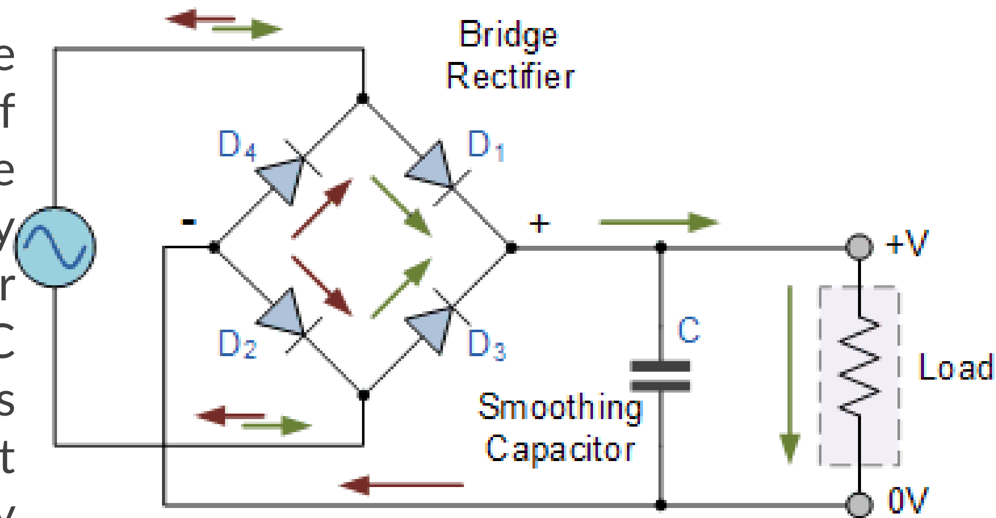
The rectified output when given to this circuit, the inductor allows dc components to pass through it, blocking the ac components in the signal. Now, from that signal, few more ac components if any present are grounded so that we get a pure dc output.

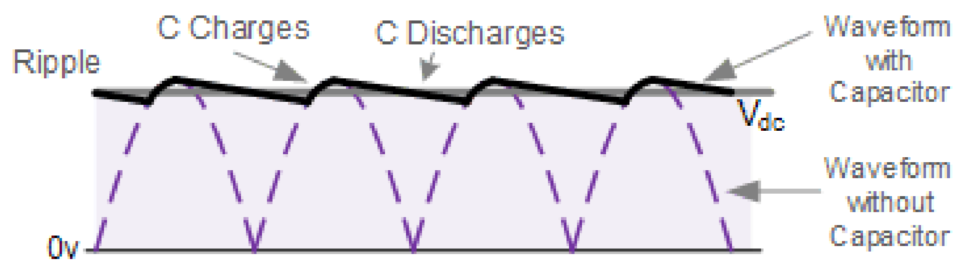
This filter is also called as a **Choke Input Filter** as the input signal first enters the inductor. The output of this filter is a better one than the previous ones.

Full wave Rectifier With Smoothing Capacitor

The single phase half-wave rectifier produces an output wave of half cycle. However, it is not practical to use this type of circuit to produce a steady DC supply. The full-wave bridge rectifier however, gives us a greater mean DC value (0.637 Vmax) with less superimposed ripple while the output waveform is twice that of the frequency of the input supply frequency.

The average DC output of the rectifier can be improved while at the same time reducing the AC variation of the rectified output by using smoothing capacitors to filter the output waveform. Smoothing or reservoir capacitors connected in parallel with the load across the output of the full wave bridge rectifier circuit increases the average DC output level even higher as the capacitor acts like a storage device as shown below.





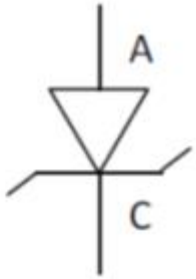
Resultant Output Waveform

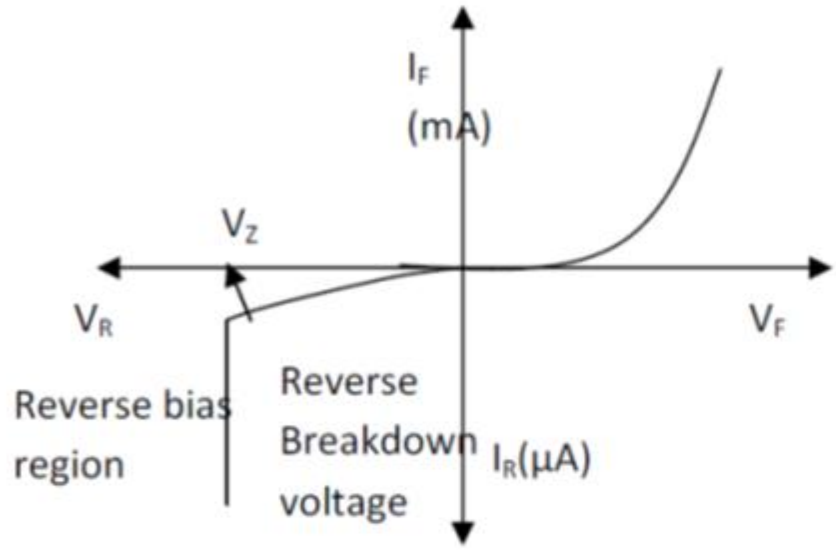
The smoothing capacitor converts the full-wave rippled output of the rectifier into a more smooth DC output voltage.

Zener Diode

The forward bias condition is same as the ordinary PN diode, but under reverse bias condition, the **breakdown voltage** depends upon the **amount of doping**. If the diode is **heavily doped**, depletion layer will be thin and consequently breakdown occurs at lower reverse voltage, besides the breakdown voltage being sharp. Thus the breakdown voltage can be selected with the amount of doping.

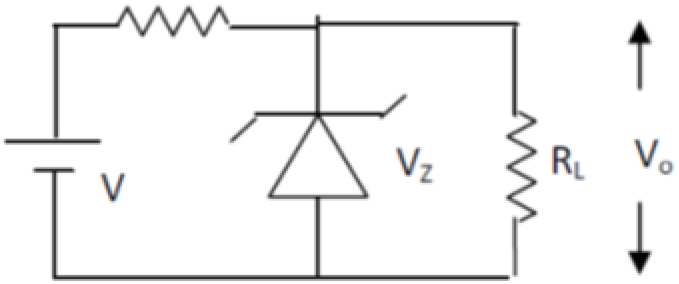
When the reverse bias field across the junction is sufficiently high, it may exert a strong force on bound electrons to tear them out from a covalent bond. Thus a large number of electron – hole pairs will be generated through a direct rupture of the covalent bond thereby resulting in large reverse current at the breakdown voltage. Though **Zener breakdown occurs for lower breakdown voltage** and avalanche breakdown occurs for higher breakdown voltage, such diodes are normally called Zener diode.





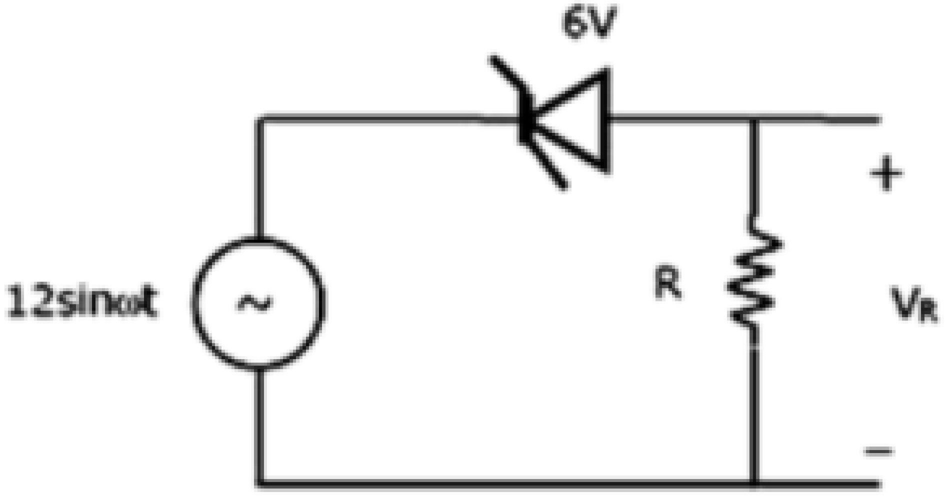
From the **Zener diode characteristics**, under the reverse bias condition, the voltage across the Zener diode remains almost constant although the current through the Zener diode increases.

Application: Thus the Zener diode serves as a reference voltage. Hence, the Zener diode can be used as a **voltage regulator**.



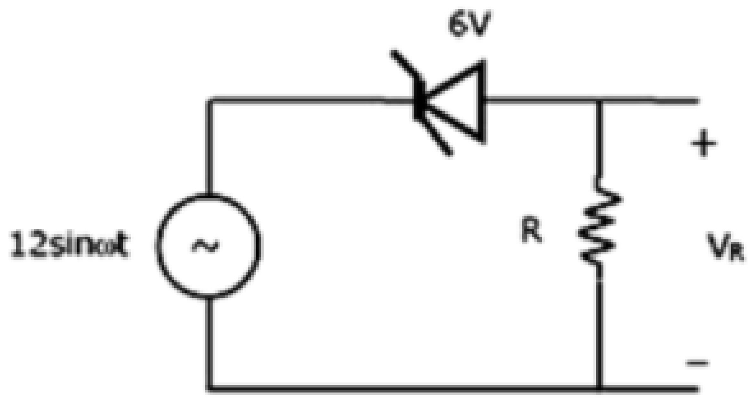
Zener diode as voltage regulator

Application of Zener diode as voltage regulator:



Assume the Zener diode as ideal, draw the waveform of voltage across Zener diode and Load resistor for one cycle.

Which is correct for V_R?



(A)

(B)

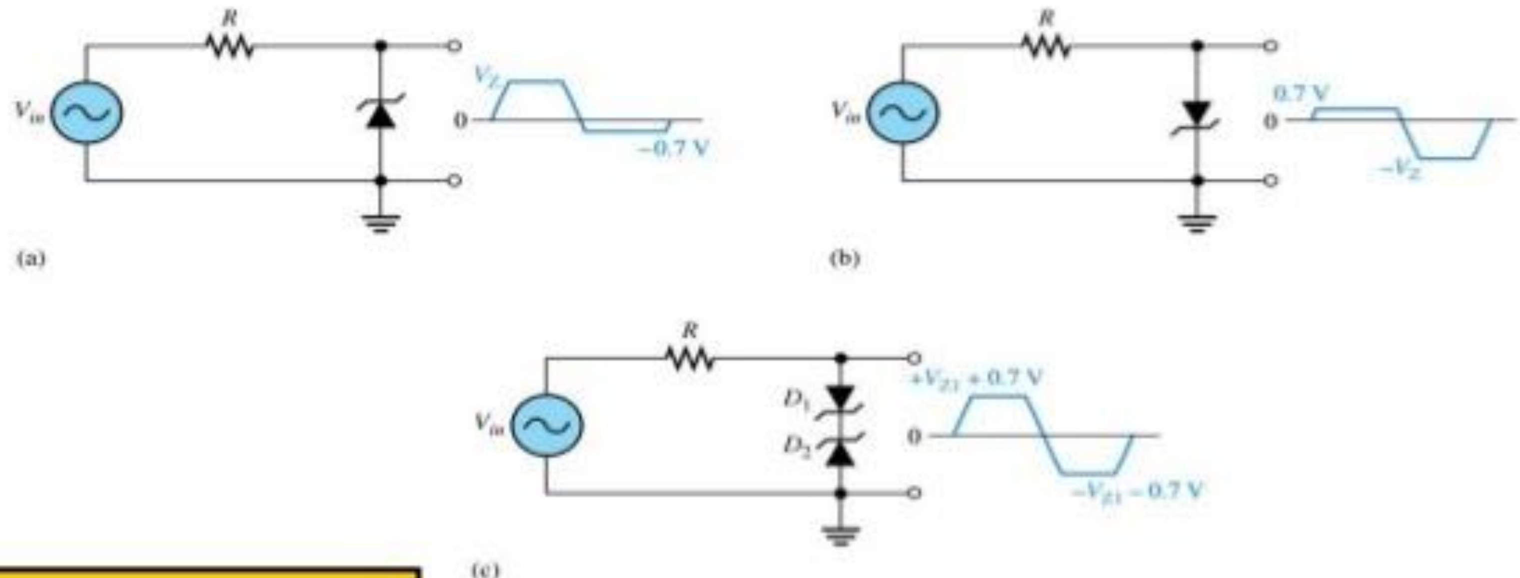
(C)

(D)

Zener diode as clipper

Zener Limiting

Zener diodes can used in ***ac applications to limit voltage swings to desired levels***.



V_Z: zener voltage

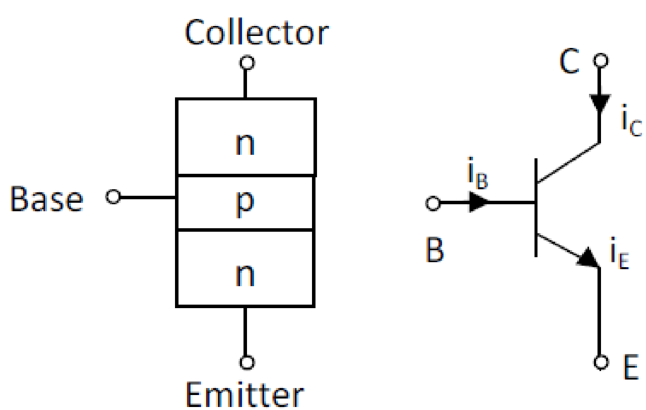
Vd: Diode voltage

Vd = 0.7

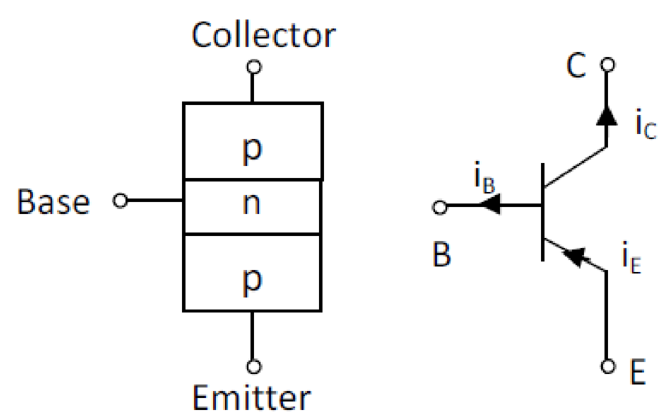
BJT

A bipolar transistor is formed by adding a second p or n region to a pn junction diode. With two n regions and one p region, two junctions are formed and it is known as an NPN-transistor. With two p regions and one n region, it is called as PNP-transistor. The three terminals are named as collector, emitter and base. A bipolar transistor has two junctions, collector-base junction(CBJ) and base-emitter junction(BEJ).

For an NPN –type, the emitter side n – layer is made wide, the p – base is narrow and the collector side n – layer is narrow and heavily doped. For a PNP – type, the emitter side p – layer is made wide, the n – base is narrow, and the collector side p – layer is narrow and heavily doped.



(a) NPN Transistor



(b) PNP Transistor

Common Base (CB) Configuration

- Base grounded
- Amplifies voltage

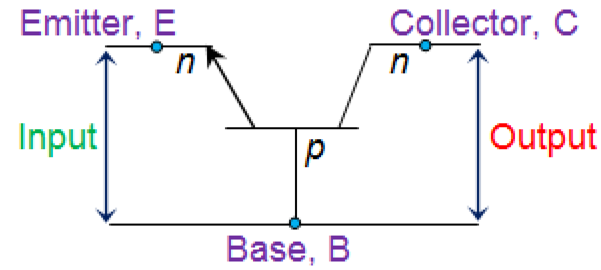


Figure 1 Common Base (CB) Configuration

Common Collector (CC) Configuration

- Collector grounded
- Amplifies current
- Emitter follower, i.e unity voltage gain.

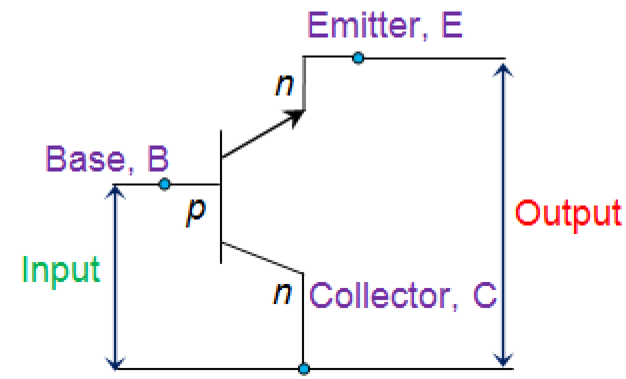


Figure 5 Common Collector (CC) Configuration

Common Emitter (CE) Configuration

- Emitter grounded
- Amplifies both current and voltage

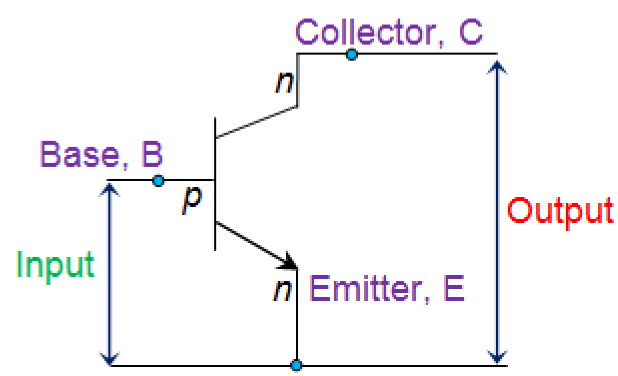


Figure 9 Common Emitter (CE) Configuration

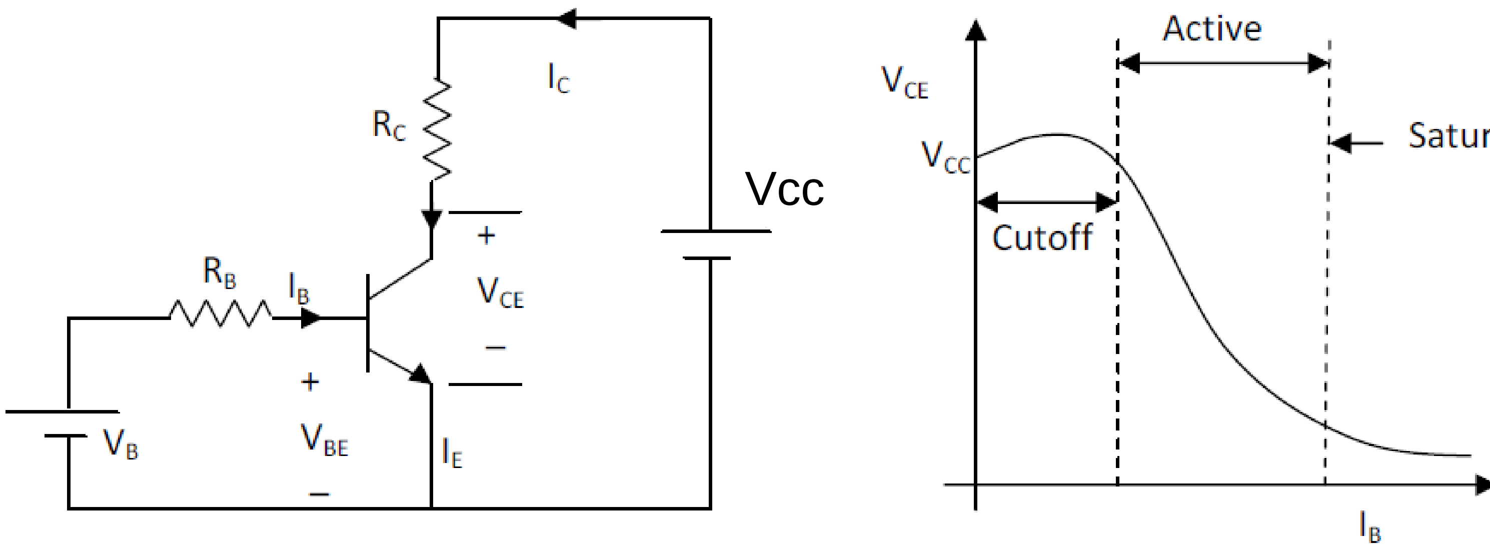
Input Characteristics: These describe the changes in input current with the variation in the values of input voltage keeping the output voltage constant.

Output Characteristics: This is a plot of output current versus output voltage with constant input current.

Current Transfer Characteristics: This characteristic curve shows the variation of output current in accordance with the input current, keeping output voltage constant.

Common Emitter (CE) Configuration

The transfer characteristics of a transistor is as shown There are three operating regions of a transistor: cutoff, active and saturation.

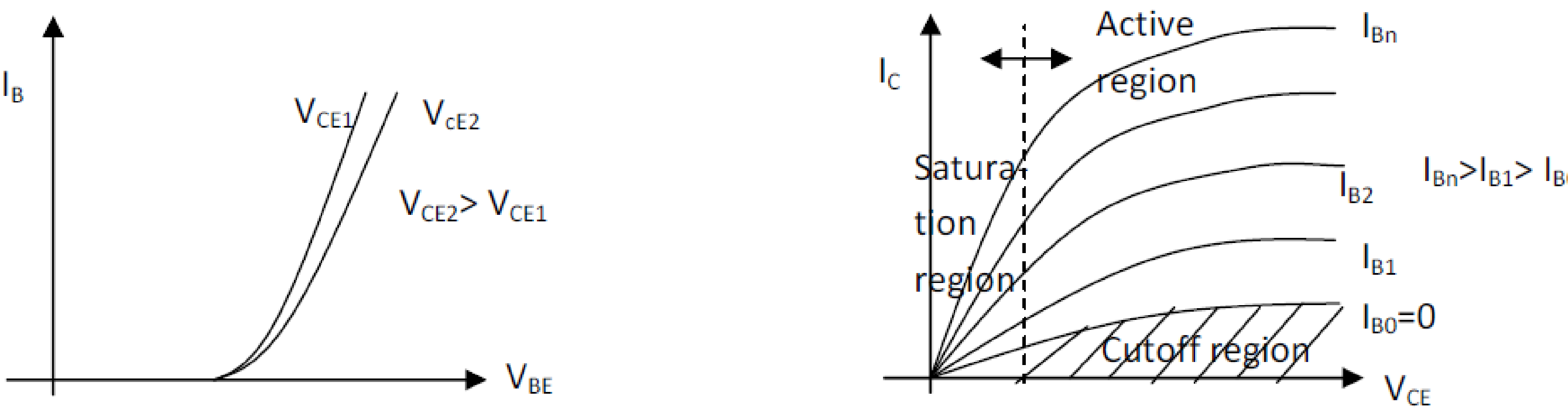


In the cut-off region, the transistor is off or the base current is not enough to turn it on and both junctions are reverse biased

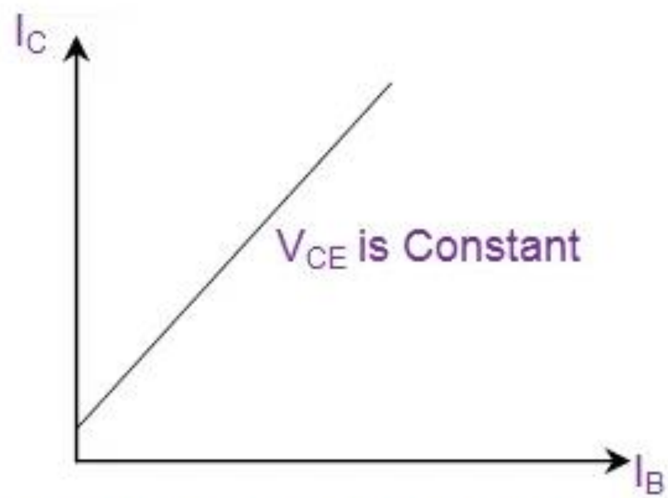
In the active region, the transistor acts as an amplifier, where the base current is amplified by a gain and the collector – emitter voltage decreases with base current. The CBJ is reverse biased and the BEJ is forward biased.

In the saturation region, the based current is sufficiently high so that the collector – emitter voltage is low, and the transistor acts as a switch. Both the junctions are forward biased.

The input and output characteristics of transistor is as shown



(a) Input characteristics (b) Output Characteristics



Transfer Characteristics for CE Configuration

The Active Region of the Transistor

The active region of the Transistor is the area on the Output curve where the Output Current is almost constant and independent of the Output Voltage. The Transistor operates in the Active region if the base resistance is greater than the maximum value allowed. A Transistor can only be used as an amplifier if it is in the active region. In addition, the emitter junction should be in forwarding bias, and the collector junction should be in reverse bias for operation in the active region.

Saturation Region of the Transistor

The saturation region of the Transistor is the area where the collector Current rapidly increases with a little increase in Output Voltage. The base resistance should be less than the maximum allowed value to run the Transistor in the saturation region. Both emitter and collector junctions should be in forwarding bias for operation in the saturation region. The Transistor works like the ON stage of a switch in the saturation zone.

Cut-off Region of the Transistor

The base Current is effectively zero in the Cut-Off region. As a result, even at higher Output Voltage, collector Current becomes zero. To operate a Transistor in the cut-off region, both the emitter and collector junctions must be in reverse-biased condition. A Transistor operates like the OFF stage of a switch in the cut-off region.

Applying Kirchhoff's law we get

$$i_E = i_C + i_B$$

We define the parameter α as the ratio of the collector current to the emitter current

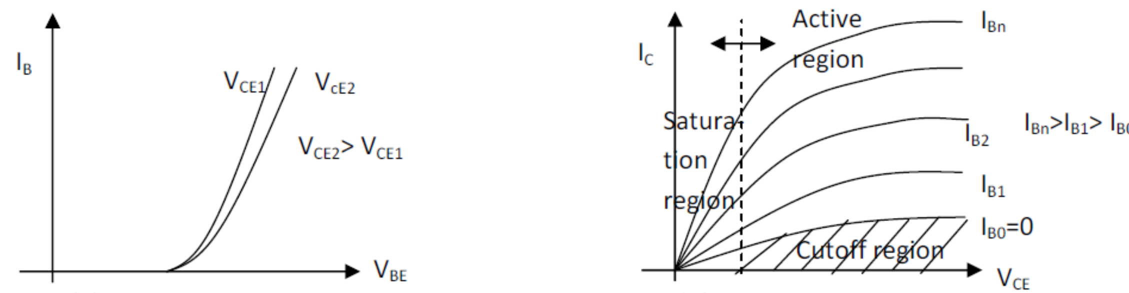
$$\alpha = \frac{i_C}{i_E} \qquad \text{or} \qquad i_E \alpha = i_C$$

Value of α ranges from 0.9 to 0.999.

Combining the above equations we get

$$i_B = (1-\alpha) i_E$$

The input and output characteristics of transistor is as shown



(a) Input characteristics

(b) Output Characteristics

We define another parameter β as the ratio of the collector current to the base current.

$$\beta = \frac{i_C}{i_B} = \frac{\alpha}{1-\alpha}$$

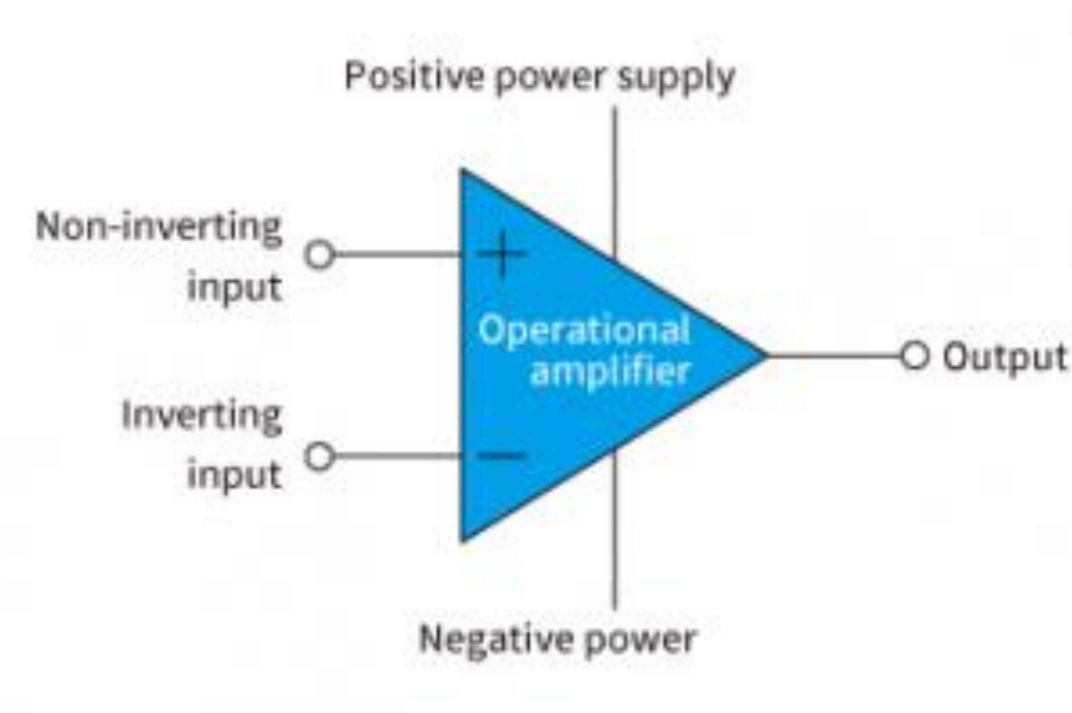
Value of β ranges from 10 to 1000. We can also rewrite the above equation as

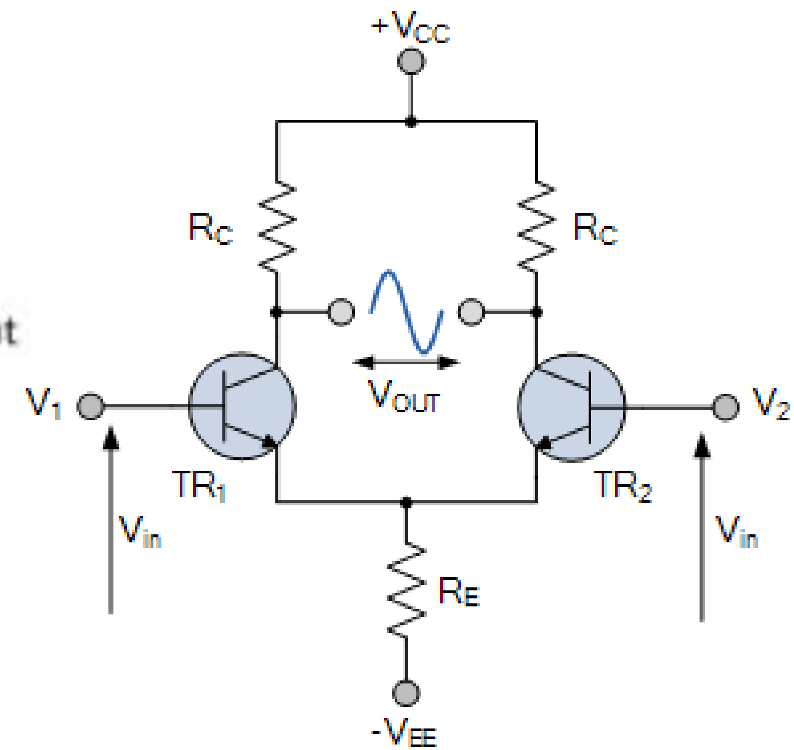
$$i_C = \beta i_B$$

Note that since β is usually very large compared to unity, the collector current is an amplified version of the base current.

What is an Operational Amplifier (Op-amp)?

An operational amplifier is an integrated circuit that can amplify weak electric signals. An operational amplifier has two input pins and one output pin. Its basic role is to amplify and output the voltage difference between the two input pins.



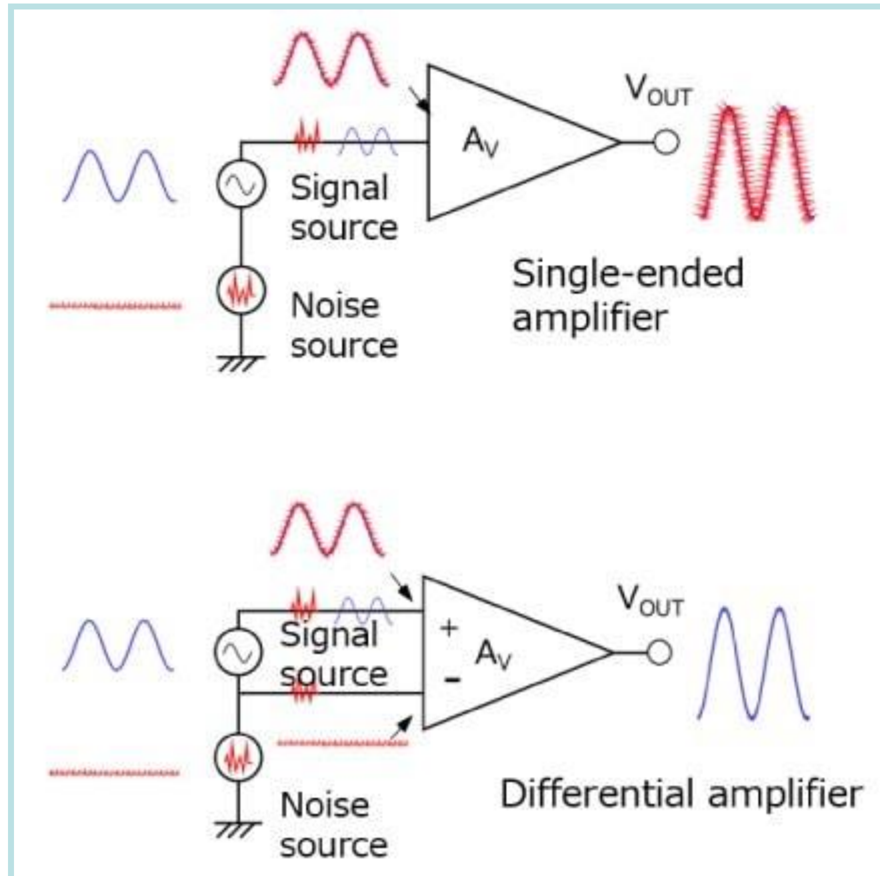


Enables substantial amplification of an input signal
Enables elimination of noise from an input signal

https://www.electrical4u.com/applications-of-op-amp/
https://www.elprocus.com/op-amp-applications-in-electronics/

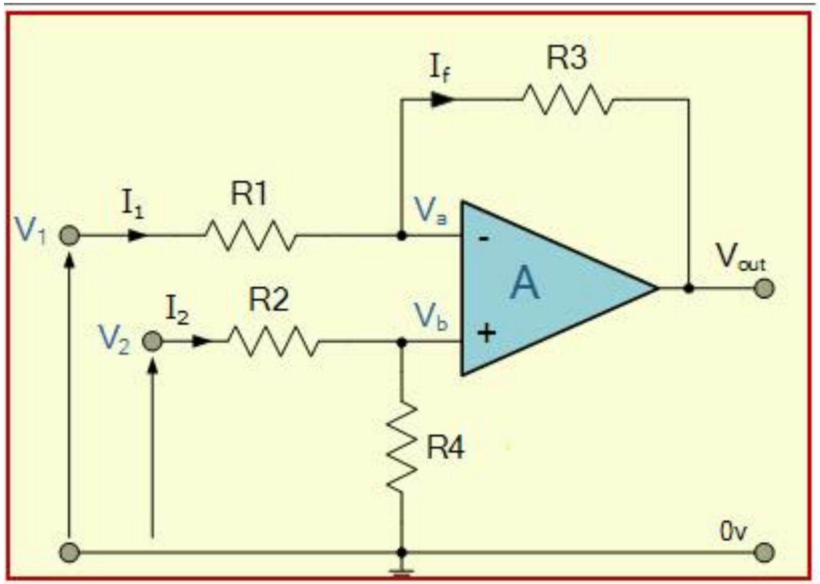
Applications of using op-amps:

- Differential amplifiers (Subtractor)
- Inverting amplifiers
- Non-inverting amplifiers
- Voltage followers
- Summing amplifiers (Adder)



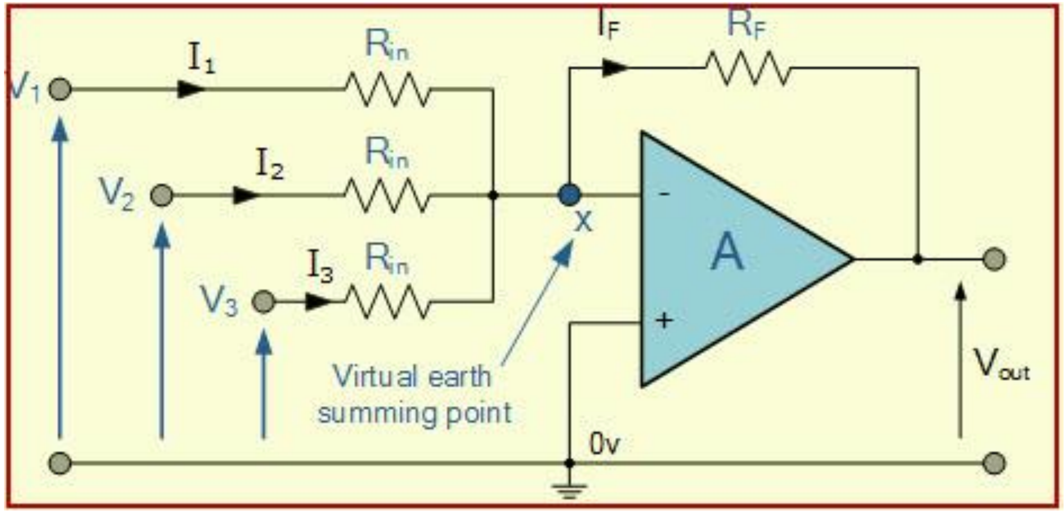
Differential Amplifiers

Differential amplifier amplifies the difference between two voltages, making this type of operational amplifier circuit a subtractor unlike a summing amplifier which adds or sums together the input voltages.



Summing Amplifier

Summing amplifier is one of the application of inverting operational amplifier, but if we add another input resistor equal in values to the other input resistor, Rin we end up another op amp is called as summing amplifier. Summing amplifier can be used to perform digital to analog conversion.



MOSFET

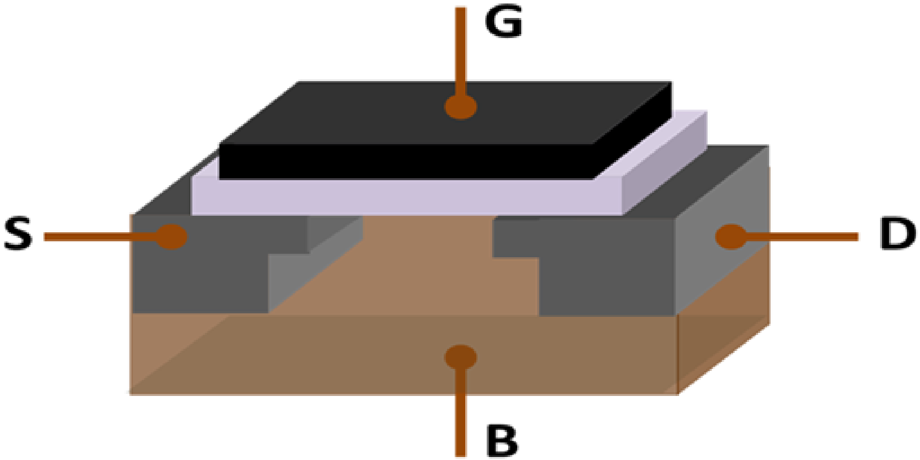
MOSFET's are unipolar conduction devices, conduction with one type of charge carrier, like a FET, but unlike a BJT.

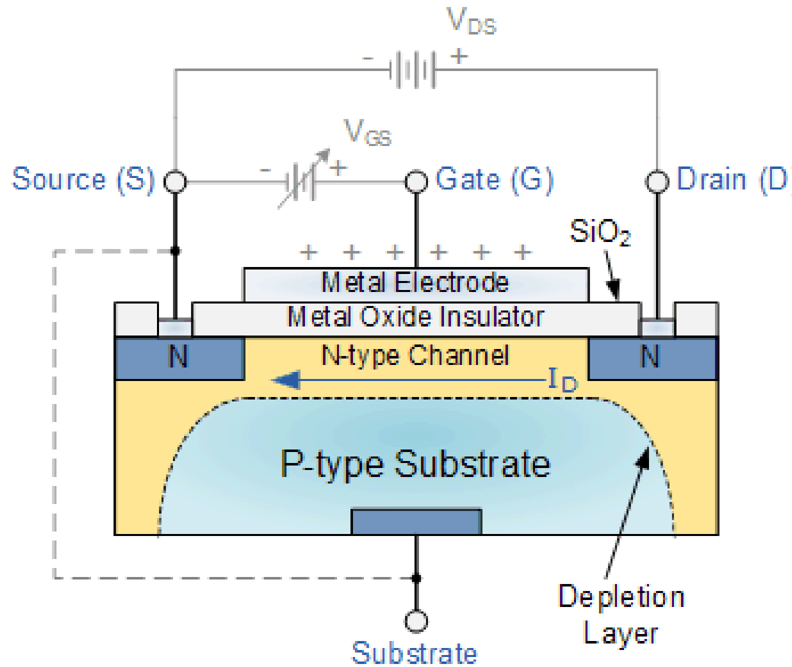
Depletion Type – the transistor requires the Gate-Source voltage, (V_{GS}) to switch the device "OFF". The depletion mode MOSFET is **equivalent to a "Normally Closed" switch**.

Enhancement Type – the transistor requires a Gate-Source voltage, (V_{GS}) to switch the device "ON". The enhancement mode MOSFET is **equivalent to a "Normally Open" switch**.

If the circuit symbol has a solid unbroken line then this represents a "depletion" (normally closed) type MOSFET as drain current can flow with zero gate potential.

MOSFET's are ideal for use as electronic switches or as common-source amplifiers as their power consumption is very small. Typical applications for metal oxide semiconductor field effect transistors are in Microprocessors, Memories, Calculators and Logic CMOS Gates etc.



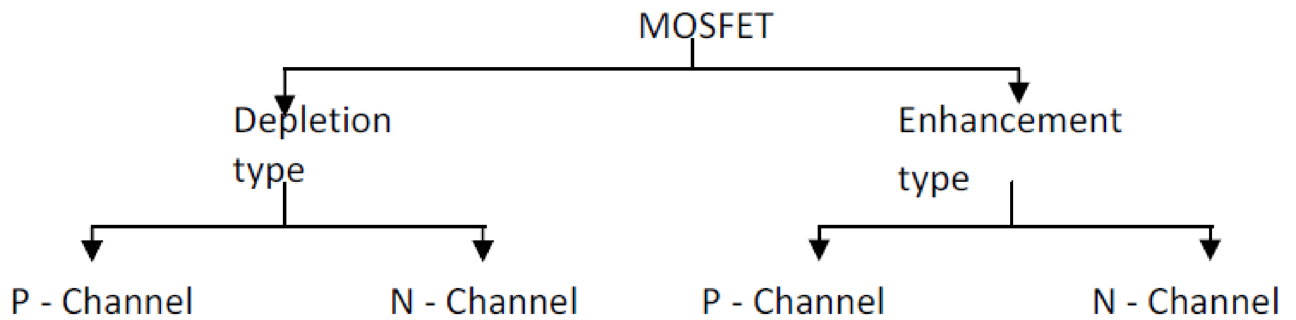


The MOSFET works by electronically varying the width of a channel along which charge carriers flow (electrons or holes). The charge carriers enter the channel at source and exit via the drain. The width of the channel is controlled by the voltage on an electrode is called gate which is located between source and drain. It is insulated from the channel near an extremely thin layer of metal oxide.

The body of the MOSFET is frequently connected to the source terminal so making it a three terminal device like field effect transistor

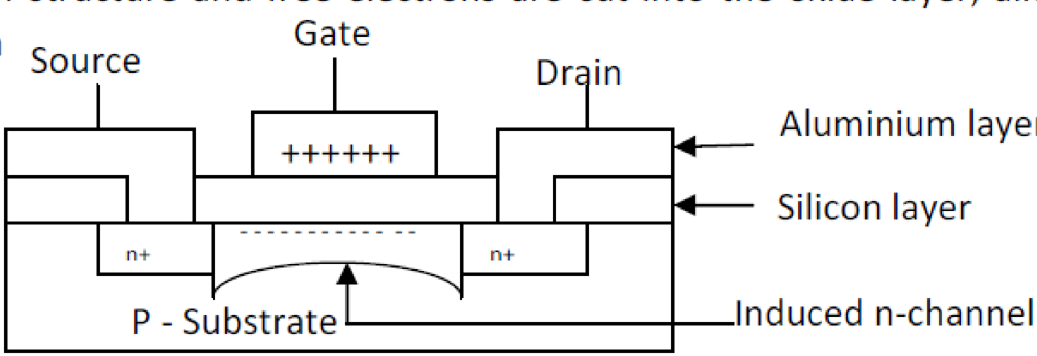
MOSFET

The MOSFET is a voltage controlled device that works on the depletion capacitor concept. In this a layer of silicon dioxide is grown on the surface, which act as a dielectric media between gate and the channel. Based on the channel created between the, the MOSFET is broadly divided as shown.



It has got three terminals, Gate, Drain and source

N-channel MOSFET consists of highly doped 'P' type substrate into which two highly doped N regions are diffused. These 'N' regions act as source and drain. A thin layer of insulating silicon dioxide (SiO_2) is grown over the surface of structure and free electrons are cut into the oxide layer, allowing to move between source and drain



The metal area is overlaid on the entire oxide layer and metal contacts are made to source and drain. The SiO_2 layer insulates the gate from the channel due to which a negligible gate current flows even if the biasing is applied to gate. So no PN junction is existing in MOSFET and hence known as Insulated Gate Field Effect Transistor.

N-channel MOSFET

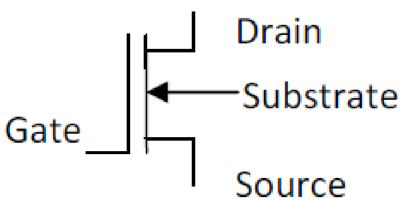
The drain and source are heavily doped n+ region and the substrate is p-type. The current flows due to the flow of negatively charged electrons, also known as n-channel MOSFET.

When we apply the positive gate voltage the holes present beneath the oxide layer experience repulsive force and the holes are pushed downwards in to the bound negative charges which are associated with the acceptor atoms (**density of negative charges increases under oxide layer**). The positive gate voltage also attracts electrons from n+ source and drain region in to the channel thus an electron reach channel is formed.

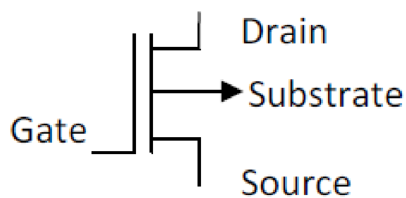
Depletion Type:

The depletion type MOSFET can be operated in two different modes: a. depletion mode b. enhancement mode

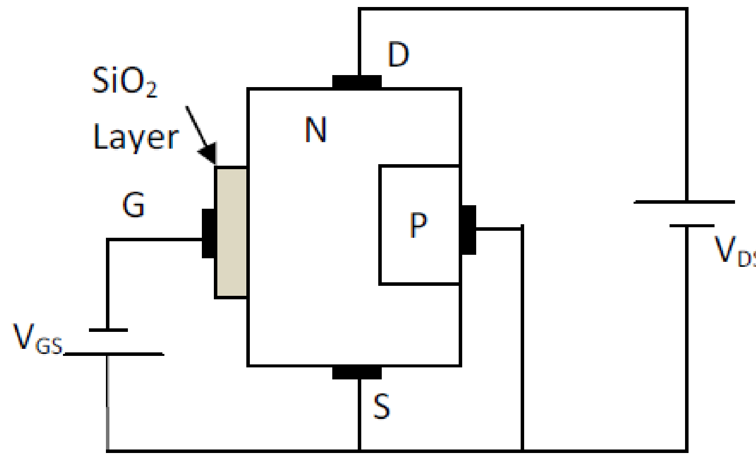
Circuit symbol and Circuit



N - Channel

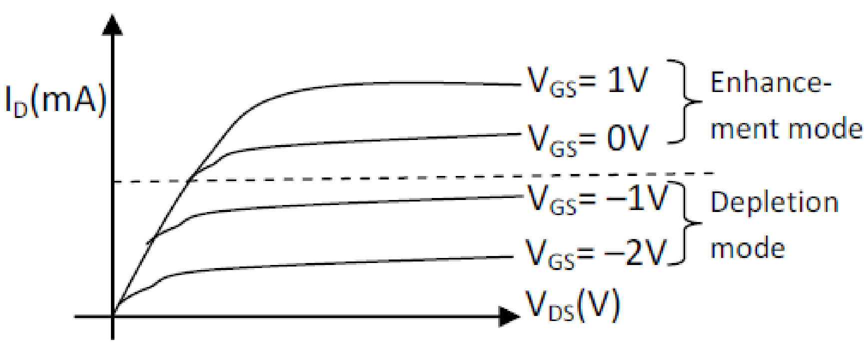


P - Channel

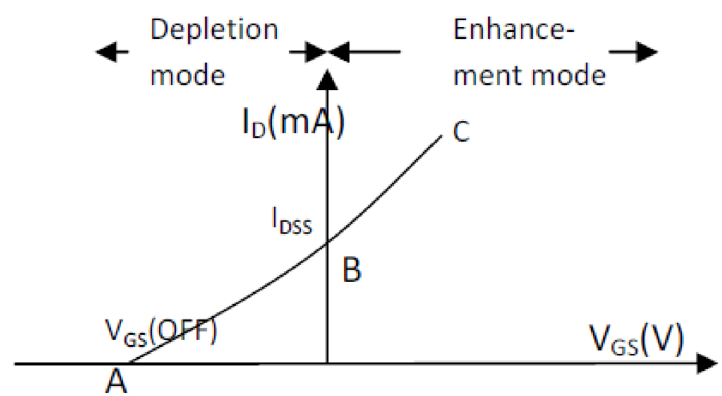


The device operates in this depletion mode, when the gate voltage is negative.

Drain Characteristics of Depletion type MOSFET



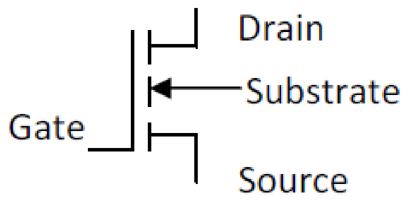
Drain Characteristics



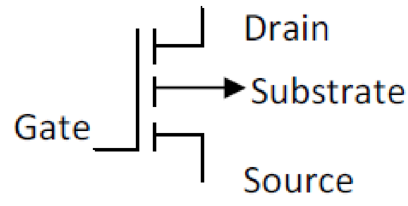
Transfer Characteristics

Enhancement Type:

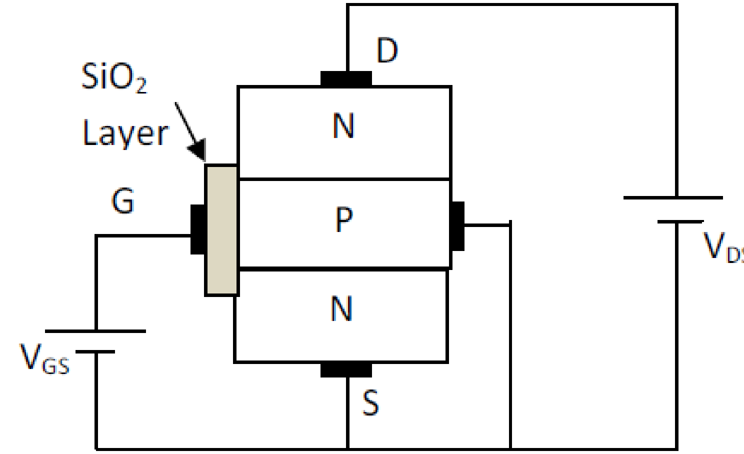
Circuit symbol and Circuit



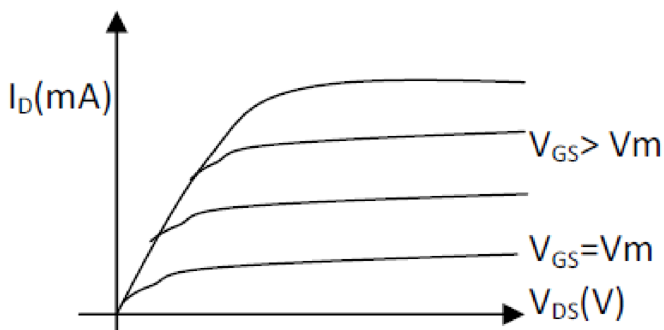
N – Channel



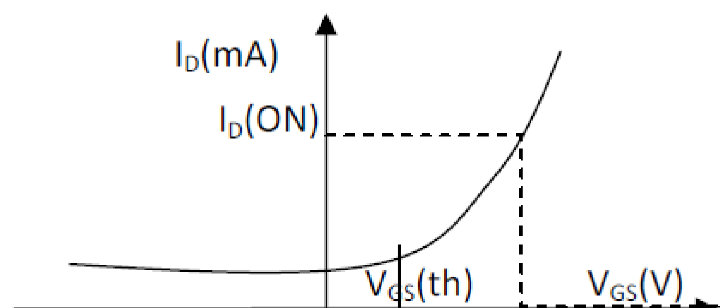
P – Channel



Drain characteristics of Enhancement type MOSFET



Drain Characteristics



Transfer Characteristics

Instructions:

Start time: 3.40 PM   End time: 5.30 PM

S. No	Component	Maximum Marks
1.	a) Workout manual calculation b) simulation/hardware circuit diagrams c) Tabulation of readings (during experiment) Write whichever is applicable	20
2.	List out software tools/hardware components	5
3.	Conduct simulation/hardware experiment	25