LOVE YOUR SEMICONDUCTUR

DASRI . AZMAN . SUHAIMI

LOVE YOUR SEMICONDUCTOR DEVICES

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Love Your Semiconductor Devices

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PREFACE

LOVE YOUR SEMICONDUCTOR DEVICES introduces readers to the basic electronic theories and devices. It covers the fundamentals of electronic devices which includes diodes, bipolar junction transistors and field effect transistors. The content encompasses devices structure to biasing basic applications.

In advance, the readers will be able to apply the theoretical characteristics and electrical properties of semiconductor by using appropriate measuring operations and theorem. At the same time readers can construct the various applications of semiconductor devices circuit by using schematic diagrams.

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4.0 FIELD EFFECT TRANSISTORS (FET)

5.0 INTRODUCTION TO OTHER ELECTRONIC COMPONENTS

REFERENCES

CHAPTER 1

INTRODUCTION TO SEMICONDUCTOR

1.1 What would you get?

- Remember characteristics and electrical properties of Semiconductors
- Understand characteristic of P-N junction and its reaction towards voltage biasing

1.2 Where Semiconductor is Used?

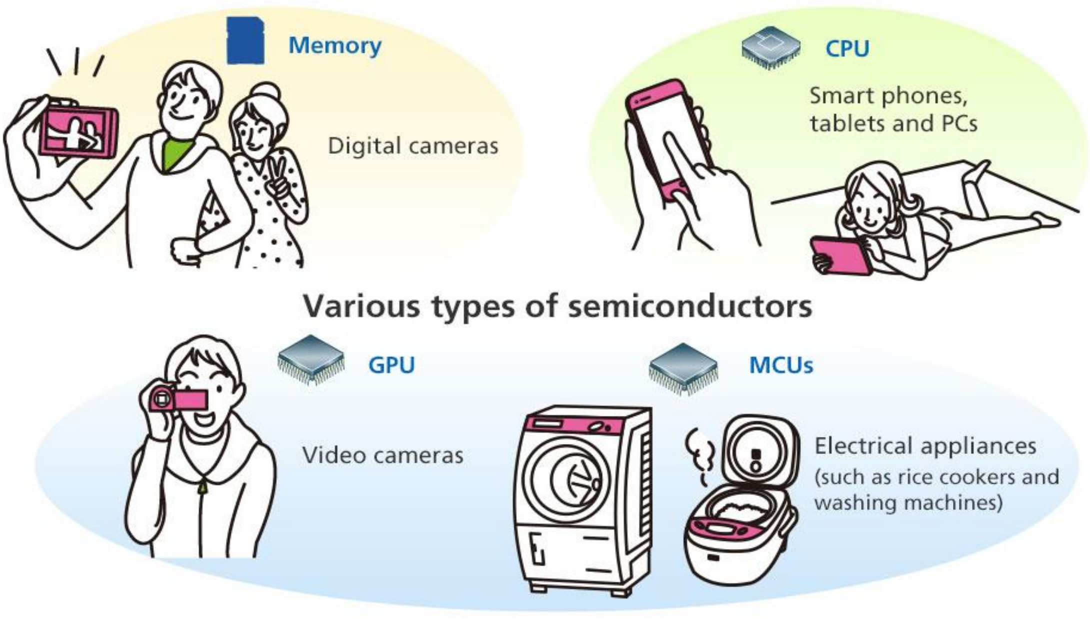


Figure 1.1: Various Types of Semiconductors

1.3 Atomic Theory

Atomic theory is the scientific theory that matter is composed of particles called atoms. The concept that matter is composed of discrete particles is an ancient idea but gained scientific credence in the 18th and 19th centuries when scientists found it could explain the behaviors of gases and how chemical elements reacted with each other. By the end of the 19th century, atomic theory had gained widespread acceptance in the scientific community.

1.3.1 Bohr's Theory

- Positively charged nucleus surrounded by electrons that travel in circular orbits around the nucleus.
- The protons are positively charged particles and the electrons are negatively charged particles.
- The outermost orbit is the ***valence*** orbit.

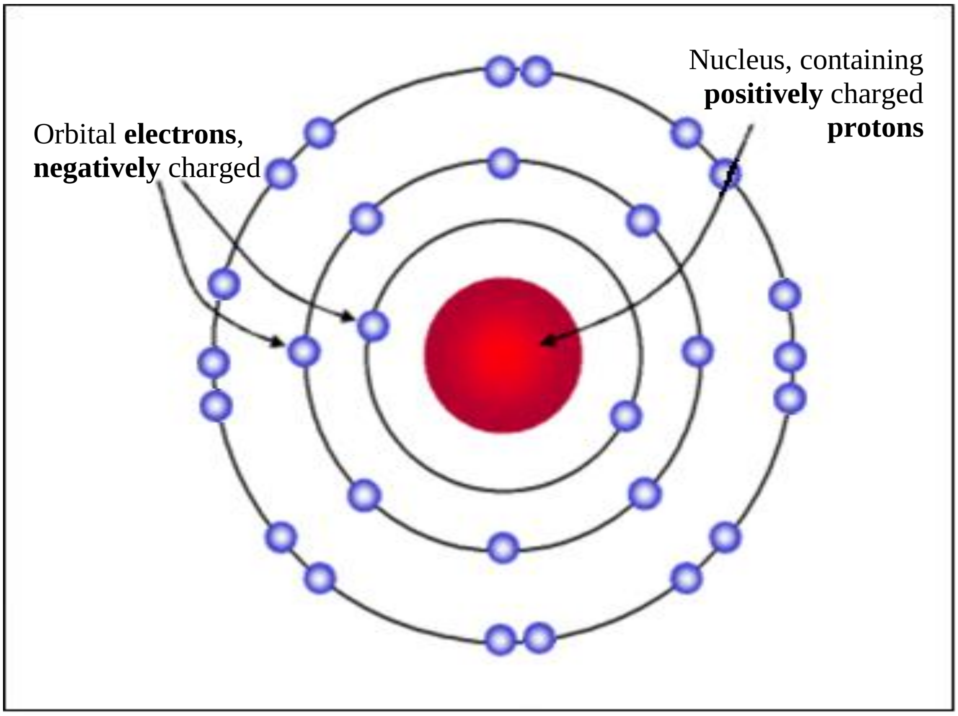


Figure 1.2: Bohr's Theory

1.3.2 Atomic Structure

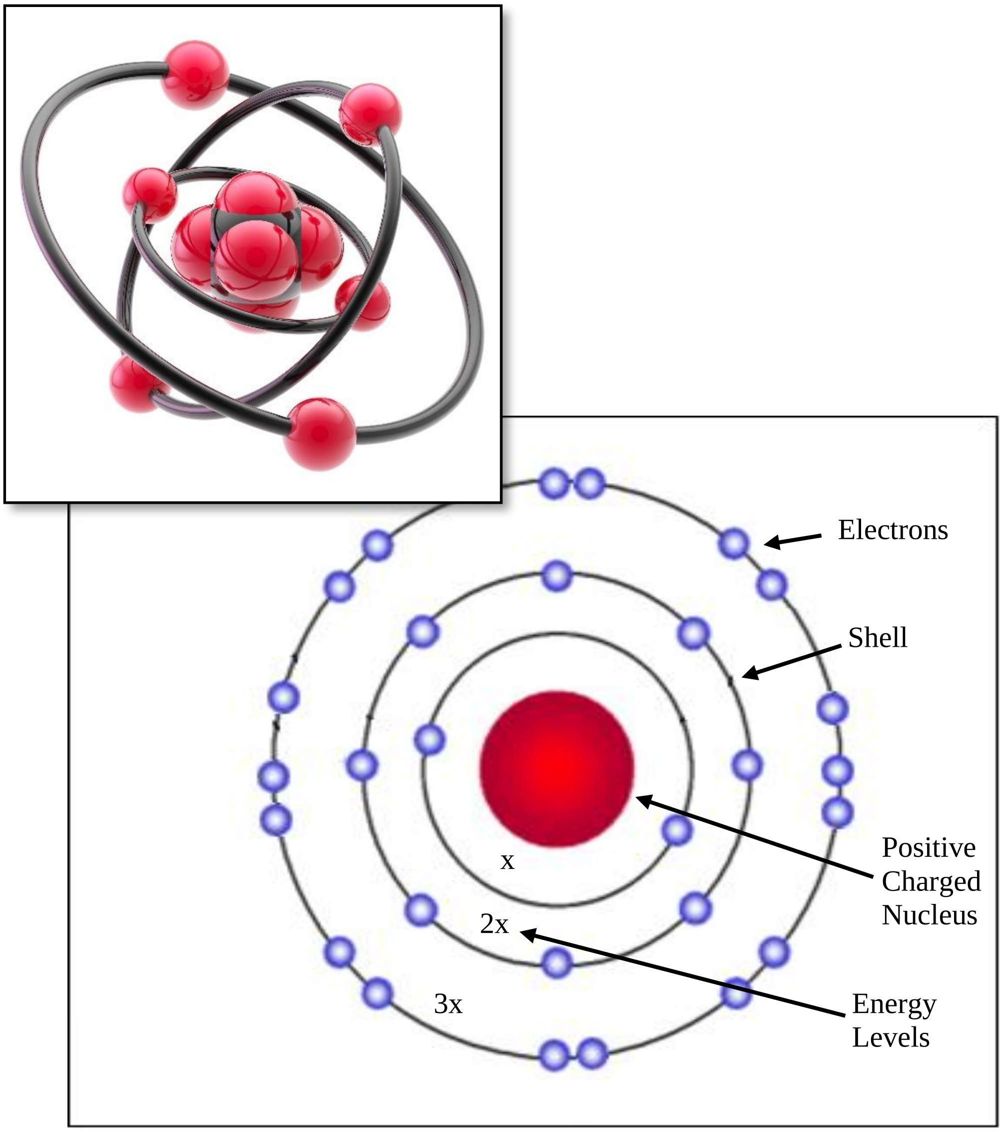


Figure 1.3: Atomic Structure

- Valence band electrons are the furthest from the nucleus and have higher energy levels than electrons in lower orbits.

- The orbit paths of the electrons surrounding the nucleus are called **shell.**

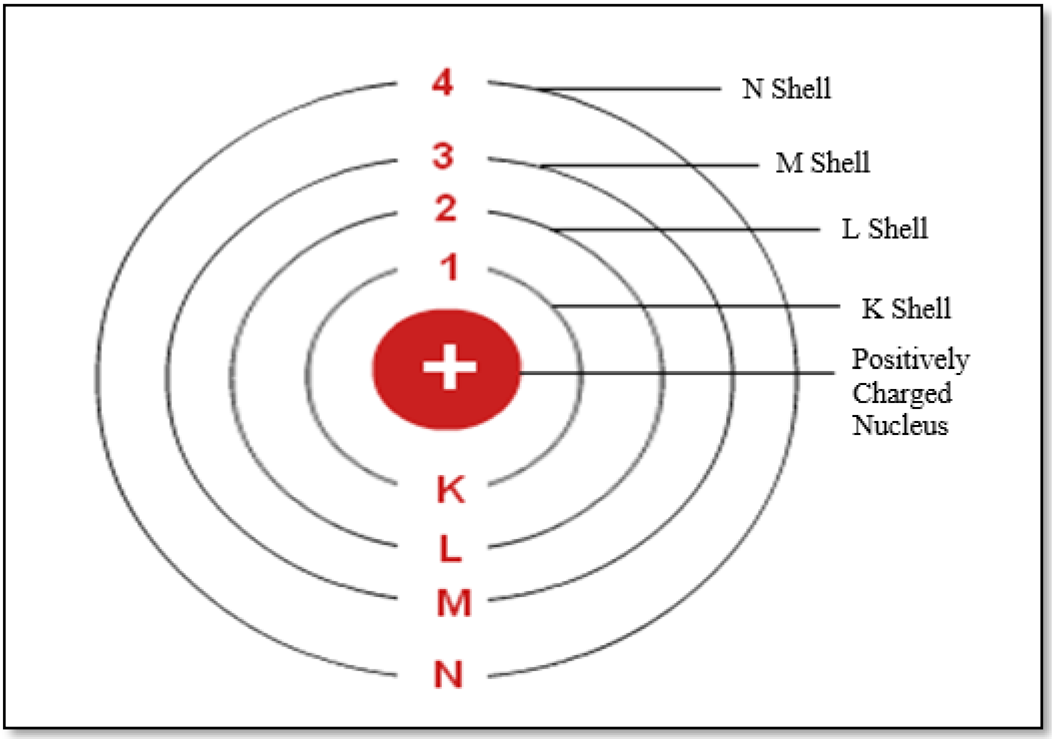


Figure 1.4: Shell Representation

- Each shell is represented by the letters K, L, M, N, etc.
- The max number of electrons in any shell is given by relation (**2 x** $\boldsymbol{n^2}$), where *n* is the order of the orbit counted from nucleus.
- The valence shell determines the ability of material to conduct current.

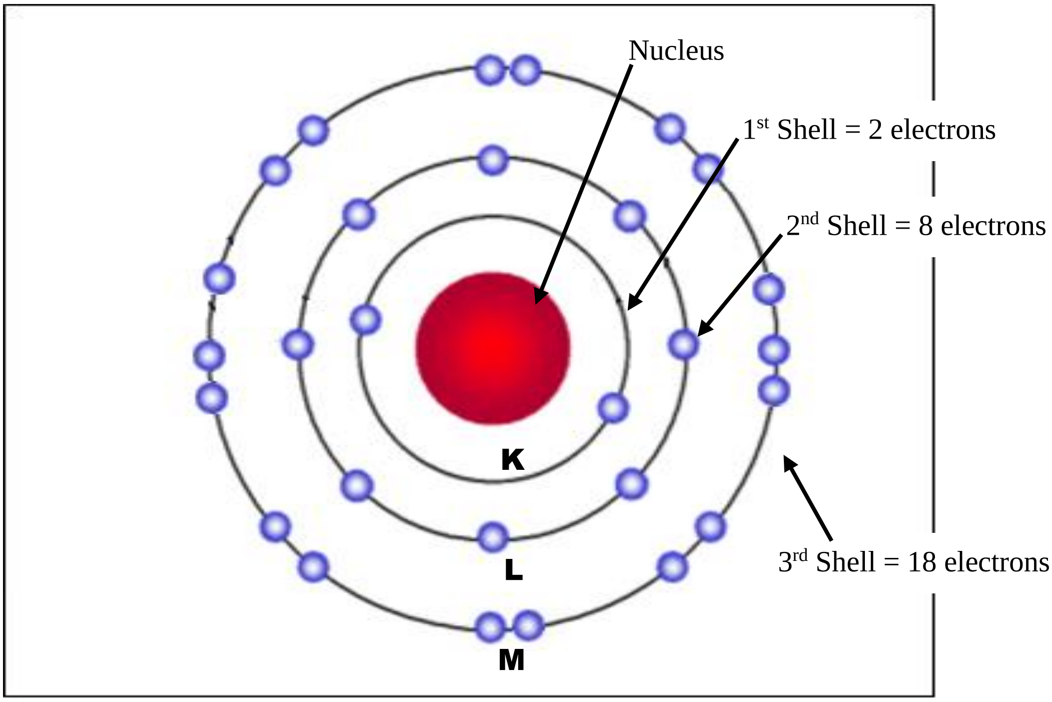


Figure 1.5: Number of Electron(s) in Shell

- K (1^{st} Shell) $= 2 \times 1^2 = 2$
- L (2^{nd} Shell) $= 2 \times 2^2 = 8$
- M (3^{rd} Shell) $= 2 \times 3^2 = 18$
- N (4^{th} Shell) $= 2 \times 4^2 = 32$
- O (5^{th} Shell) $= 2 \times 5^2 = 50$

$$Number\ of\ electrons = 2 \times n^2$$

Table 1.1: Material *(in terms of electrical properties)*

Electron Valence	*Electric Properties*	*Characteristic*	*Examples*
1-3	Conductor	• material that allows the flow current. • with a bit of valence electrons, electrons available to move from one atom to 1 other atoms.	• Aluminium • Copper • Gold • Silver
5-8	Insulator	• material that does not allow the flow an electric current through it. • has a very high resistance and no current can flow through it. • atomic Vales tend to accept electrons from other atoms to fill the valence layer and make it as stable atoms.	• Glass • Wood • Sulfur • Rubber
4	Semiconductor	• material that has properties between conductors and insulators. • not easy to remove / receiving valence electrons from other atoms.	• Silicon • Germanium • Carbon

1.4 The Characteristics and Electrical Properties of Semiconductor

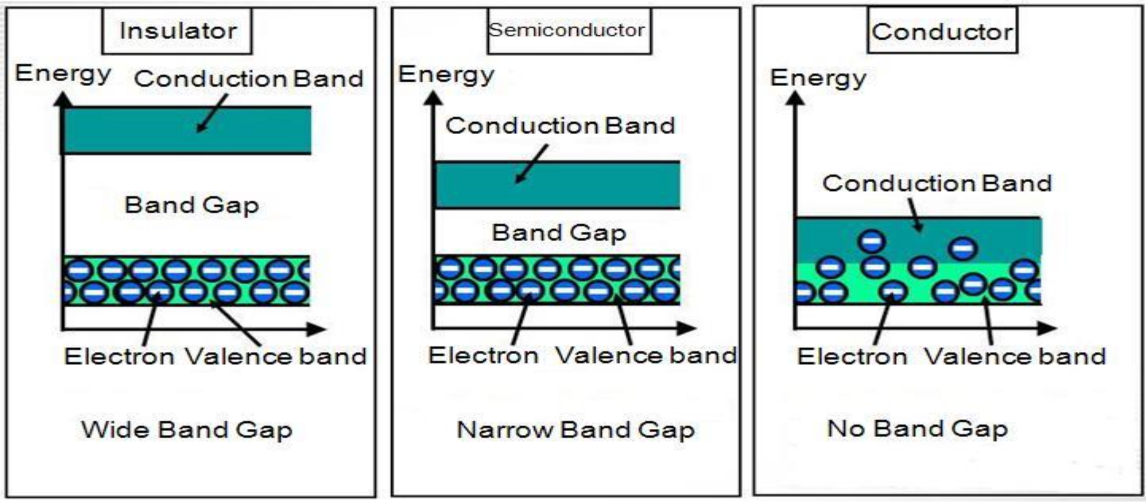


Figure 1.6: Energy Bands

- The size of the band gap determines the electrical conductivity of a given material. Insulators have the largest band gap and conductors have no band gap since the conduction and valence band overlap and there is free movement of electrons.

Figure 1.7: Semiconductor Material

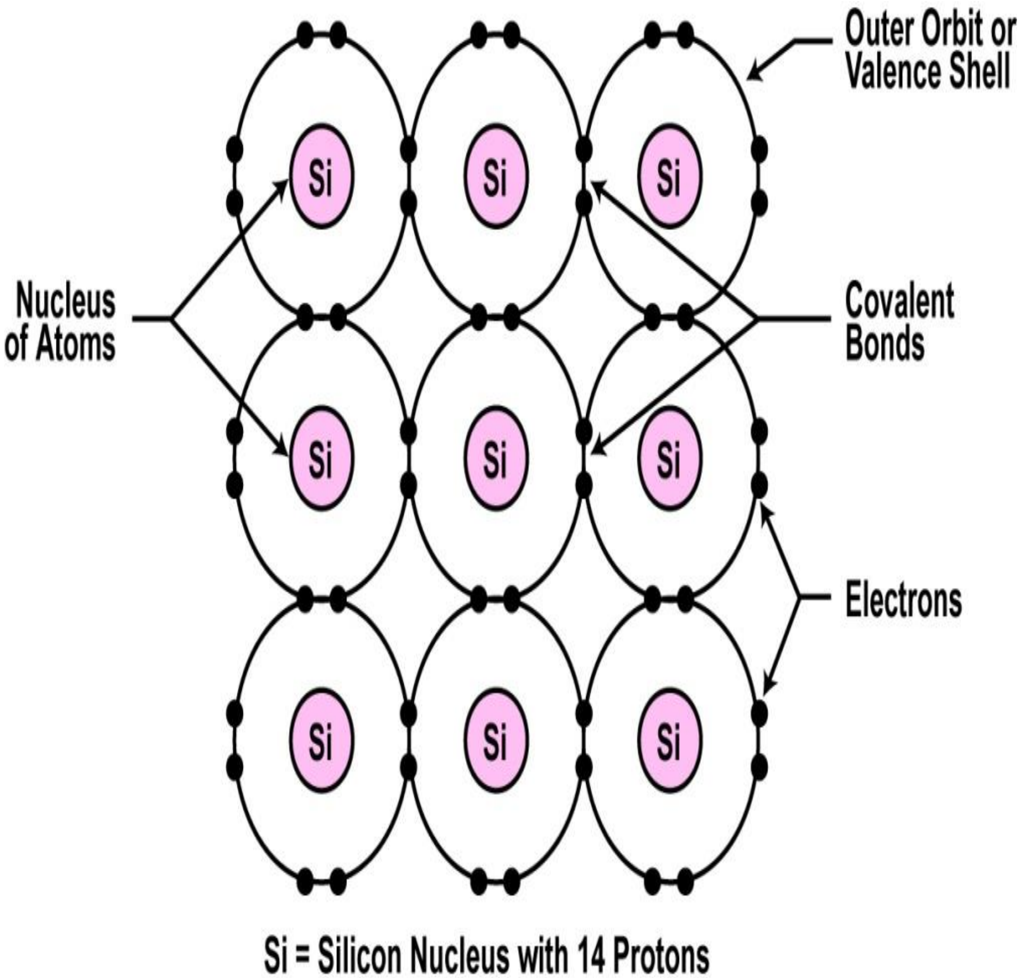


Figure 1.8: Crystal Lattice Structure

- The atoms link together with one another sharing their outer electrons.
- These links are called **covalent bonds.**
- Bond is relatively strong and stable because it has 8 valence electrons.
- Disturbing factor stability:
    - × Heat
    - × Temperature rise
    - × Doping (absorption)
    - × Potential different

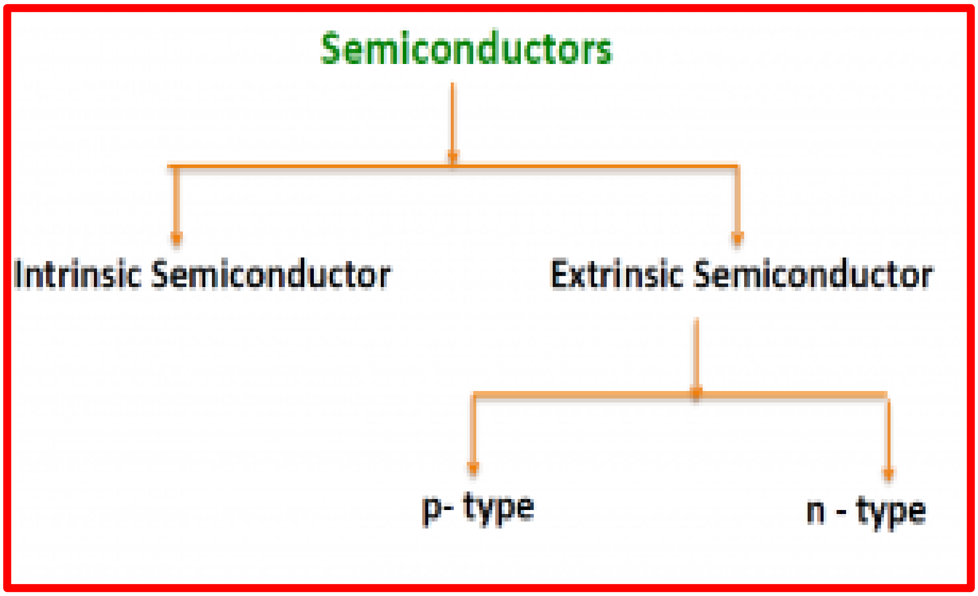


Figure 1.9: Types of Semiconductors

1.4.1 Intrinsic Semiconductors

- A semiconductor in an extremely pure form is known as intrinsic semiconductor. The silicon (Si) and germanium (Ge) are two important intrinsic semiconductor.
- Both silicon and germanium have four valence band electrons, and so they are referred to as ***tetravalent*** atoms.

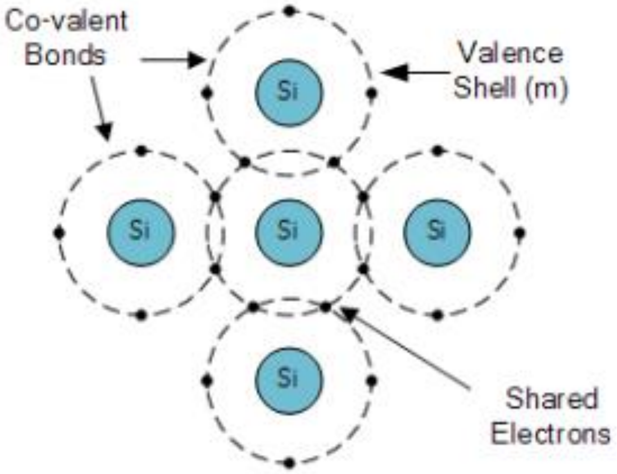


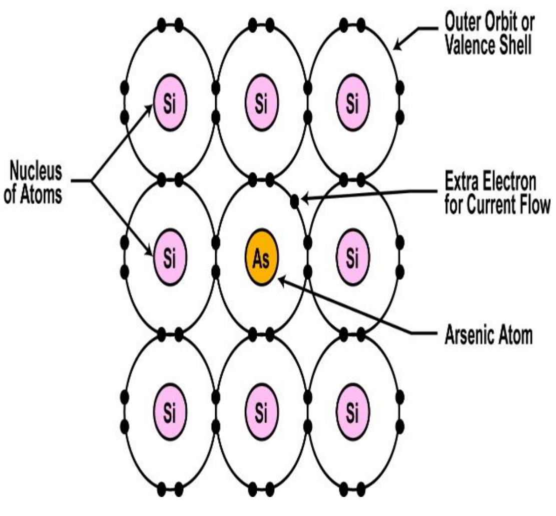
Figure 1.10: Silicon Crystal Lattice

1.4.2 Extrinsic Semiconductors

- An extrinsic semiconductor is a semiconductor **doped** by a specific impurity.
- The process of adding impurity to an intrinsic or pure semiconductor is known as **doping.**

Table 1.2: N-TYPE vs P-TYPE Semiconductor

N-TYPE SEMICONDUCTOR	P-TYPE SEMICONDUCTOR
A **pentavalent** impurity like arsenic, phosphorous is added (**doping**) with pure semiconductor like silicon or germanium.	A **trivalent** impurity such as boron is added (doping) to an intrinsic or pure semiconductor (silicon or germanium)
The one electron left over for each arsenic atom becomes available to conduct current flow.	One electron is missing from the bond and referred to as a **hole**. The hole assumes a positive charge so it can attract electrons from some other source.
Such impurities which donate free electrons to the semiconductor crystal are known as ***donor impurities.***	Such impurities which accept electrons to the semiconductor crystal are known as acceptor impurities.
majority current carriers - Electron	**majority current carriers - Hole**
minority current carriers - Hole	**minority current carriers - Electron**



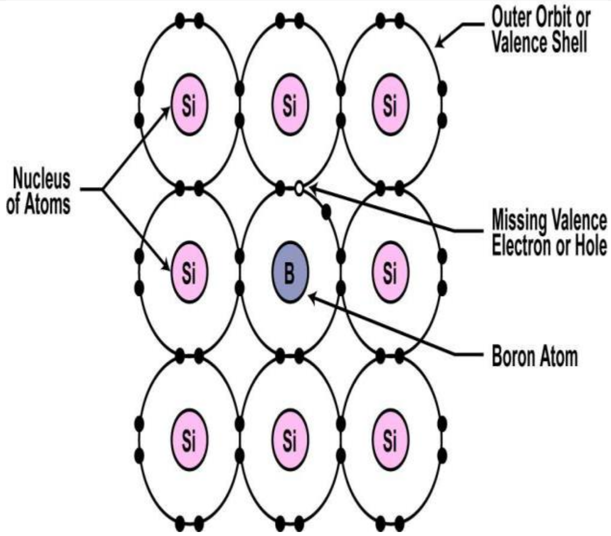
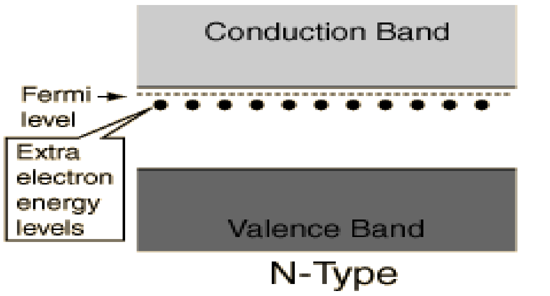
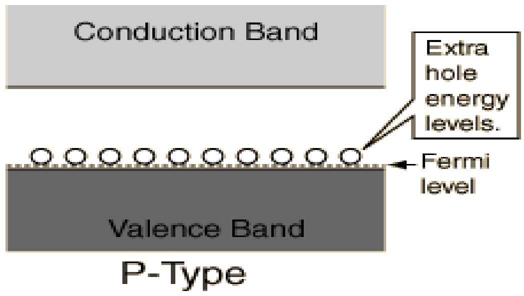


Table 1.3: Energy Levels

	
The addition of donor impurities contributes electron energy levels high in the semiconductor band gap so that electrons can be easily excited into the conduction band. This shifts the effective Fermi level to a point about halfway between the donor levels and the conduction band.	*The addition of acceptor impurities contributes hole levels low in the semiconductor band gap so that electrons can be easily excited from the valence band into these levels, leaving mobile holes in the valence band. This shifts the effective Fermi level to a point about halfway between the acceptor levels and the valence band.*

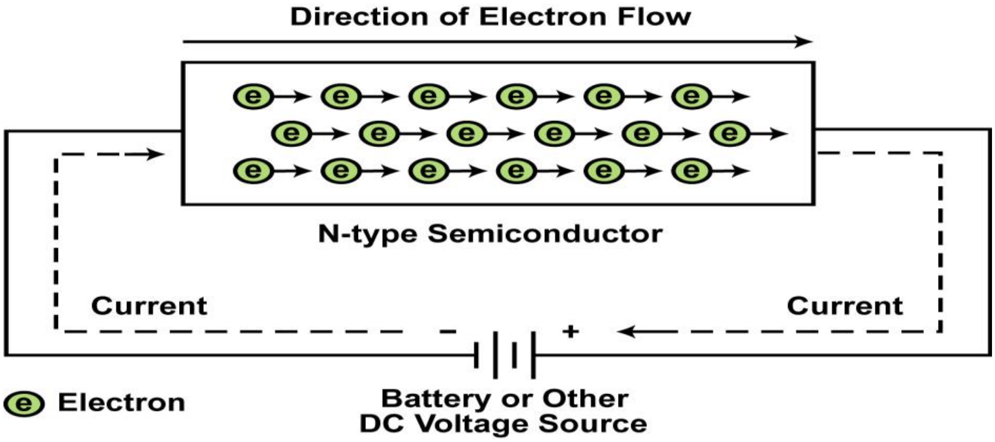


Figure 1.11: N-type Conductivity

- This type of conductivity is called ‘negative’ or N-type conductivity because the current flow through the crystal is due to free electrons.

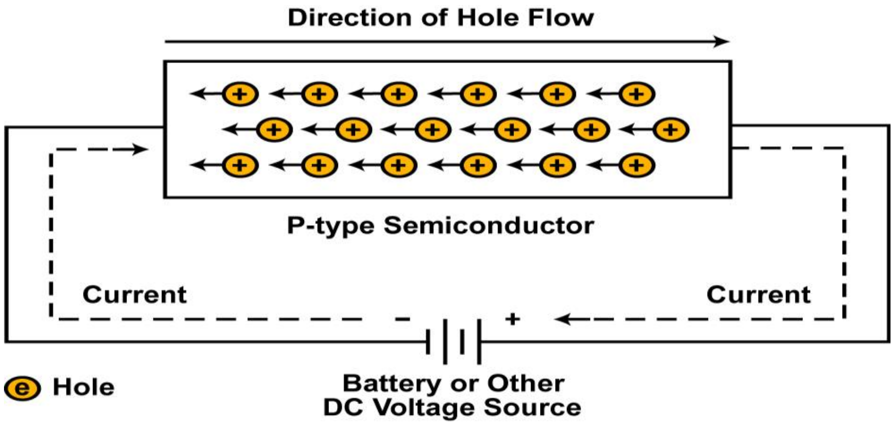


Figure 1.12: P-type Conductivity

- This type of conductivity is called 'positive' or P-type conductivity because the current flow through the crystal is due to holes.

1.5 The Characteristics of P-N Junction and Its Reaction Towards Voltage Biasing

- A PN junction is formed from a piece of semiconductor by diffusing P-type material to one half side and N-type material to other half side.
- The plane dividing the two zones is known as a **junction**.

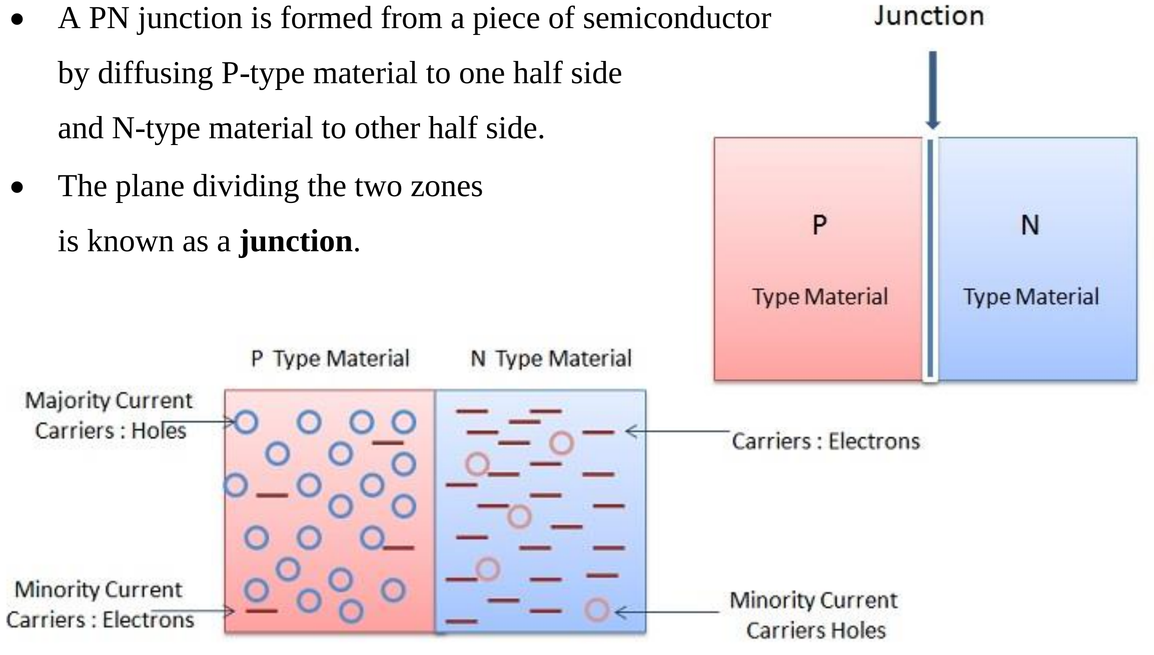


Figure 1.13: PN Junction

- In N type material, the electrons move readily across the junction to fill holes in the P material. This act is commonly called **diffusion**.
- Generally, the current carriers which are near to the junction only takes part in the process of diffusion.
- Electrons departing the N material cause positive ions to be generated in their place. While entering the P material to fill holes, negative ions are created by these electrons.

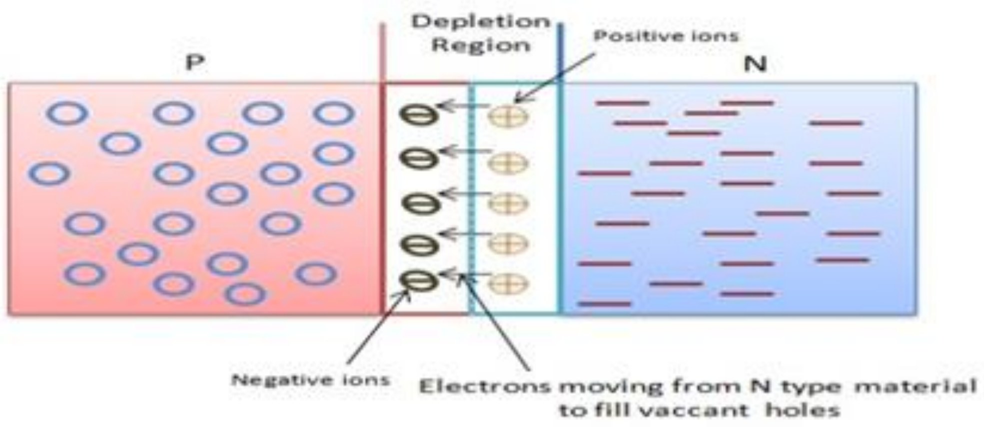


Figure 1.14: Diffusion Process

- Combination between the electrons and holes around the junction will cause an area near the junction to be neutral.
- Crossing of the electron will eventually stop, it called the **depletion region** where the area does not have a current flow. It acts as resistance, but its value is very small.
- Combine with positive ions and negative ion it will show result in a potential difference between the two materials.
- Voltage potential difference is called the **barrier voltage/ threshold voltage**.
- The value of barrier voltage is small.
  (Ge semiconductor ≈ 0.3V
  Si semiconductor ≈ 0.7V).

1.5.1 Forward Biased

- Definition:
    - Positive terminal of the voltage supply is connected to the P-type and negative terminal to the N-type.

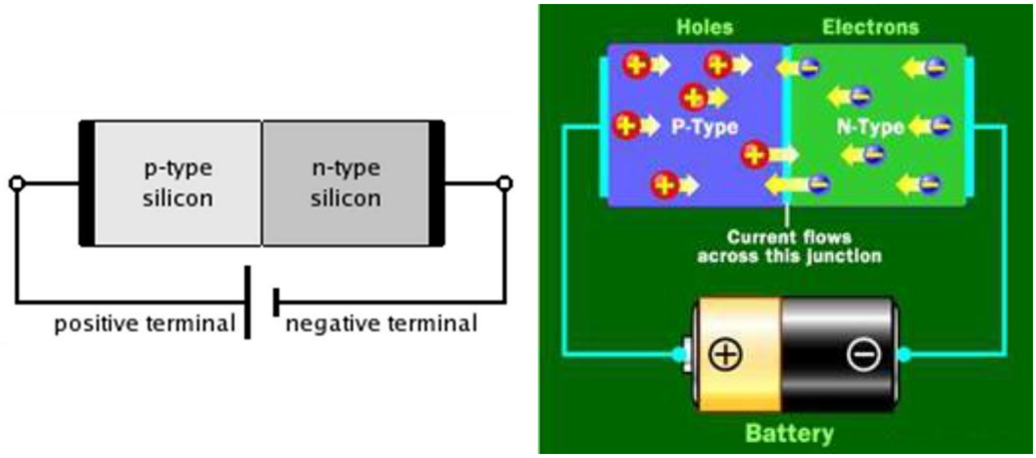


Figure 1.15: Forward Biased Positive and Negative Terminals

- Electrons in N type material will move forward to the junction that cause the **depletion region become smaller** and the **resistant across it will decrease.**

- When forward bias increased over the value of barrier voltage (0.3V for Ge semiconductor and 0.7V for Si semiconductor), the resistance for joined P-N decreased so that the electrons can move across the joined region and try to move to the positive supply voltage.

- If the value for forward-bias voltage increased, the value of current will increase.

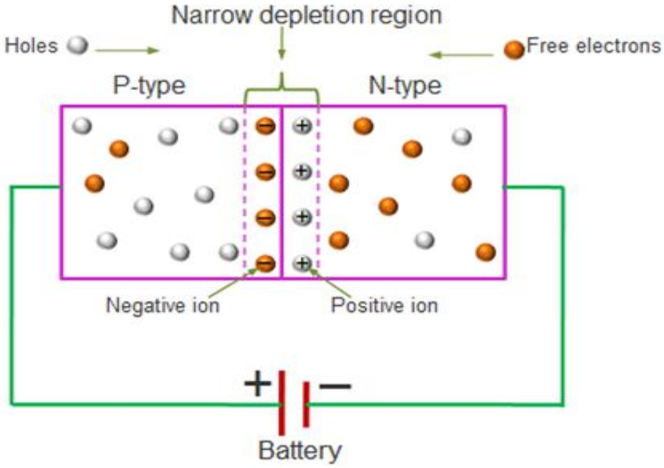
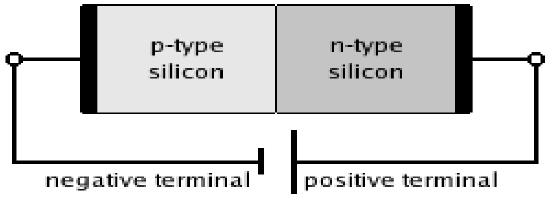


Figure 1.16: Forward Biased

1.5.2 Reverse Biased

- Definition:
  - Positive terminal of the voltage supply is connected to the N-type and negative terminal to the P-type.



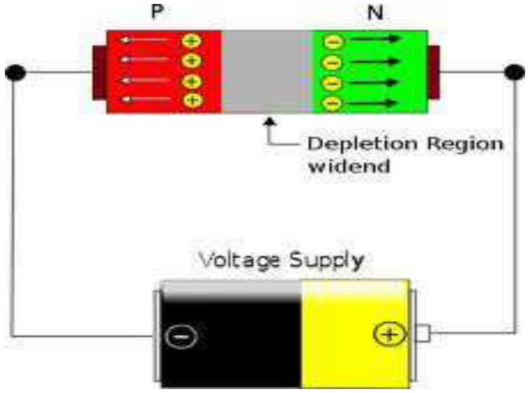


Figure 1.17: Reverse Biased Positive and Negative Terminals

- Electrons in N type material is attracted to the +ve terminal of voltage supply (VS). This will cause the **depletion region become larger (widen)**.
- The resistant become **higher**.
- Due to that, there is **<u>no current flow</u>** across the joint region.

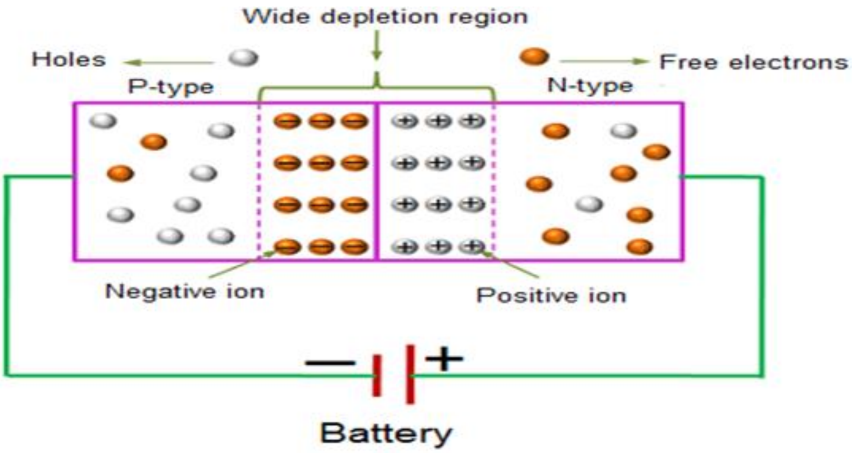


Figure 1.18: Reverse Biased

1.6 Effect When a P-N Junction Is Supplied

Table 1.4: The Effect When a P-N Junction Is Supplied

Effect	Forward biased (fb)	Reverse biased
Area of depletion region	When P-N junction is supplied with FB voltage the area of depletion region become **smaller/thinner/narrow**	When P-N junction is supplied with RB voltage the area of depletion region become **larger**
Junction resistance	When P-N junction is supplied with FB voltage the junction resistance become **low**	When P-N junction is supplied with RB voltage the junction resistance become **high**
Current flow (including leakage current)	In ideal diode concept, during FB, diode as a closed switch (ON) because empty resistance and do not have voltage fall. **Current can flow.**	during RB diode as a open namely infinity resistance and do not have a little leakage current. **Current cannot flow.**

1.7 Breakdown Occurs When P-N Junction Is Reversed Biased

- When a reverse bias is applied to a P-N junction (diode), the electric field in the depletion region increases.
- The electric field may become large enough that covalent bonds are broken and electron hole pairs are created.
- Electrons are swept into the n-region and holes are swept into the p-region by the electric field, generating a large reverse current.

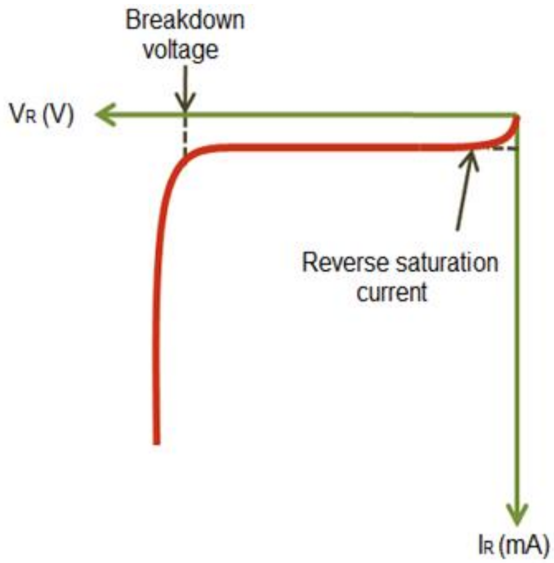


Figure 1.19: Reverse Characteristic

1.8 Leakage Current

- It is a minority current in materials.
- It exists when the reverse bias voltage is applied to the P-N joint.
- Electrons in P-type material is pushed by the reverse-bias voltage to the joint region and passed through it.
- Hence, a very small amount of current flow is produced.
- This current is known as leakage current or reverse current.
- This current is based on the temperature. The lower the temperature, the lower the value of current.

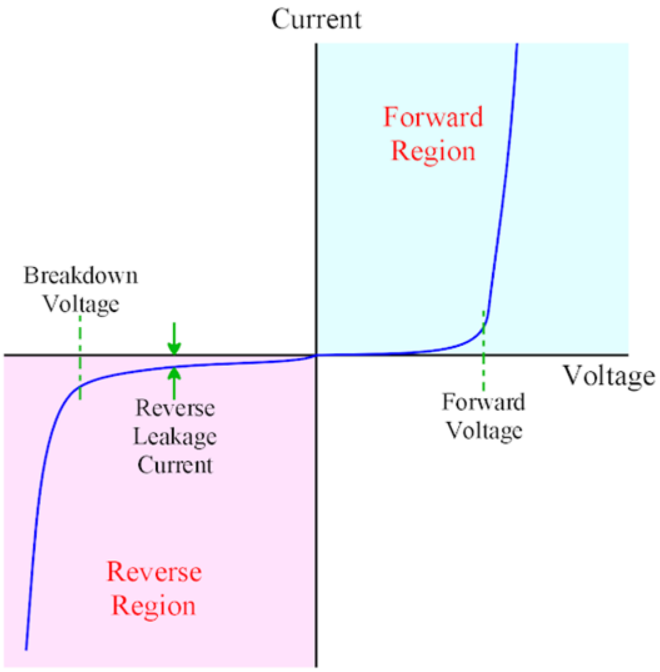


Figure 1.20: Leakage Current

CHAPTER 2

DIODES

2.1 What would you get?

- Remember characteristics of diode as a semiconductor
- Outline IV characteristic curve for silicon diode
- Apply diode in rectifiers circuits
- Construct application of the rectifiers
- Apply diode in other electronic circuits
- Understand the Zener diode
- Remember other type of diodes

2.2 Schematic Symbol and Physical Structure of a Diode

- Silicon (Si) and Germanium (Ge) are the two most common single elements that are used to make diodes.
- Diode allows electricity to flow in one direction only and blocks the flow in the opposite direction.
- The lead connected to the P-types is called Anode.
- The lead connected to the N-types is called Cathode.

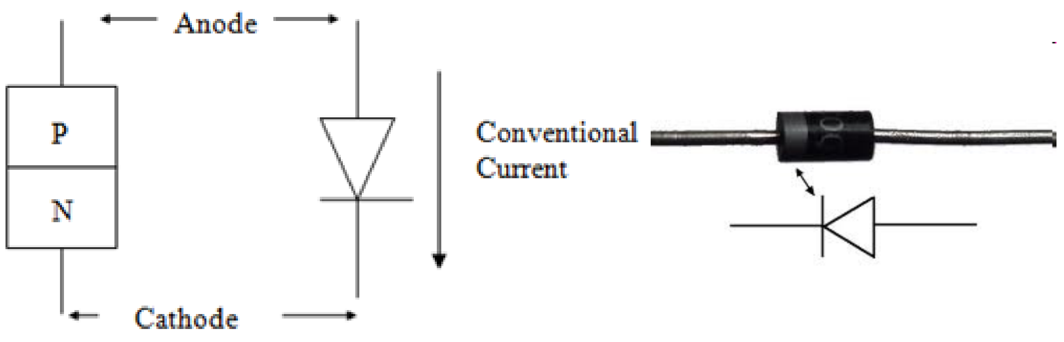


Figure 2.1: Diode

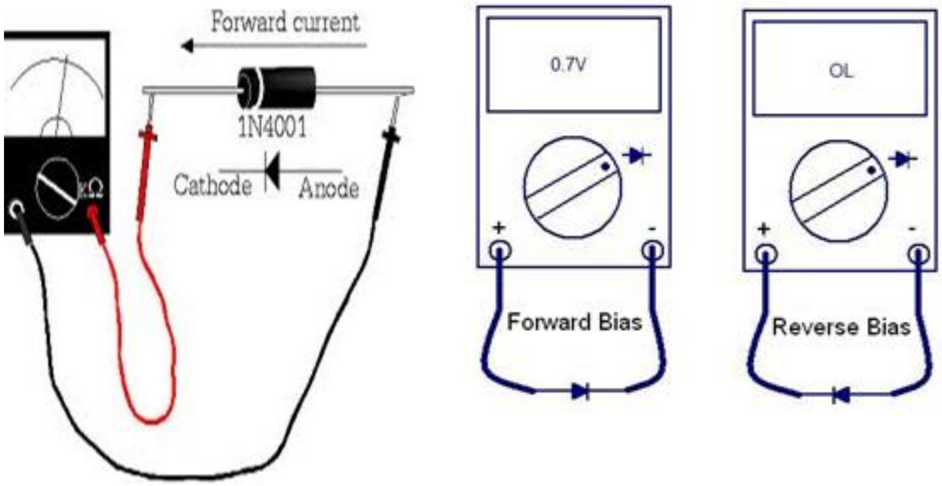


Figure 2.2: Testing Diode Using Digital Multimeter

2.3 Physics of a Diode

- When a diode is absent of a voltage source, the protons and electrons are aligned in their proper layers (as shown in Figure 2.3) by default.
- A region exists between the P-Type and N-Type layers called the *depletion zone.*
- The size of the depletion zone in a diode changes as voltage or the configuration of a circuit is changed.
- The depletion zone has some very interesting characteristics. Because it is made of a material similar to the P-Type and N-Type material, it has "holes" that electrons fill in to prevent positive charges from going through, thus preventing current from flowing. There is only one way the holes can be opened for positive charges to flow through and current to be produced.

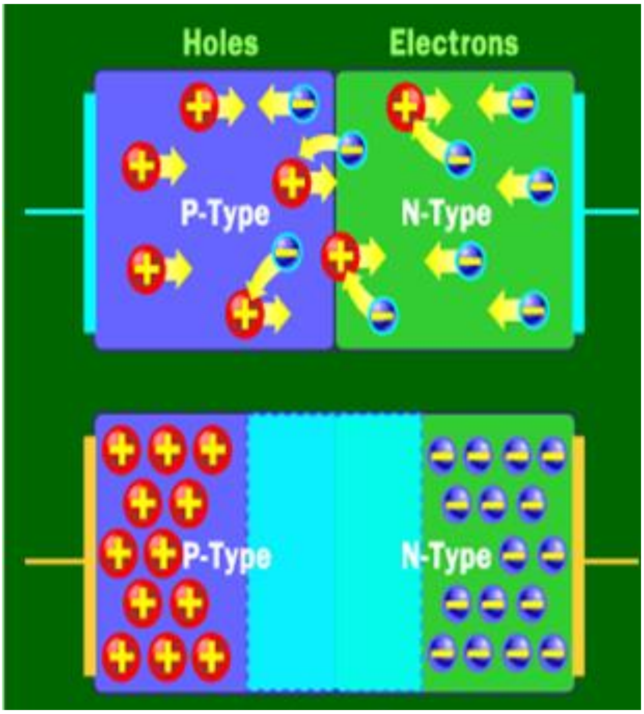


Figure 2.3: Depletion Zone

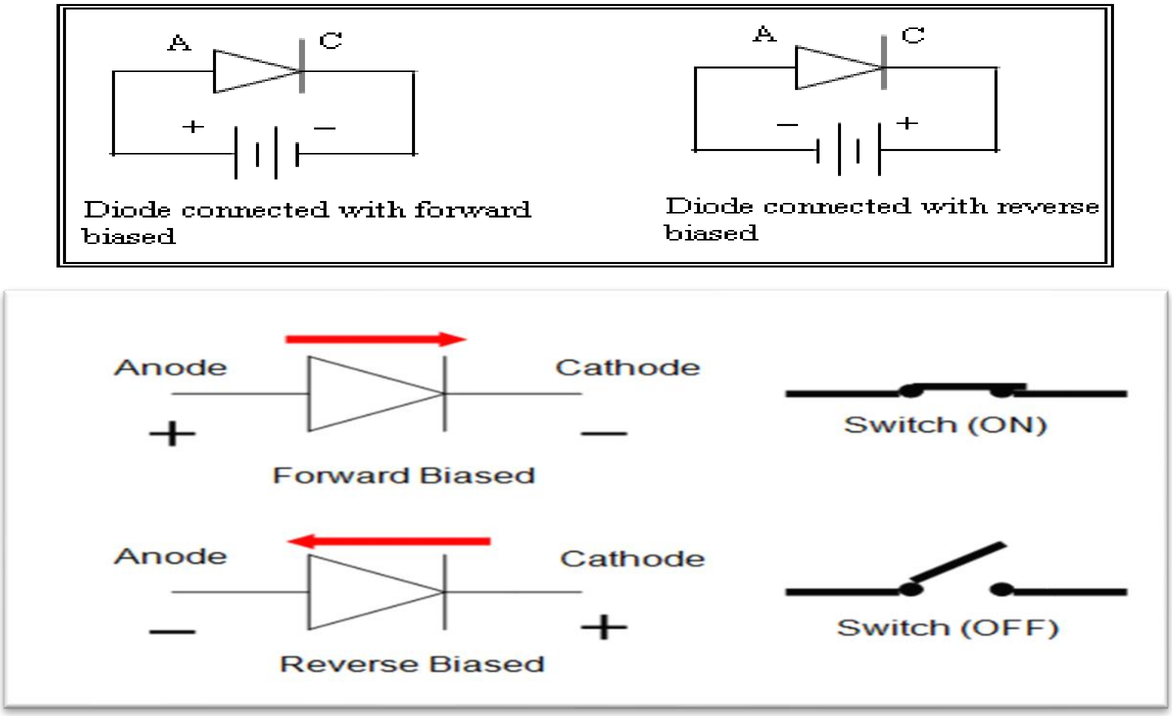
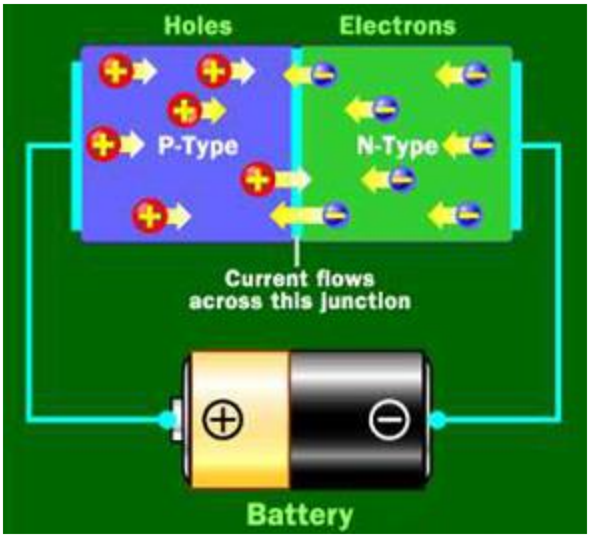


Figure 2.4: Diode During Forward and Reverse Biased Operation

2.4 Forward Biased

- Forward biased – ***When the positive terminal of the battery is connected to the P region (anode) and the negative terminal of the battery is connected to the N region (cathode)***
- The negative terminal of the battery diffuses the electrons in the N region towards the junction while the positive terminal diffuses the holes in the P regions towards the junction.
- When the barrier potential is reached, then the current will flow from positive supply to negative supply.
- In this "active" state, the depletion zone is at its minimum size.
- Diode will act as close switch (Diode ON)



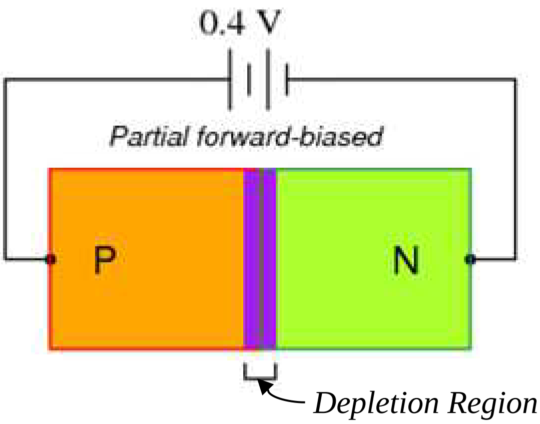


Figure 2.5: Forward Biased

2.5 Reversed Biased

- Reversed biased – ***When the positive terminal of the battery is connected to the N region (cathode) and the negative terminal of the battery is connected to the P region (anode)***
- The negative terminal of the battery attracts holes in the P regions away from the junction while the positive terminal also attracts electron electrons away from the junctions.
- As electrons and holes move away from the
- junction, the depletion area widens.
- No protons are able to flow through the depletion zone, current does not flow in this state.
- Diode act as open switch which is infinity resistance and no leakage current. (Diode OFF)

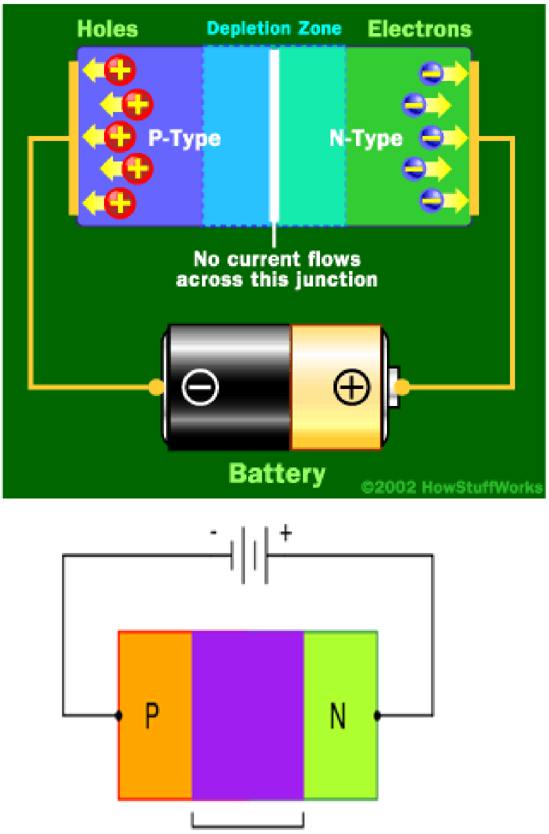


Figure 2.6: Reversed Biased

2.6 I-V Characteristic Curve

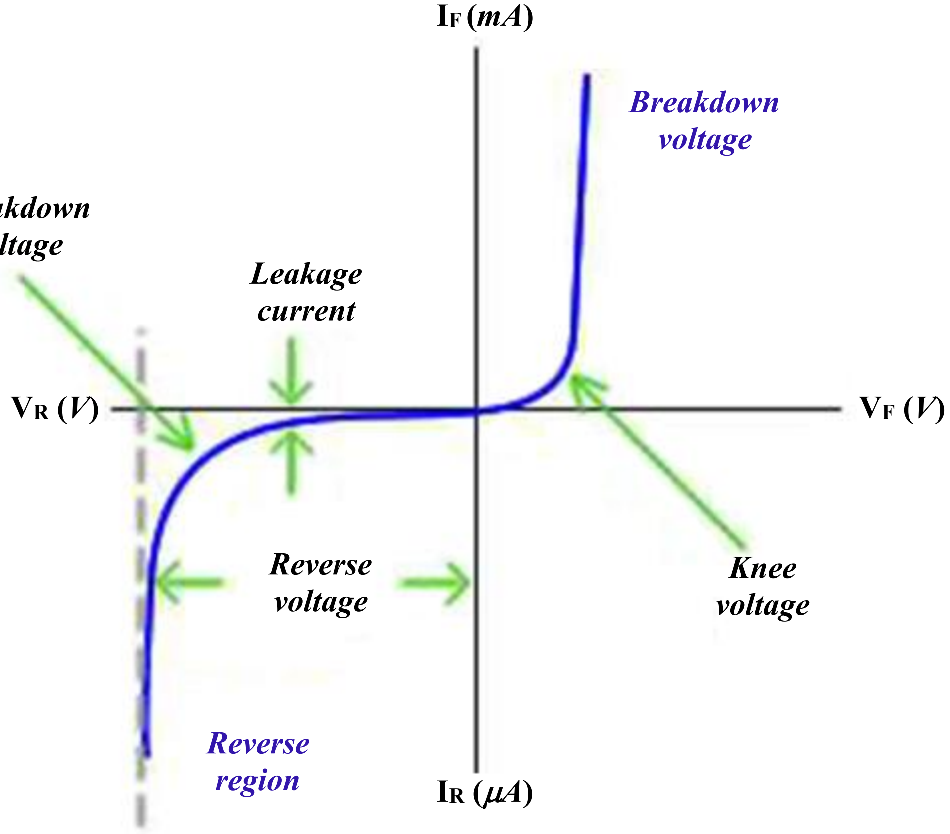


Figure 2.7: Diode Curve

Table 2.1: Characteristic for Diode Curve

Forward current	**current flow when forward bias voltage is given. (unit *mA*)**
Reverse current	small leakage current, flow when reverse bias voltage (unit µA)
Knee Voltage	**Voltage that current flow immediately.** **Also known as threshold voltage/barrier voltage. (Si-0.7V, Ge-0.3V).**
Breakdown voltage	voltage that reverse current flow immediately. A large increase in current will damages the PN junction of the diode
Leakage Current	**When a diode is reverse biased, a very small amount of current can and does go in reverse direction giving rise to leakage current.**
Burning Level	When I_d and V_d exceed maximum, the components will burn.

2.7 Applications of Diode

2.7.1 Rectifier

- Rectifier is the circuit that used one or more diode to convert the AC voltage to the pulsating dc voltage
- There is 3 type of rectifiers:
  - Half wave rectifier (1 diode)
  - Full wave rectifier (2 diodes)
  - Bridge rectifier (4 diodes)
- **Half-wave rectifier**

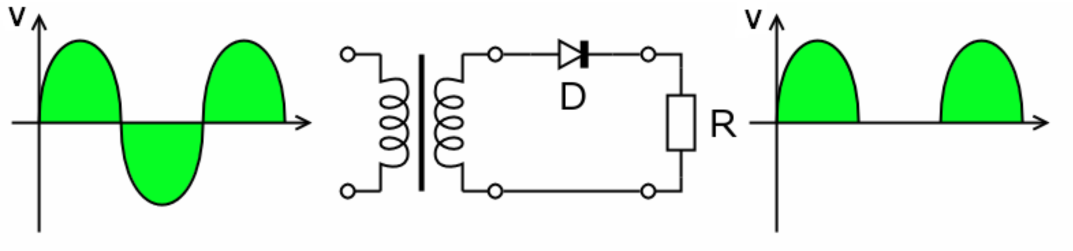


Figure 2.8: Operation of Half-wave Rectifier

  - During the positive circle of input supply, diode D is in forward biased and act as close switch. So the current can flow through it, producing an output voltage as shown above.
  - During the negative circle of the input supply, diode is reverse bias and act as open switch, so the current can't flow through diode. No voltage appears at output.
  - The average value is the value that would be indicated by a dc voltmeter.

$$V_{rms} = \frac{V_{peak}}{1.414}$$

$$V_{dc} = \frac{V_{peak}}{\pi}$$

$$V_{dc} = V_{avg}$$

- Example 2.1:

What is the average value of the half wave rectifier voltage if given

Vp = 50V?

Solution:

$$V_{avg} = \frac{V_p}{\pi} = \frac{50}{\pi}$$

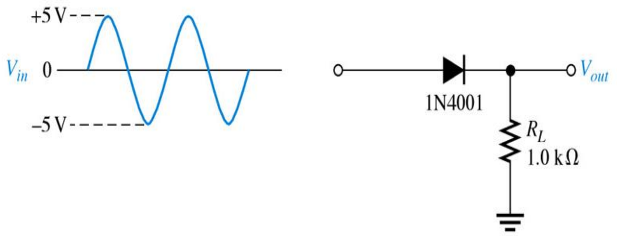
$$= 15.9\ V_{\#}$$

- **Effect of the barrier potential on the half-wave rectifier output**
  - Practical Diode - barrier potential of 0.7V *(assume S_i)* taken into account.
  - During the positive half-cycle, the input voltage V_{in} must overcome the barrier potential $V_{potential}$ before the diode.
  - This results in a half-wave output with a peak value that is 0.7V less than the peak value of the input.

$$V_{out} = V_{in} - 0.7V$$

- Example 2.2:

Calculate the peak output voltage, V_{out} for the circuit given



$$V_{out} = V_{in} - 0.7V$$

$$= 5V - 0.7V$$

$$= 4.3V$$

- **Full-wave rectifier**

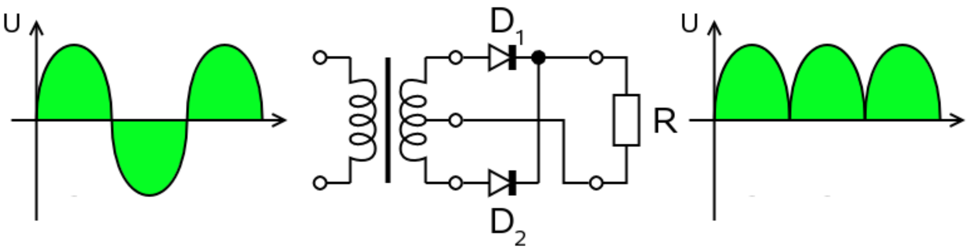


Figure 2.9: Operation of Full-wave Rectifier

- For single-phase AC, center-tapped transformer is required to produce two opposite phase output waveforms.
- A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to DC (direct current) and it's more efficient.

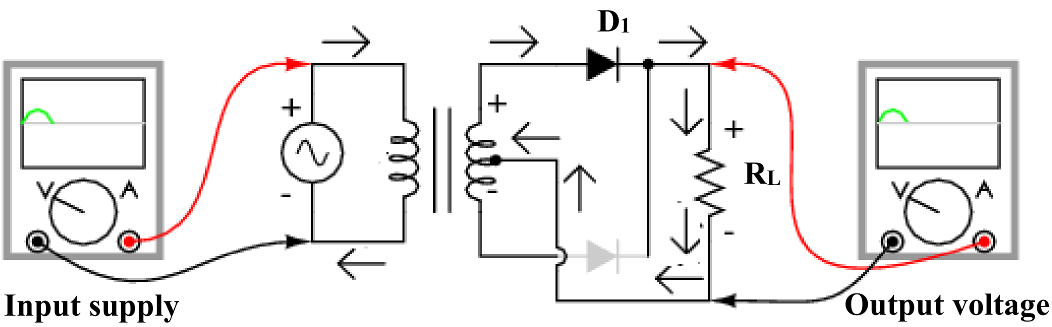


Figure 2.10: Positive Cycle of Full-wave Rectifier

- During **positive cycle** of the signal, diode D_1 in forward biased. D_1 act as closed switch so current can go through it. Current then flow through R_L and will flow back to the negative terminal.

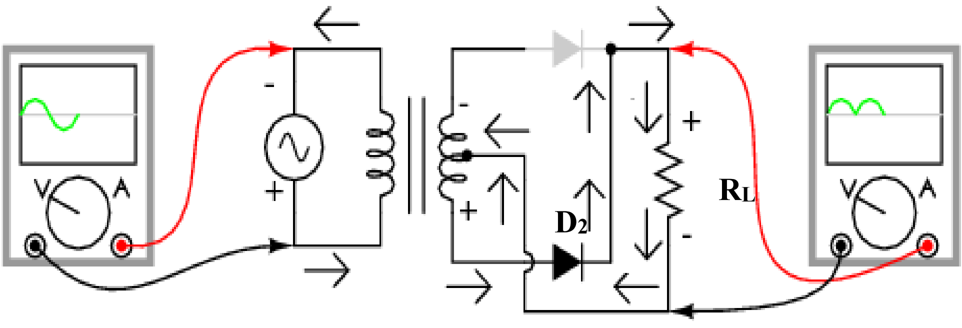


Figure 2.11: Negative Cycle of Full-wave Rectifier

- During **negative cycle** of the signal, diode D_2 in forward biased. D_2 act as closed switch so current can go through it. Current then flow through R_L and will flow back to the negative terminal.
- The average (avg) and root-mean-square (rms) output voltages *(V_{avg} and V_{rms})* of an ideal single phase full wave rectifier can be calculated as:

$$V_{dc} = V_{avg} = \frac{2V_p}{\pi}$$

$$V_{rms} = \frac{V_p}{\sqrt{2}}$$

$$V_{out} = V_{in} - 0.7V$$

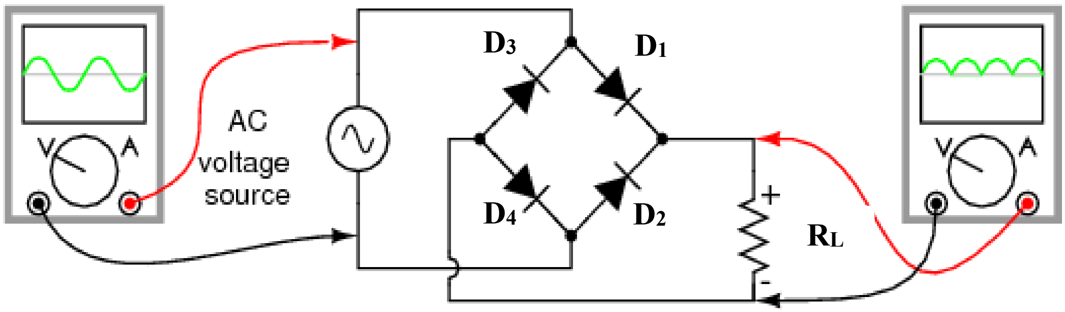


Figure 2.12: Full-wave Rectifier Bridge

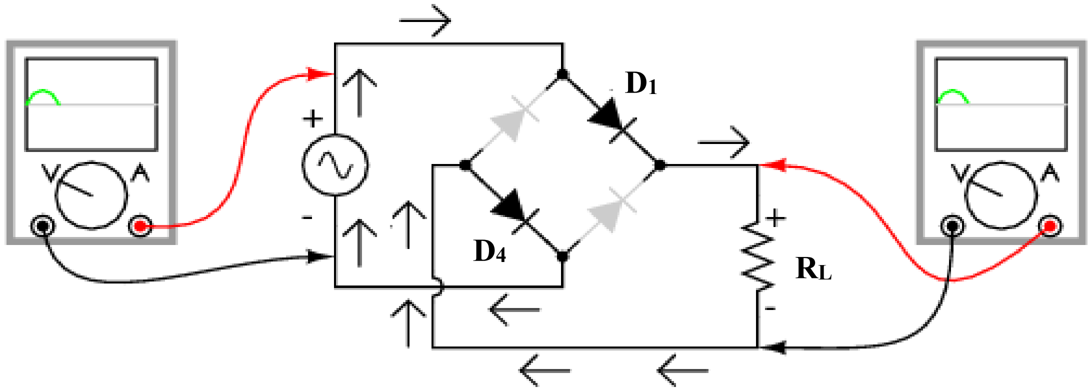


Figure 2.13: Positive Half-cycle of Full-wave Rectifier Bridge

- During the **positive half-cycle**, Diode D_1 and diode D_4 are forward biased.
- Current flow from positive supply to diode D_1, R_L, D_4 and current will flow back to the negative terminal of the battery.
- The current flowing up through the load produces a pulse of voltage across the load as shown in the right-hand waveform.

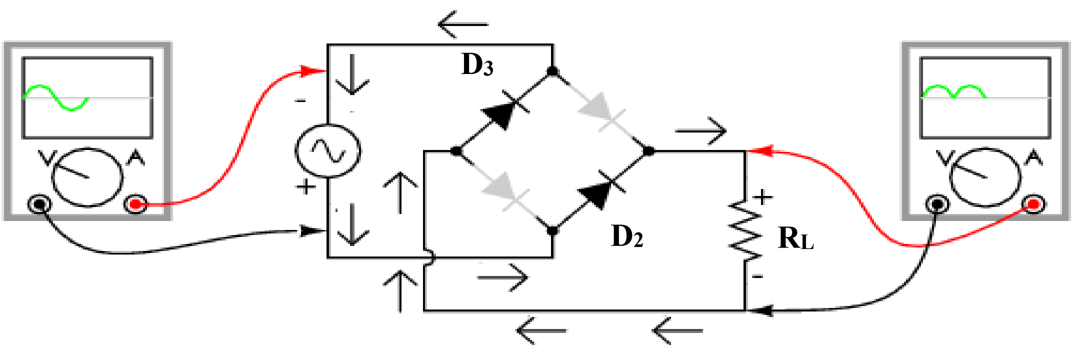


Figure 2.14: Negative Half-cycle of Full-wave Rectifier Bridge

- During the **negative half-cycle**, diode D_3 and D_2 are forward biased so we can think the circuit being equivalent as shown as follows.
- Current flow from positive supply to diode D_2, R_L, D_3 and current will flow back to the negative terminal of the battery.
- The current flowing in the same direction through the load and producing another pulse of voltage.

$$V_{out} = V_{in} - (2 \times 0.7V)$$

- **Application of the rectifier (*Regulated Power Supply*)**

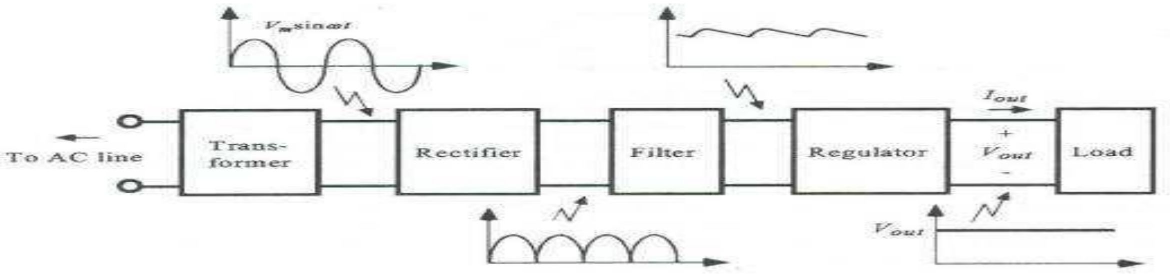


Figure 2.15: Components of A Typical Linear Power Supply

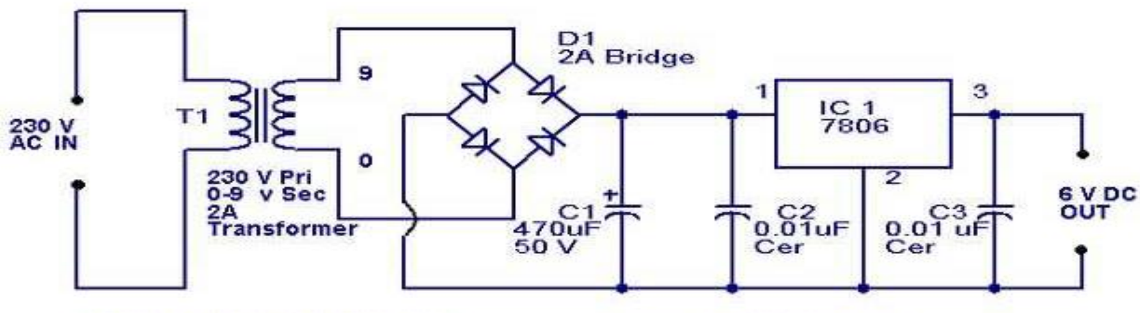


Figure 2.16: 6V DC Regulator Using 7806

2.7.2 Diode Clipper Circuit

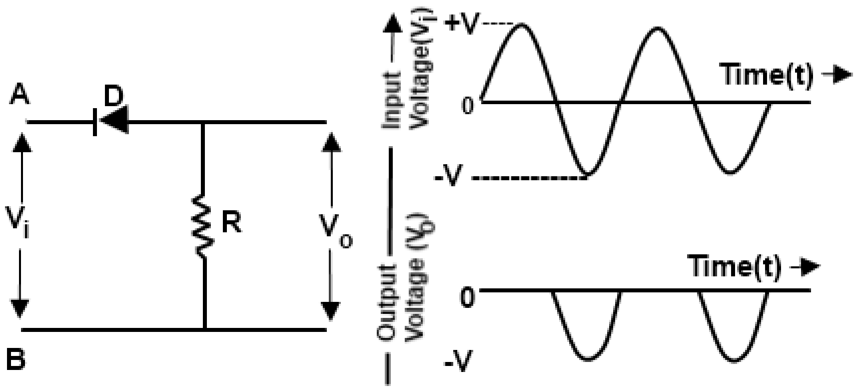
- **Clipping circuit** *(also known as **limiters**)* are used to remove the part of a signal that is above or below some defined reference level. The circuit basically cut off everything at the reference level of zero and let only the positive-going (or negative-going) portion of the waveform through.
- Need at least TWO (2) components:
  - o An ideal diode,
  - o A resistor,
  - o and sometimes a DC battery *(to fix clipping level).*

- Positive or negative region of the input signal is "clipped" off depends on the orientation of the diode. Two **categories of clippers**:

  i. **Series** *(diode is in series with the load)*
     - ✓ positive series/negative series

  ii. **Shunt/Parallel** *(diode in a parallel to the load)*
     - ✓ positive shunt / negative shunt

- **Series Positive Clipper**
  - During the positive half cycle of the input waveform, the diode 'D' is reverse biased, which maintains the output voltage at 0 Volts. Thus causes the positive half cycle to be clipped off.
  - During the negative half cycle of the input, the diode is forward biased and so the negative half cycle appears across the output.

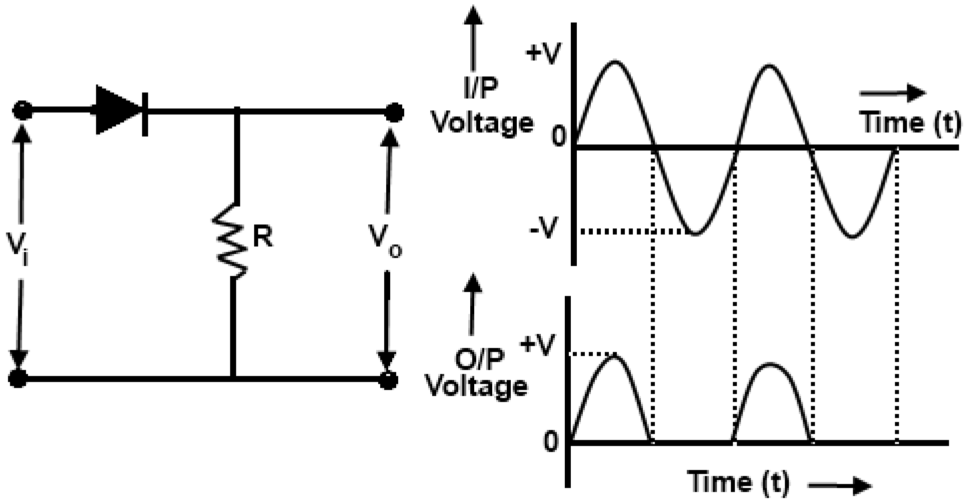


Positive Clipper ***Output Waveform***

Figure 2.17: Series Positive Clipper

- **Series Negative Clipper**
  - During the positive half cycle of the input waveform, the diode 'D' is forward biased, so the positive half cycle appears across the output.

- During the negative half cycle of the input, the diode is reverse biased which maintains the output voltage at 0 Volts. Thus causes the negative half cycle to be clipped off.



Negative Clipper ***Output Waveform***

Figure 2.18: Series Negative Clipper

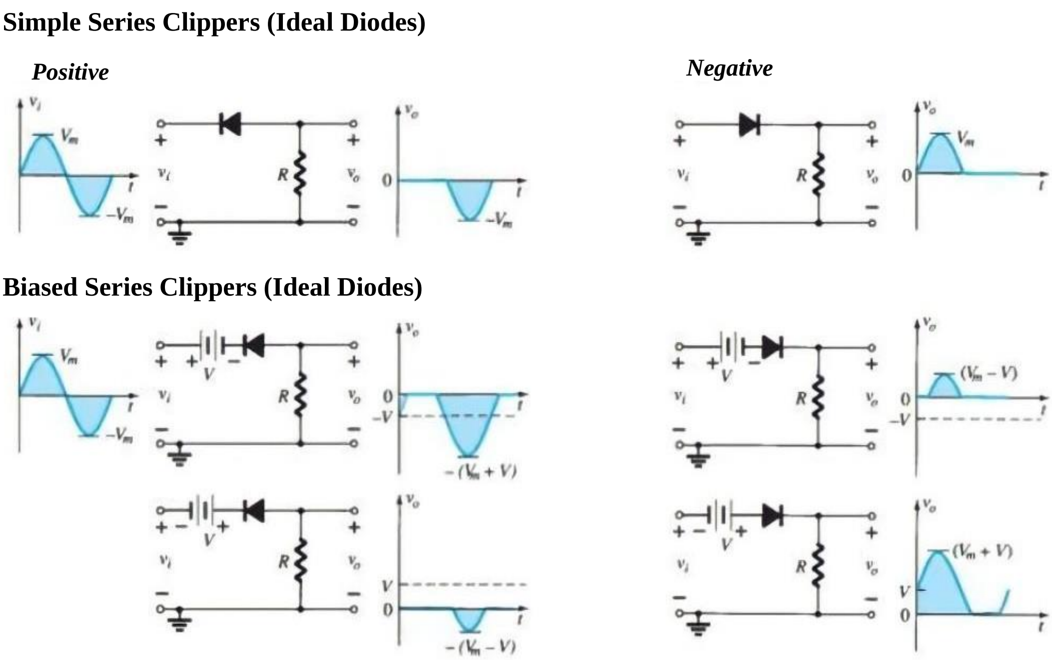


Figure 2.19: Clipping Circuits

- **Shunt/Parallel Positive Clipper**
  - A parallel clipper circuit uses the same diode theory and circuit operation a resistor and diode are connected in series with the input signal and the output signal is developed across the diode.
  - The output is in parallel with the diode hence the circuit name is parallel clipper. The parallel clipper can limit either the positive or negative alternation of the input signal.
  - Figure 2.20 shows the diode acts:
    - ✓ as a closed switch (**ON**) when the input voltage is positive ($V_i > 0$), voltage dropped across R.
    - ✓ as an open switch (**OFF**) when the input voltage is negative ($V_i < 0$), voltage across R is zero and $V_o = V_i$
  - The output waveform is the same as the series positive clipper in the parallel clippers.

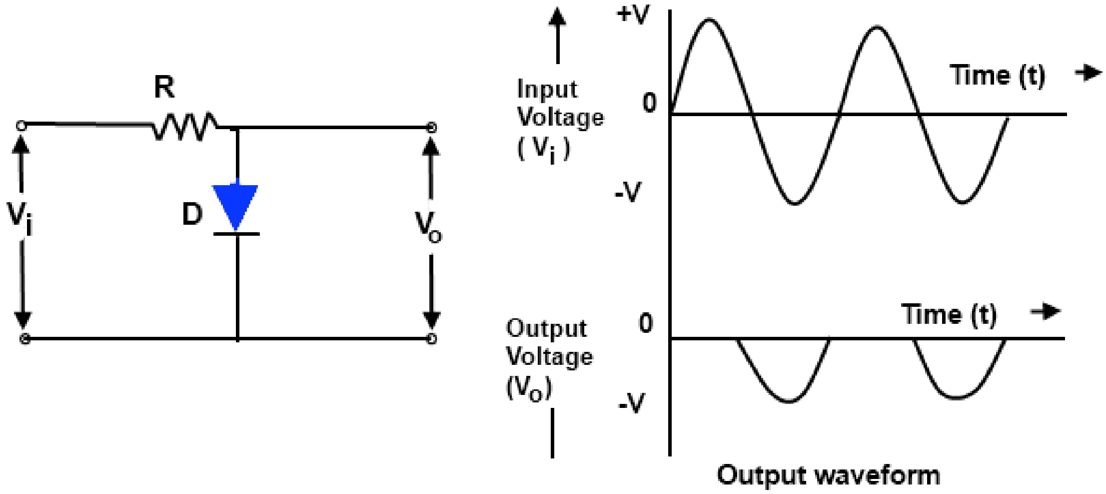


Figure 2.20: Shunt/Parallel Positive Clipper

- **Shunt/Parallel Negative Clipper**
  - The negative clipper has allowed to pass the positive half cycle of the input voltage and completely clipped the negative half cycle.
  - In such a circuit the diode acts:
    - ✓ as a closed switch (**ON**) for a negative input voltage ($V_i < 0$), V_i is dropped across R and $V_o = 0$
    - ✓ as an open switch (**OFF**) for a positive input voltage ($V_i > 0$), voltage across R is zero and $V_o = V_i$
  - The output waveform of the circuit is the same as the series negative clipper.

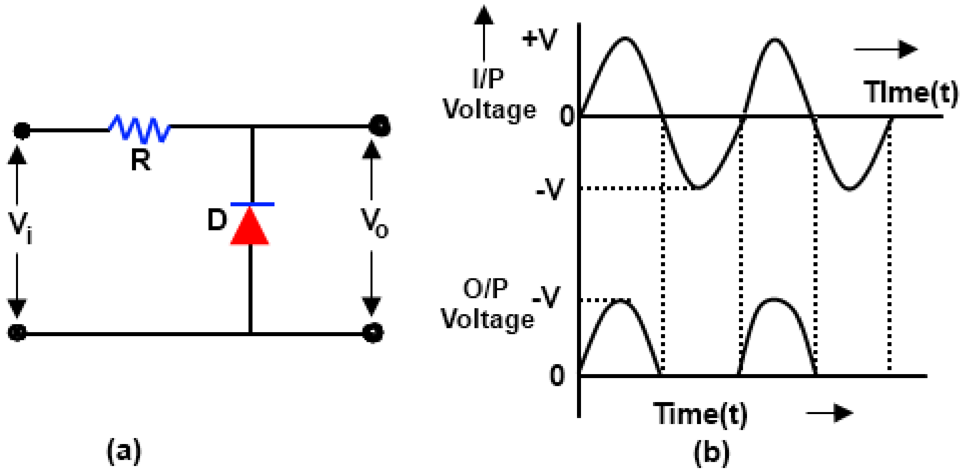
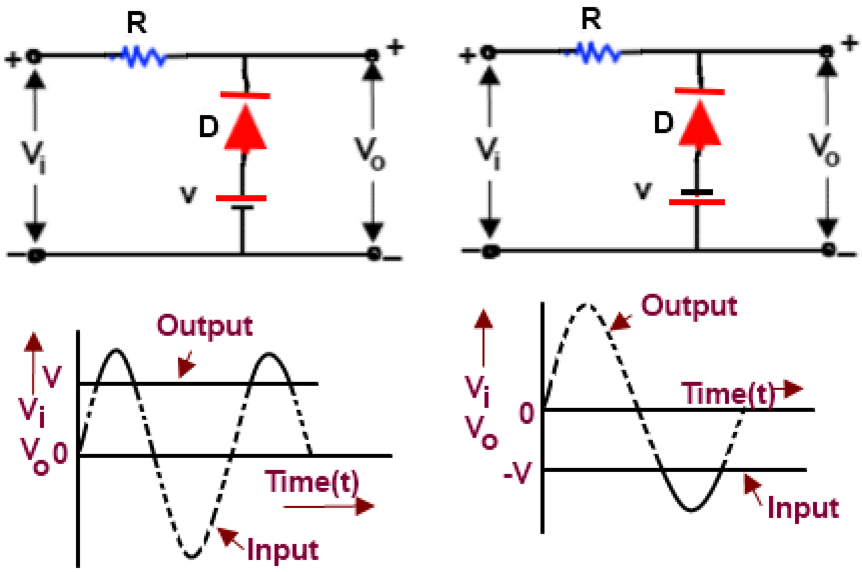


Figure 2.21: Shunt/Parallel Negative Clipper

  - Shunt/Parallel negative clipper with bias
    - ✓ In such a circuit clipping take place during the negative half cycle only when the input voltage ($V_i < V_B$) the clipping level can be shifted up or down by varying the bias voltage ($-V_B$).
    - ✓ If the polarity of the bias voltage is reversed, then the resulting circuits will be as shown in Figure 2.22 (b). Here the entire signal below the voltage level VII has been clipped off.



(b) Positive bias (a) Negative bias

Figure 2.22: Biased Shunt/Parallel Negative Clipper

- Dual (combination) diode clipper
  - ✓ The clipper combines a parallel negative clipper with a negative bias (D_1 and B_2) and a parallel positive bias (D_1 and B_1). Hence the combination of a biased positive clipper and a biased negative clipper is called a combination or dual diode clipper. Such a clipper circuit can clip at both two dependent levels depending upon the bias voltages.
  - ✓ For example, a sinusoidal AC voltage is applied at the input terminals of the circuit. Then during the positive half cycle, the diode D_1 is forward biased, while diode D_2 is reverse biased. Therefore, the diode D_1 will conduct and will act as a short circuit. On the other hand, diode D_2 will act as an open circuit. However, the value of output voltage cannot exceed the voltage level of V_{B1} as shown in Figure 2.23.

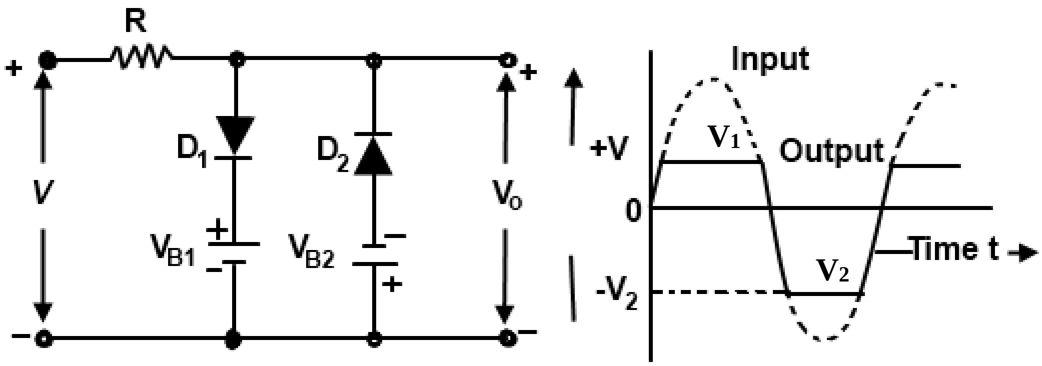
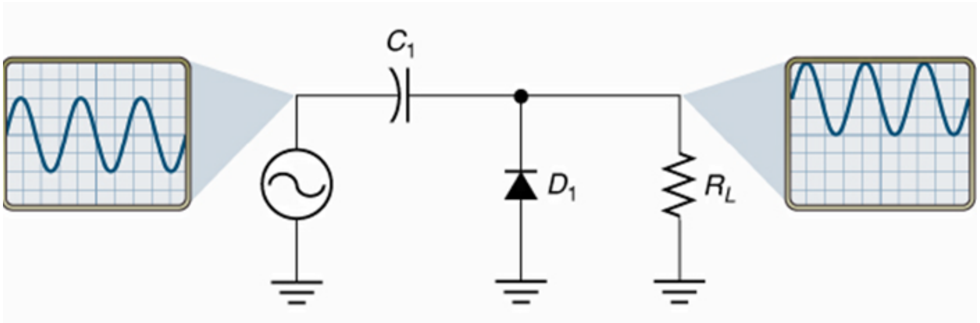


Figure 2.23: Dual (combination) Clipper Circuit

✓ Similarly, during the negative input half-cycle, diode D_2 acts as a short circuit while the diode D_2 as an open circuit However the value of output voltage cannot exceed the voltage level of V_{B2} It may be noted that the clipping levels of the circuit be varied by changing the values of V_{B1} and V_{B2} If the values of V_{B1} and V_{B2} are equal, the circuit will clip both the positive and negative half cycles at the same voltage level. Such a circuit is known as a symmetrical clipper.

2.7.3 Diode Clamper Circuit

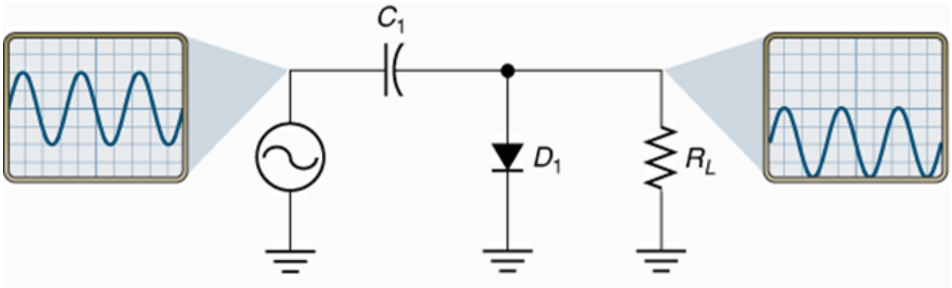
- A clamper (DC restorer) is a network constructed of a diode, resistor and a capacitor that shifts a waveform to a different dc level without changing the appearance of the applied signal.
- There are two types of clampers:
  - Positive clamper
  - Negative clamper
- Positive clamper
  - During the negative half cycle of the input signal, the diode conducts and acts like a short circuit.
  - The output voltage $V_o = 0$ volts.



2.24: Positive Clamper

- The capacitor is charged to the peak value of input voltage V_m and it behaves like a battery.
- During the positive half of the input signal, the diode does not conduct and acts as an open circuit.
- Hence the output voltage $V_o = V_i + V_{peak}$. This gives a positively clamped voltage**.**

- Negative clamper
  - During the positive half cycle the diode conducts and acts like a short circuit.



2.25: Negative Clamper

- The capacitor charges to peak value of input voltage V_i.
- V_o which is taken across the short circuit will be zero.
- During the negative half cycle, the diode is open.
- $V_o = V_i + V_{peak}$

2.7.4 Zener Diode

- A **Zener diode** is a type of diode that permits current not only in the forward direction like a normal diode, but also in the **reverse direction** if the voltage is larger than the breakdown voltage known as "Zener knee voltage" or "Zener voltage".

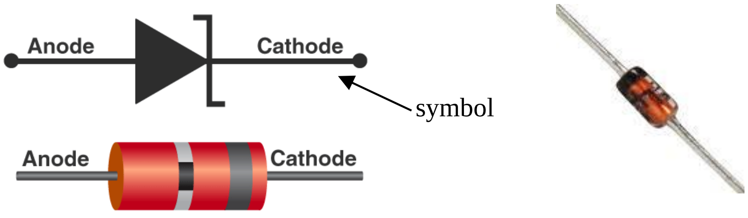


Figure 2.26: Zener Diode

- IV Characteristic for Zener Diode
  - With a Zener diode connected in the **forward direction**, it behaves exactly the same as a standard **diode**; a small voltage drop of 0.3 to 0.7V with current flowing through pretty much unrestricted.
  - However, in the **reverse direction,** there is a very small *leakage current* between 0V and the Zener voltage; just a tiny amount of current is able to flow. Then, when the voltage reaches the **breakdown voltage** (V_z), suddenly current can flow freely through it.

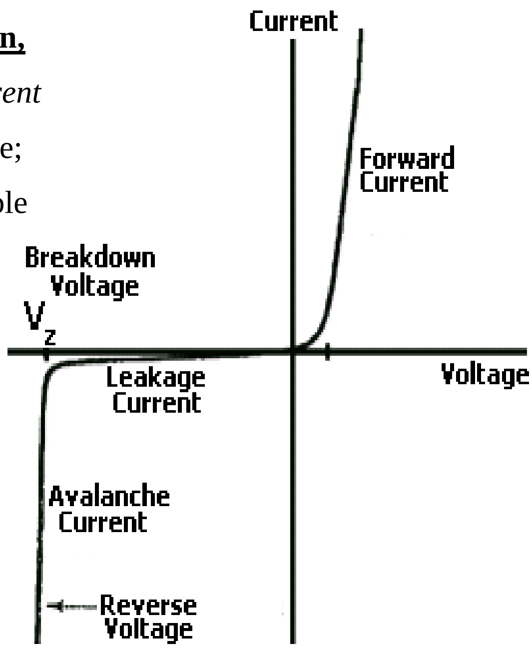


Figure 2.26: The Phenomenon in a Current vs Voltage Graph

- Advantages of Zener Diode
    - It can work at high reverse current without damaging the diode.
    - Voltage across the **zener diode** in reverse bias is constant after reaching certain value.
    - Normal **diodes** distort at its breakdown voltage but the **Zener diode** still runs after this voltage and keeps the voltage across the **diode** constant even the supply voltage increases.

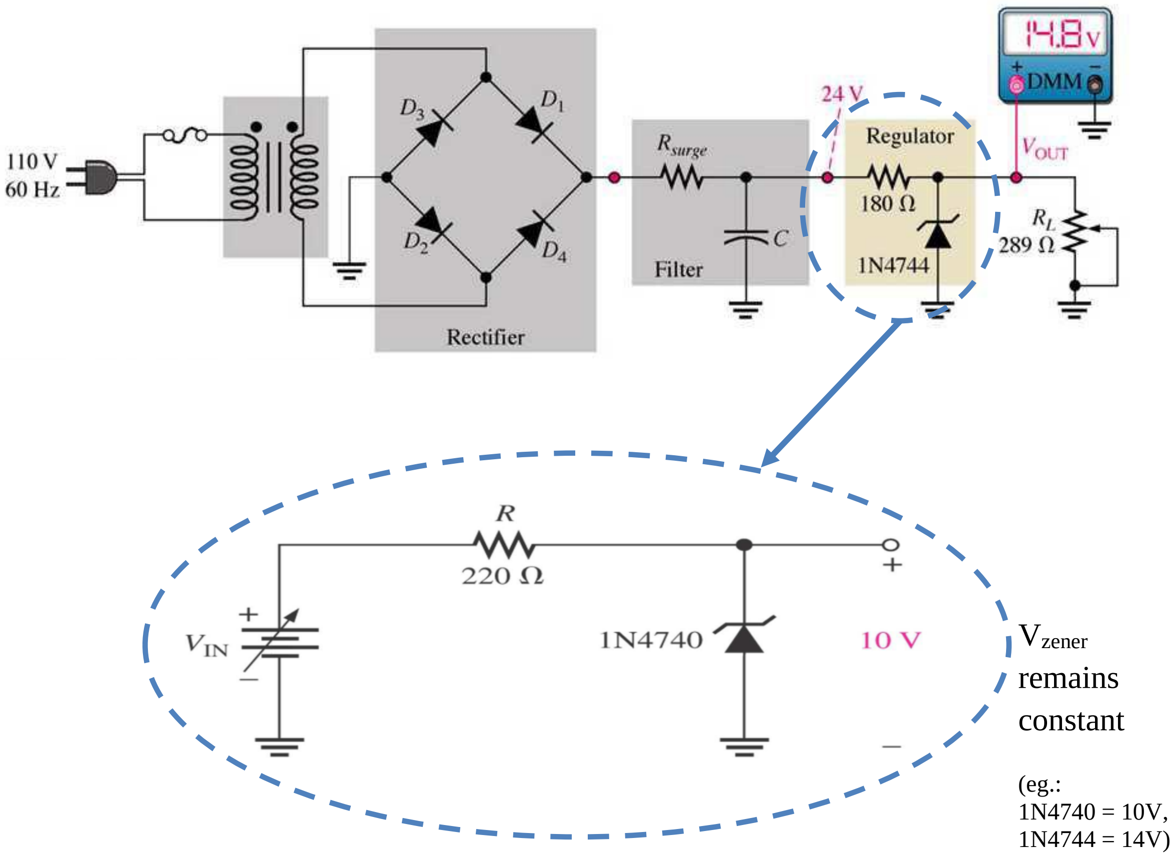


Figure 2.27: Zener Diode as Regulator

- Light Emitting Diode (LED)
  - LED is a specially made forward biased PN junction diode which emits visible light when current flows through it.

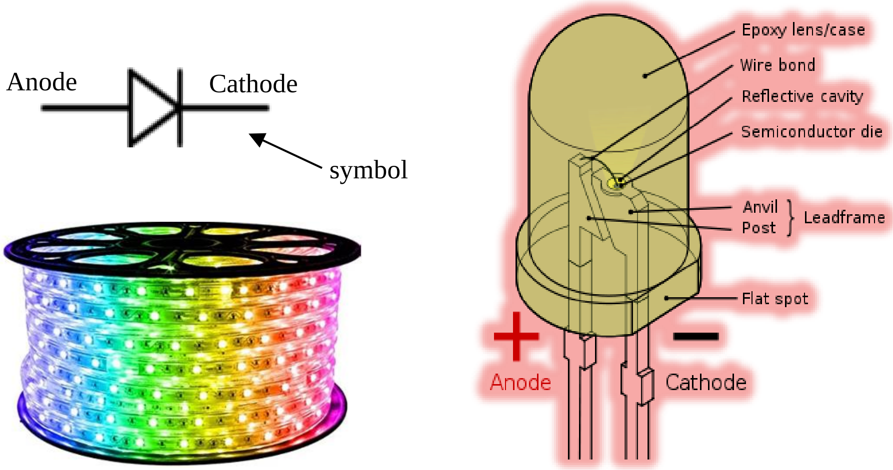


Figure 2.28: Light Emitting Diode

  - Electron from N-type material will merge with the P-type material hole.
  - If the material is silicon and germanium the merger will generate heat.
  - The emitter light depends upon the type of material used as given below:
    - GaAs : infra-red radiation (invisible)
    - GaP : red or green light
    - GaAsP : red or yellow (amber) light
  - LED operate at low voltage between 1 to 4V and conduct between 10 to 40mA.
  - Applications of LED:
    - It is used in optional switching applications
    - It is used in the field of optional communication
    - It is used in instrument displays, digital watches, calculators etc.
    - It is used for indicating power ON-OFF conditions.
    - It is used in 7-segment and dot matrix displays.

- Photodiode
  - A photodiode is designed to operate in **reverse bias**.
  - Unlike LED’s, photodiodes receive light rather than produce light.
  - The photodiode varies it’s current in response to the amount of light that strikes it.
  - A photodiode is a type of PHOTODETECTOR capable of converting light into either current or voltage, depending upon the mode of operation.
  - Photodiodes are similar to regular semiconductor diodes except that they may be either exposed (to detect vacuum UV or X-rays) or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device.

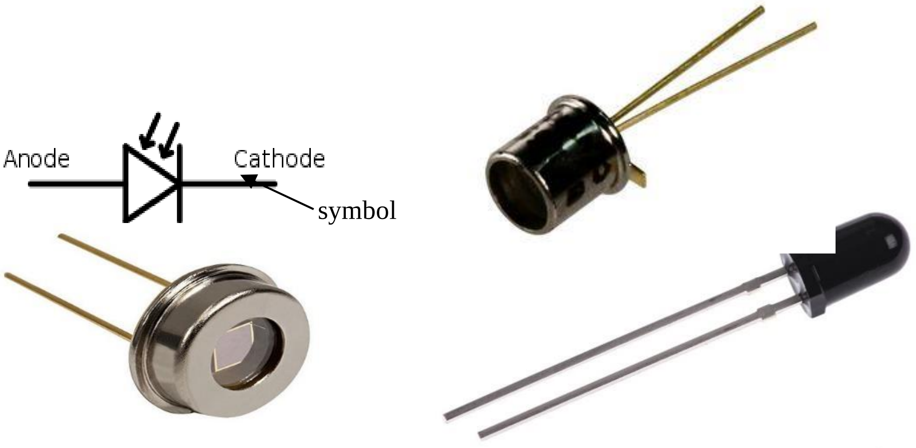


Figure 2.29: Photodiode

  - Applications of Photodiode:
    - It is used where light is required to be switched ON and OFF at a very fast rate.
    - It is used in light detection
    - It is used in reading of computer punched cards and tapes.
    - It is used in optical communication system.
    - It is used in demodulation.
    - It is used in logic circuits.

- Laser Diode
    - The word LASER stands for ***Light Amplification by Stimulated Emission of Radiation.***
    - The laser diode is **forward biased** by an external voltage source.

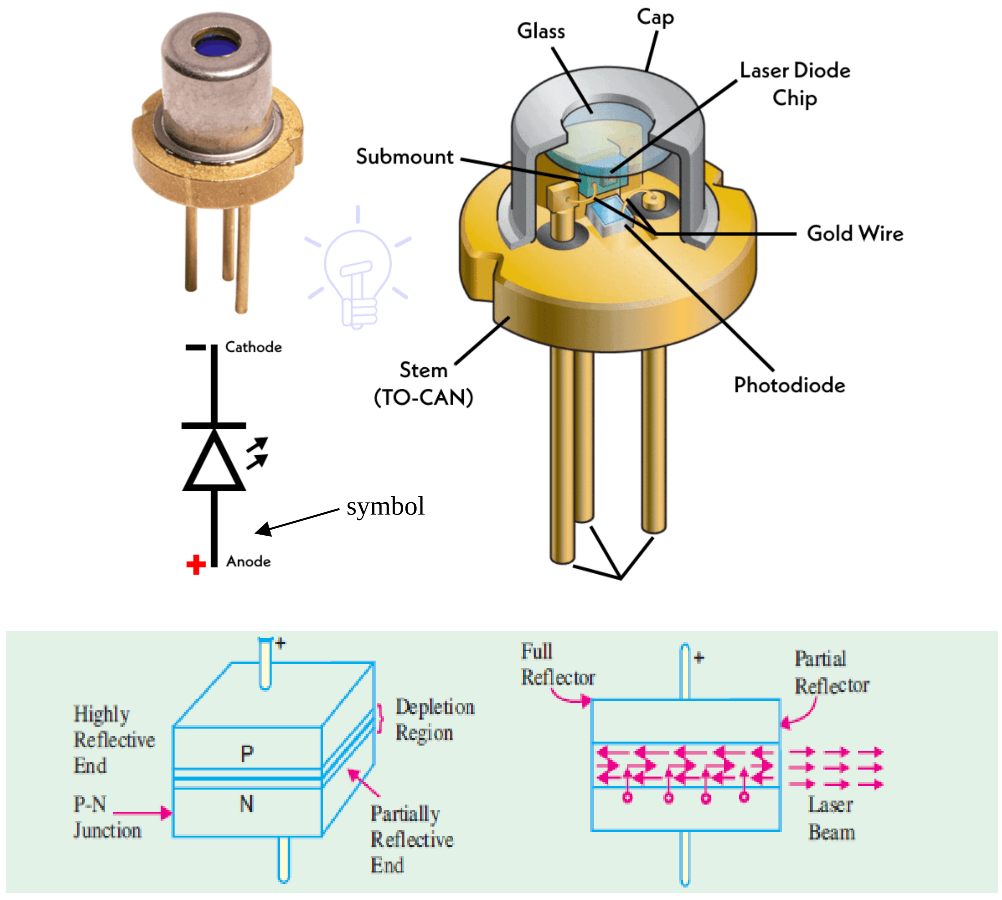


Figure 2.30: Laser Diode

-
    - Laser light is monochromatic. which means that it consists of a single color and not a mixture of colors. Laser light is also called coherent light, a single wavelength, as compared to incoherent light, which consists of a wide band of wavelengths. The laser diode normally emits coherent light, whereas the LED emits incoherent light.

- As electrons move through the junction. recombination occurs just as in an ordinary diode. As electrons fall into holes to recombine, photons are released.
- Applications of Laser Diode:
    - barcode readers
    - optical fiber systems
    - laser printers
    - laser pointers
    - laser surgery
    - compact disc (CD) players
    - medical imaging instruments

CHAPTER 3

BIPOLAR JUNCTION TRANSISTORS (BJT)

3.1 What would you get?

- Basic of bipolar junction transistor (BJT).
- Characteristics and operations of BJT.
- Principle and operations of BJT to the basic transistor configurations.
- DC operations of BJT
- Frequency response curve.
- Frequency response characteristics of an amplifier.
- Classification of amplifier.
- Other biasing techniques of common emitter transistor configuration.
- Other applications of BJT.
- Concept of feedback.

3.2 Basic of Bipolar Junction Transistor (BJT)

- A bipolar transistor essentially consists of a pair of **PN Junction diodes** that are joined back-to-back.
- There are two types of BJT namely **NPN transistor** and **PNP transistor**.
- Physically, the transistor consists of three parts: **Collector, Base, Emitter.**

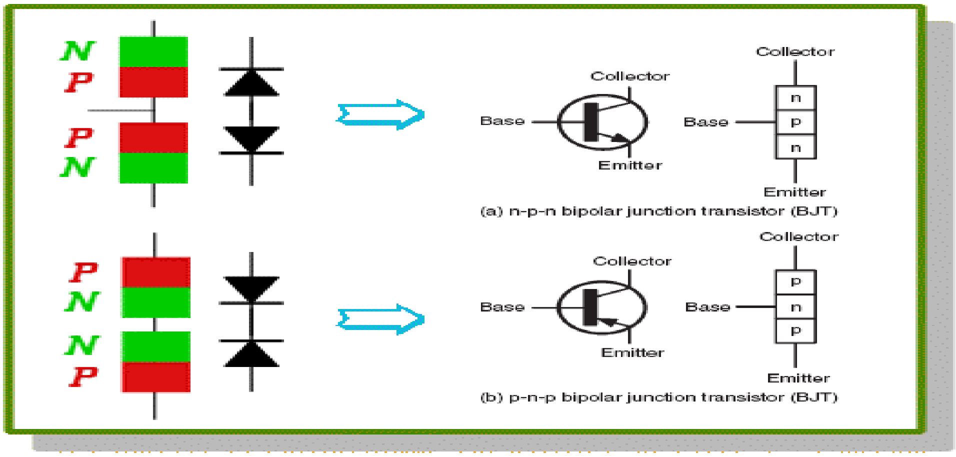
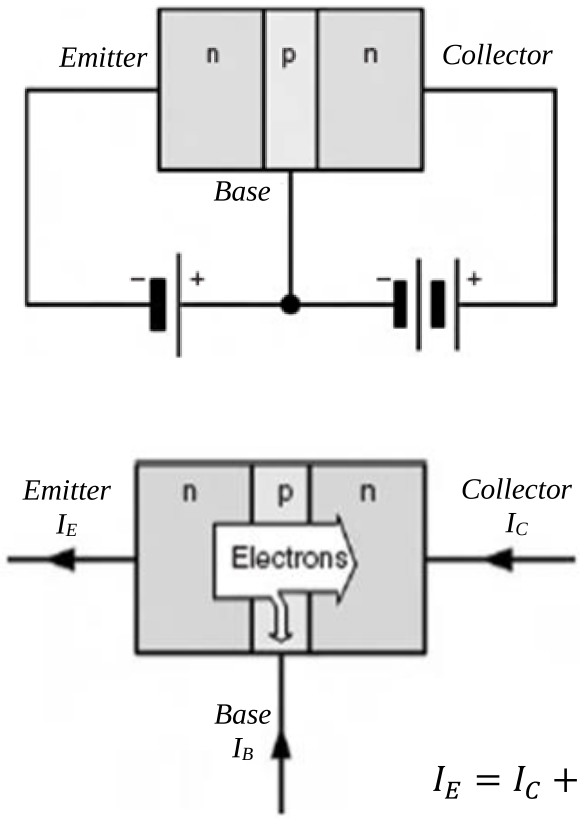


Figure 3.1: Physical Structure and Symbols of BJT

- The arrow at the transistor symbol shows the direction of conventional current when it is operates.
- Emitter
  - It is always **forward biased** with respect to base. Its function is to supply majority charge carriers (either electrons or holes) to the other two layers.
- Base
  - Very thin and lightly doped central region. It forms two junctions. The **base emitter** junction is **forward biased** ant the **base collector** is **reverse biased.**
- Collector
  - It is always reverse biased. Its function is to collect majority charge carriers supplied by the emitter.
- Transistor Biasing
  - The application of suitable DC voltage across the transistor terminals is called ‘biasing’.
  - The **emitter base** junction is **always forward biased** while the **collector base** junction is **always reverse biased.**

- Basic Transistor Operation (NPN)
  - the majority carriers in the n-type emitter material are electrons.
  - the **base-emitter** junction is **forward biased** to these majority carriers and electrons cross the junction and appear in the base region.
  - the base region is very thin and only lightly doped with holes, so some recombination with holes occurs but many electrons are left in the base region.
  - the **base-collector** junction is **reverse biased** to holes in the base region and electrons in the collector region but is forward biased to electrons in the base region; these electrons are attracted by the positive potential at the collector terminal.



$$I_E = I_C + I_B$$

Figure 3.2: NPN Bipolar Junction Transistor

- Basic Transistor Operation (PNP)
    - the **majority carriers** in the emitter p-type material are **holes**.
    - the **base-emitter** junction is **forward biased** to the majority carriers and the holes cross the junction and appear in the base region.
    - the base region is very thin and is only lightly doped with electrons so although some electron hole pairs are formed, many holes are left in the base region.
    - the **base-collector** junction is **reverse biased** to electrons in the base region and holes in the collector region, but forward biased to holes in the base region; these holes are attracted by the negative potential at the collector terminal.

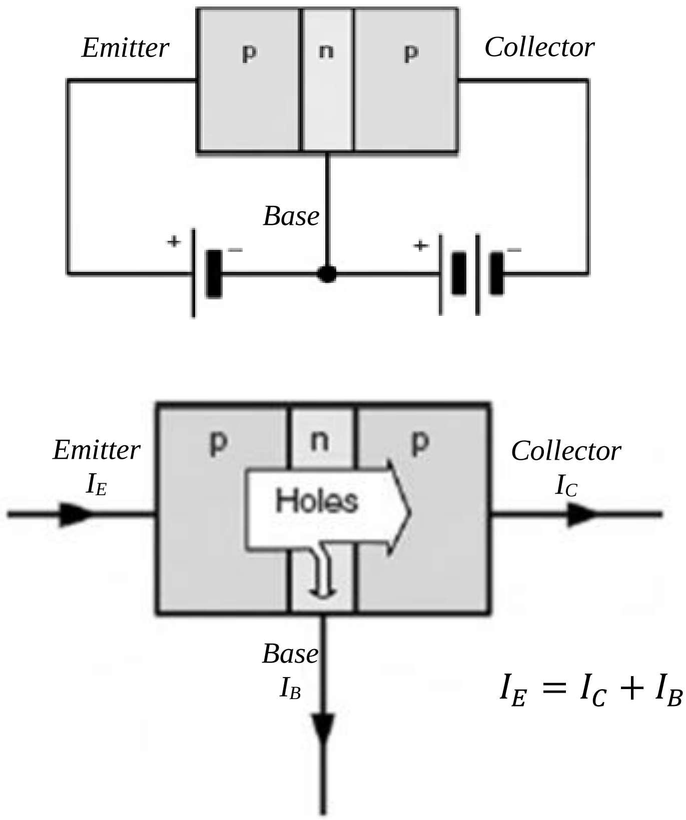


Figure 3.3: PNP Bipolar Junction Transistor

- Applications of Transistor
  - It is used as an amplifier.
  - It is used as a switch.
  - It is used in oscillator circuit.
  - It is used as buffer.
  - It is used in logic circuits.

3.3 Characteristic and Operations of BJT

- The Characteristic Curve
  - **CUTOFF POINTS**

    i. When $I_B = 0$, $I_C= 0$, $V_{CE} = V_{CC}$, the transistor is cut off.

    ii. Ideal transistor acts like an open switch.
  - **SATURATION POINTS**

    i. When I_B increased, I_C also increased, V_{CE} decreased reach a point where V_{CE} less than the base voltage.

    ii. Ideal transistor will act like a closed switch.
  - **ACTIVE REGION**

    i. Most importance mode, e.g., for amplifier operation.

    ii. The region where current curves are practically flat.

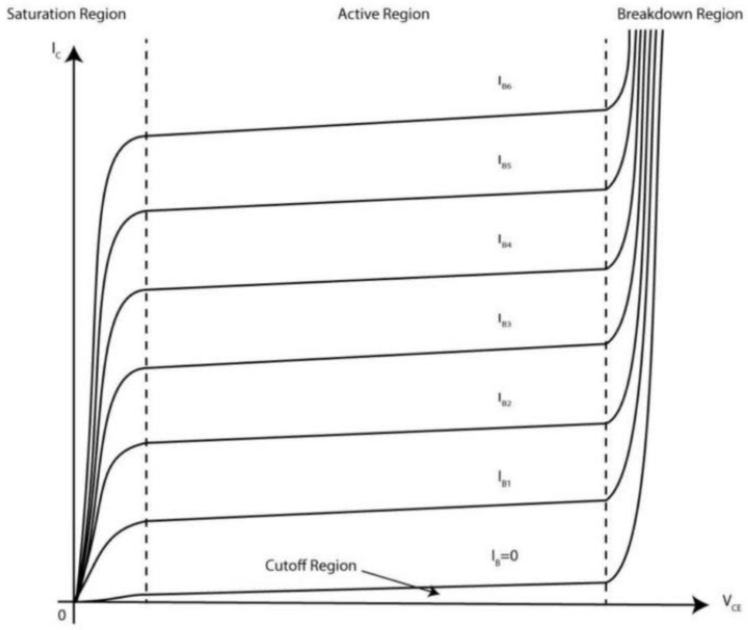


Figure 3.4: The Characteristic Curve

- BJT as Amplifier
  - DC bias is to allow a transistor to operate as amplifier.
  - In order to use the BJT as an amplifier, it should operate in the active region.

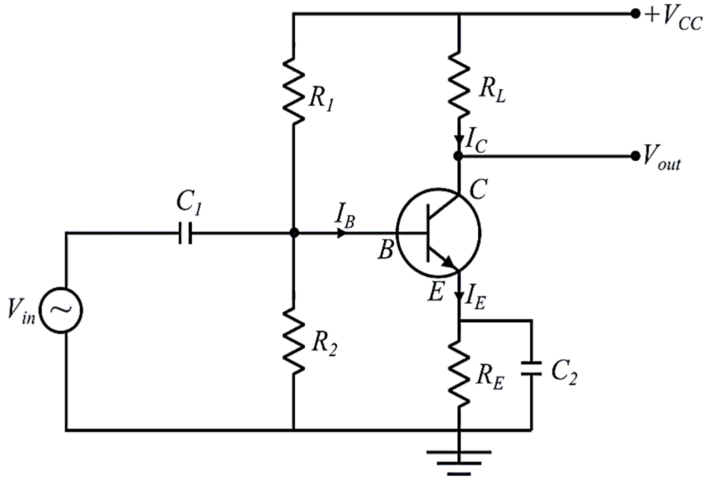


Figure 3.5: Common Emitter BJT Amplifier

- BJT as Switch
    - When the transistor is off, it is in **cutoff condition** (no current, switch **OFF**).
    - When the transistor is on, it is in **saturation condition** (maximum current, switch **ON**).

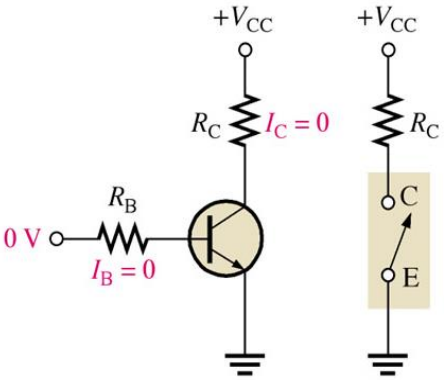


Figure 3.6: Open Switch *(Cutoff)*

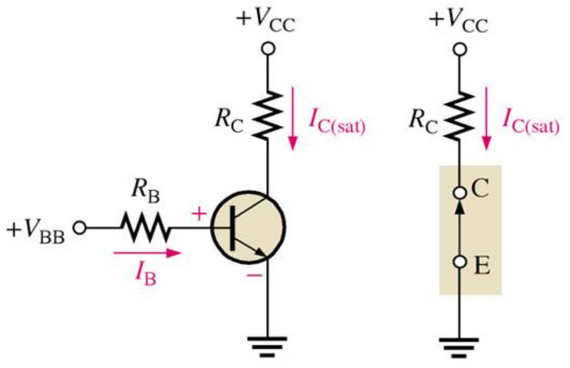


Figure 3.7: Closed Switch *(Saturation)*

- Transistor Operating Configurations

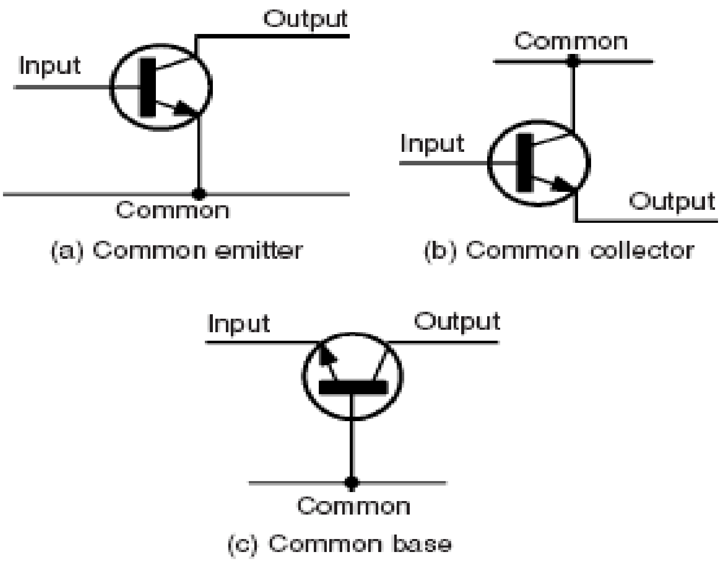


Figure 3.8: Transistor Operating Configurations

3.4 Principle and Operations of BJT to The Basic Transistor Configurations

- Common Base Circuit
  - In the configuration, emitter current **IE** is the **input current** and collector **IC** is the **output current**. The **input signal** is applied between the emitter and base (V_{EB}) whereas **output** is taken out from the collector and base (V_{CB}).
  - The ratio of the collector current to the emitter current is called dc alpha with equation:

$$\alpha(dc) = \frac{I_C}{I_E}$$

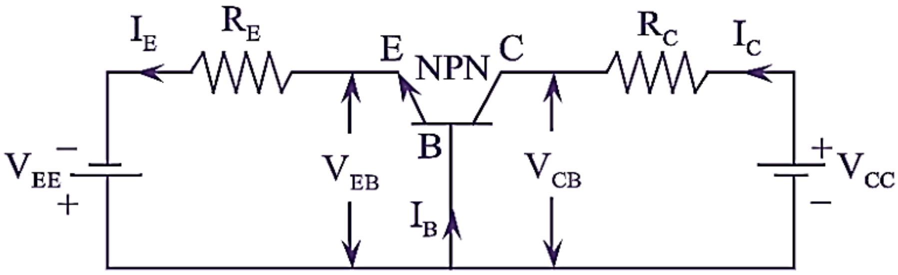


Figure 3.9: Common Base Configuration

- Common Emitter Circuit
  - The **input signal** is applied between the base and emitter (V_{BE}) and the **output signal** is taken out from collector and emitter current (V_{CE}).
  - I_B is **input current** whereas I_C is **output current**.
  - The ratio of dc collector current (I_C) to dc base current:

    (I_B) is called ß dc;

$$ß = \frac{I_C}{I_B}$$

  - also known as the current gain of the transistor

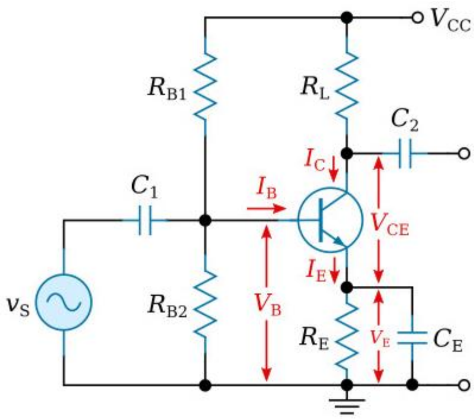


Figure 3.10: Common Emitter Configuration

- Common Collector Circuit
  - The **input signal** is applied between the base and collector (V_{CB}) and the **output signal** is taken out from emitter collector (V_{CE}) circuit.
  - I_B is **input current** whereas I_E is **output current**.

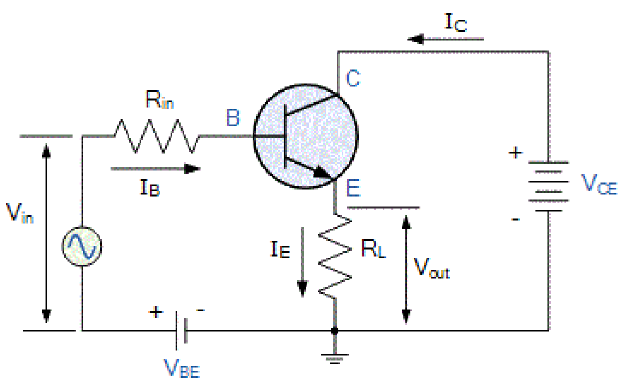


Figure 3.11: Common Collector Configuration

- The Electrical Characteristics (CE)
  - Due to the base emitter is forward bias, so **input resistance** for this circuit is low (normally around 500Ω to 1.5kΩ)
  - For collector base section is reverse bias, so **output resistance** is high (normally around 30kΩ to 50kΩ).
  - The value of I_C is higher than I_B, **current gain** for common emitter circuit is high.
  - **Voltage gain** value for common emitter diagram is high.

Table 3.1: CE's Features

Input resistance	Low
Output resistance	High
Current gain, $A_I = \frac{output\ current,\ I_C}{input\ current,\ I_B}$	High
Voltage gain	High
Power gain, $A_P = \frac{output\ power,\ P_{out}}{input\ power,\ P_{in}}$ $A_P = \frac{{I_{out}}^2 \times R_{out}}{{I_{in}}^2 \times R_{in}}$	High
Different phase	180°

- The Electrical Characteristics (CB)
  - Due to emitter base is in forward bias this **input resistance** is low (around 20 to 200Ω only)
  - The collector base is in reverse bias, so the **output of resistance** is high (normally between 100kΩ to 1MΩ)
  - No **difference phase** between output and input.

- Since the input current, I_C flow through the low input resistance and the output current, I_E flow through high output resistance, the circuit will produce a high-power **gain**.

Table 3.2: CB's Features

Input resistance	**Low**
Output resistance	High
Current gain, $A_I = \frac{output\ current,\ I_{out}}{input\ current,\ I_{in}}$	**No**
Voltage gain	High
Power gain, $A_P = \frac{output\ power,\ P_{out}}{input\ power,\ P_{in}}$ $A_P = \frac{{I_{out}}^2 \times R_{out}}{{I_{in}}^2 \times R_{in}}$	**High**
Different phase	No

- The Electrical Characteristics (CC)
  - **Input resistance** for this circuit very high (about 100kΩ to 500kΩ).
  - **Output resistance** for this circuit very low (about 50Ω to 1kΩ).
  - The highest current in the circuit is I_E and the smallest current is I_B so the **current gain** is also high.
  - Due to the output voltage value is small comparing to input voltage value, so the **voltage gain** value can be small or less than 1.
  - Since the output resistance is very low while the input resistance is very high, the power gain for CB's circuit would be in the smallest value.
  - Output waveform phase can follow the input waveform phase.

Table 3.3: CC's Features

Input resistance	**High**
Output resistance	Low
Current gain, $A_I = \frac{I_E}{I_B}$	**High**
Voltage gain, $A_V = \frac{V_{out}}{V_{in}}$	Low
Power gain	**Low**
Different phase	No

- The Characteristic Curve (I_C – V_C) for Common Emitter Amplifier

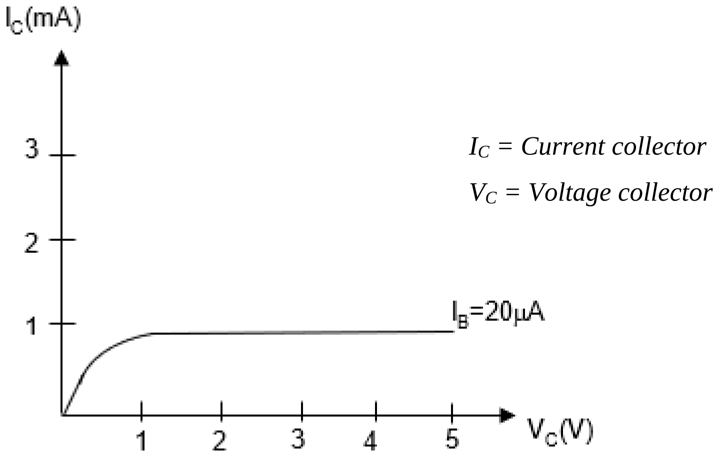


Figure 3.12: The I-V Curve

- Figure 3.12 illustrates the condition of a transistor during the changes of current and voltage.
- I_B value is low (in µA). If V_{BB} (forward bias voltage) being added, the base current, I_B should also be increased but still in a low value. (µA range)

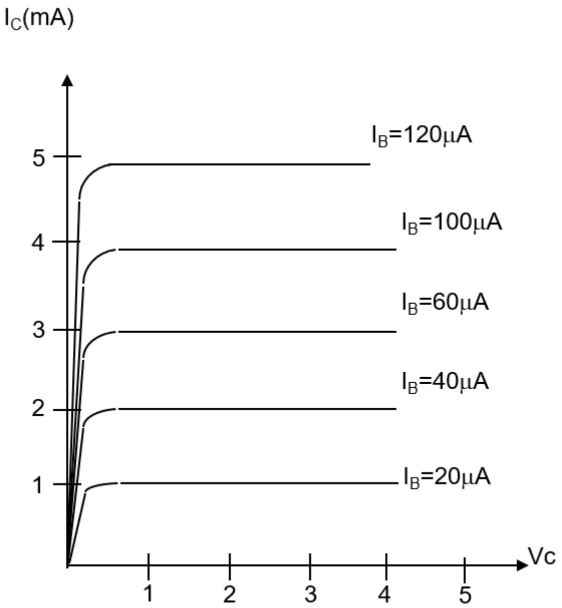


Figure 3.13: I-V Curve with Several Values of I_B

- If V_{BB} is variable, base current, I_B = 20μA and V_C = 1V, collector current, I_C = 0.98mA.
- For the same value, I_B = 20μA meanwhile V_C = 4V or above, there will be only a small increment for I_C due to current leakage. It can be assumed that the I_C value while V_C = 4V is in the same value while V_C = 1V.
- For I_B = 40μA and V_C = 1V, I_C would be 1.98mA.
- For the same value, I_B = 40μA meanwhile V_C = 4V or above, there will be only a small increment for I_C due to current leakage. It can be assumed that the I_C value while V_C = 4V is in the same value while V_C = 1V.
- Conclusion:
  - I_B value depends on forward bias voltage (V_{BB}).
  - The value of I_B determines the I_C value, which is always higher than the I_B value.

- The values of I_B, I_C, and I_E are unaffected by the V_{CC} value.
- The current source in the common emitter amplifier circuit diagram has a current base value that controls its value.

3.5 DC Operations of BJT

- Beta A.T ($\beta_{a.t}$) Beta A.U ($\beta_{a.u}$)
  - Beta factor can be divided to 2 conditions:

i. Beta A.T - collector current (I_C) value that flow following current base value condition (I_B) at V_C value is in constant condition.

$$ß_{a.t} = \frac{I_C}{I_B}$$ ** V_C constant*

ii. Beta A.U - changes value that happen at current collector when current base is change at Vc constant condition.

$$ß_{a.u} = \frac{\Delta I_C}{\Delta I_B}$$ ** V_C constant*

- Current and Voltage Calculation for Common Emitter Circuit

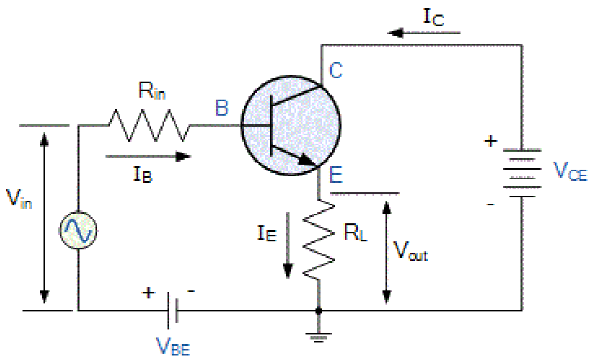
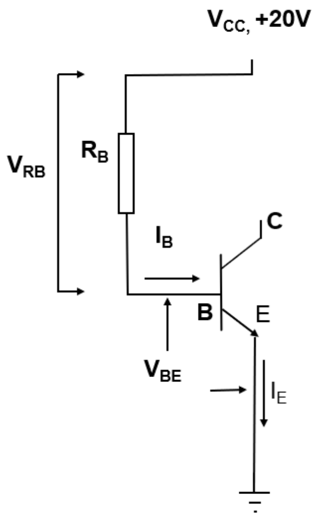


Figure 3.14: Common Emitter Circuit

- To quickly determine the current value, this circuit can be divided into two parts: the input and the output.
- Input section:



V_{CC} = voltage source DC (bias voltage)
V_{RB} = voltage that produce through R_B
V_{BE} = voltage that produce between base and emitter (B – E)
= barrier voltage ($V_{B\text{-}E}$)

Equation:

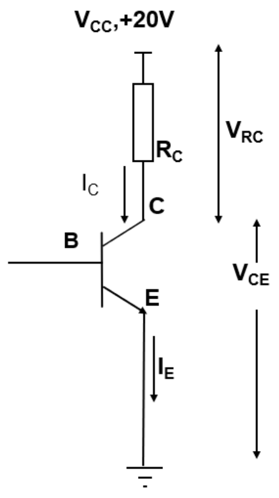
$$V_{CC} = V_{RB} + V_{BE}$$

$$V_{CC} = I_B \cdot R_B + V_{BE}$$

$$\boldsymbol{I_B = \frac{V_{CC} - V_{BE}}{R_B}}$$

Figure 3.15: Input Section for Common Emitter Circuit

- Output section:



V_{CC} = reverse bias voltage for collector
V_{RC} = voltage drop at the load resistor at the collector
V_{CE} = voltage drop between collector and emitter

Equation:

$$I_C = \beta \cdot I_B$$

$$V_{CC} = V_{RC} + V_{CE}$$

$$V_{CC} = I_C \cdot R_C + V_{CE}$$

$$\boldsymbol{V_{CE} = V_{CC} - I_C \cdot R_C}$$

Figure 3.16: Output Section for Common Emitter Circuit

- DC Operational Point (Q-Point)
    - When a transistor receives the proper bias DC voltage, it can begin to operate, albeit without AC voltage input.
    - Both the current collector (I_C) and the current base (I_B) can flow. The collector current flowing across the circuit is referred to as current operation (I_{CQ}).
    - V_{CE} value can be obtained when current operation operates through a load resistor at the collector section (R_C):
    - Under this condition, the V_{CE} value would be known as '*voltage value at the operating point*', (V_{CEQ})
    - The meet point, known as Q-point, so named because the Q stands for the word '*quiescent*' which means tranquil, is where we meet.

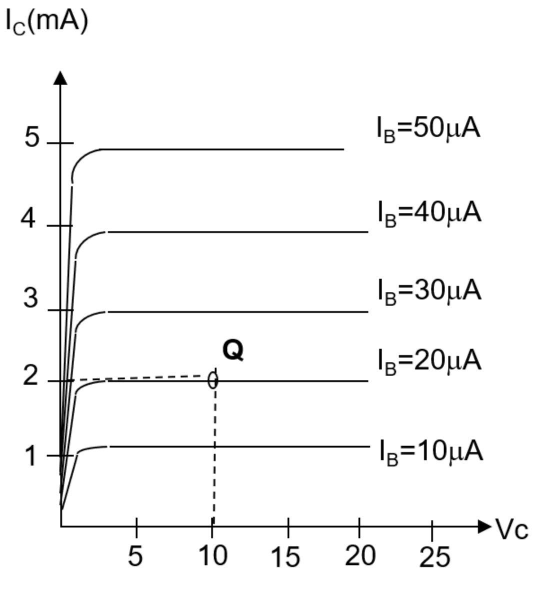


Figure 3.17: DC Operational Point

- DC Saturated Point
    - The DC saturation region is the area where the V_C value is equal to zero and the collector current (I_C) is at its maximum. Currently, collector current is referred to as I_C (saturation).
    - The maximum collector current for a circuit is known as I_C (DC saturation).
    - Equation:

$$V_{CC} = V_{RL} + V_C$$

$$saturation, V_C = 0$$

$$\therefore V_{CC} = V_{RL}$$

$$V_{CC} = I_{C(DCsaturation)} \cdot R_L$$

$$\boldsymbol{I_{C(DCsaturation)} = \frac{V_{CC}}{R_L}}$$

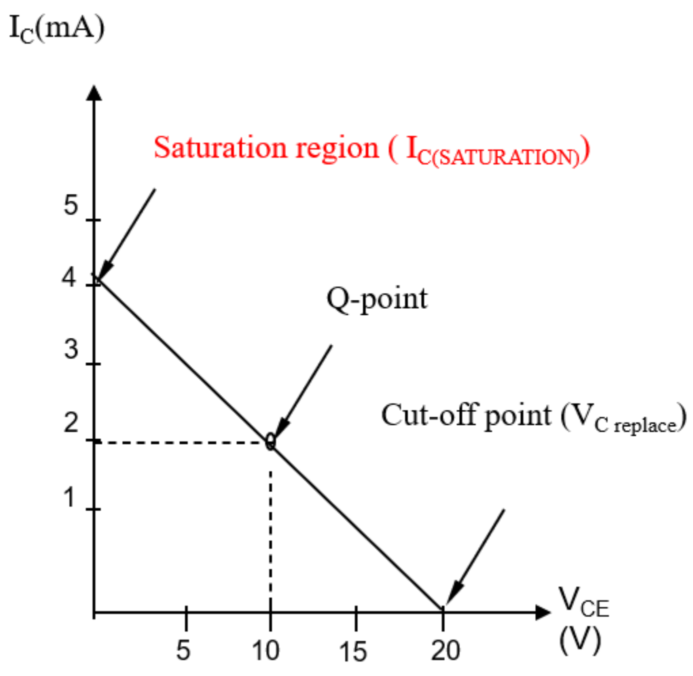


Figure 3.18: DC Saturated Point

- DC Cut-off Point
    - When the I_B value is low, the I_C value may likewise be low and the V_C value may be higher. If the I_B value keeps falling, the I_C value goes to zero and the V_{CE} value can reach the V_{CC} value.

$$V_C = V_{CC} - V_{RL}$$
$$V_C = V_{CC} - I_C \cdot R_L$$

$$cut - off, I_C = 0$$

$$V_C = V_{CC}$$

$$V_{CE(DCcut-off)} = V_{CC}$$

- Cut-off region is where there is no current flow.

- DC Load Line
    - ***The line that connected the cut-off point and the DC saturation*** point is known as **DC load line**.
    - The voltage drop at the emitter and collector sections is represented by the voltage that is obtained between 0 and V_{CE}. Moreover, the voltage drop at the load resistor is represented by the voltage between V_{CE} and V_{CC}.
    - There are two factors that can alter the slope of the load line:
        - Value of the load resistor RL is altered.
          - The saturation point position may shift when the RL value is changed because we know the equation that defines the Q-point is:

$$\boldsymbol{Q - point = \frac{V_{CC}}{R_L}}$$

        - Set the supply voltage to V_{CC} (collector). Since $V_{CE(cut\text{-}off)} = V_{CC}$, the maximum voltage at the collector can be obtained.

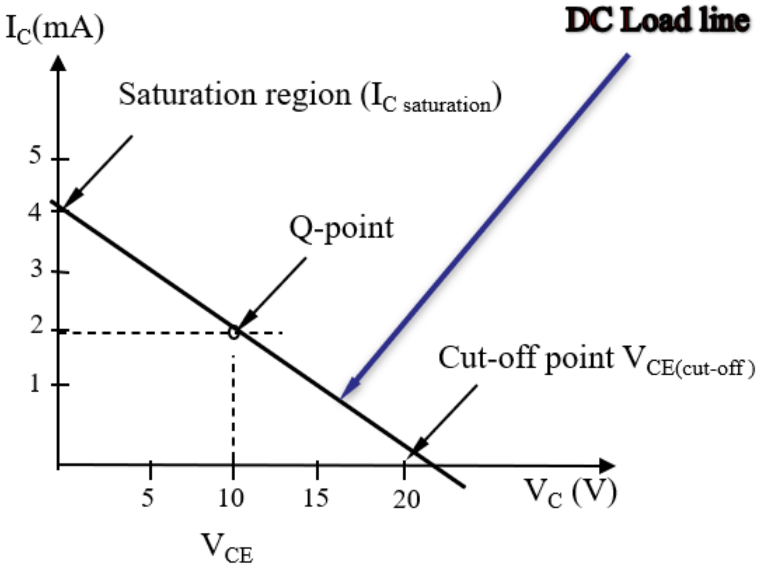


Figure 3.19: DC Load Line

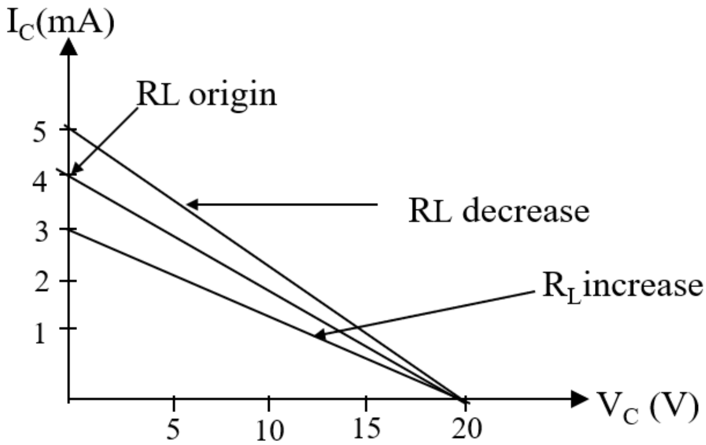


Figure 3.20: Illustration what happens when the R_L value is altered.

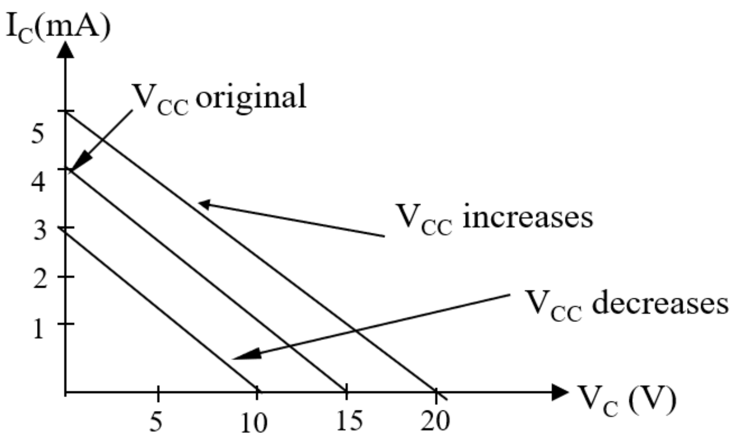
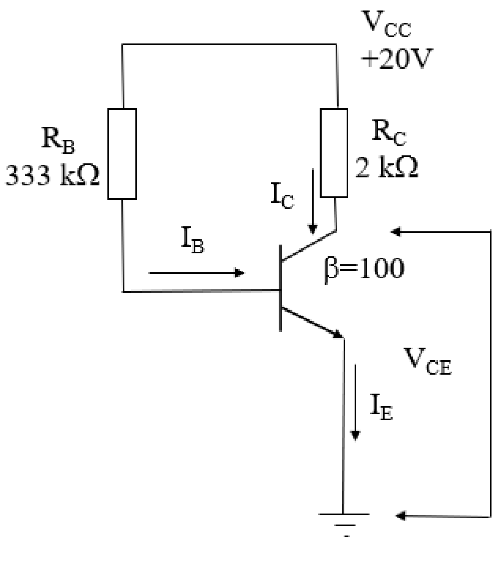


Figure 3.21: Illustration what happens when the V_{CC} value is altered.

- Example 3.1:
  - Draw the DC load line for common emitter circuit and sign the Q-point position. Assume β=100



$\underline{\textbf{\textit{Solution}}: \textbf{\textit{Operation point}}\ (\boldsymbol{Q-point})}$

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

$$= \frac{20\,V - 0.7}{333\,k\Omega} = 57.96\,\mu A_{\#}$$

$$I_C = \beta \cdot I_B$$

$$= (100)(57.96\,\mu A) = 5.8\,mA_{\#}$$

$$V_C = V_{CC} - I_C \cdot R_L$$

$$= 20\,V - (5.8\,mA)(2\,k\Omega)$$

$$= 20\,V - 11.6\,V = 8.4\ V_{\#}$$

$$V_{CQ} = V_C = \mathbf{8.4\,V}_{\#}$$

$$I_{CQ} = I_C = \mathbf{5.8\,mA}_{\#}$$

Solution: DC Saturation point

$$I_{C(DC\ Saturation)} = \frac{V_{CC}}{R_L} = \frac{20}{2\ k}$$

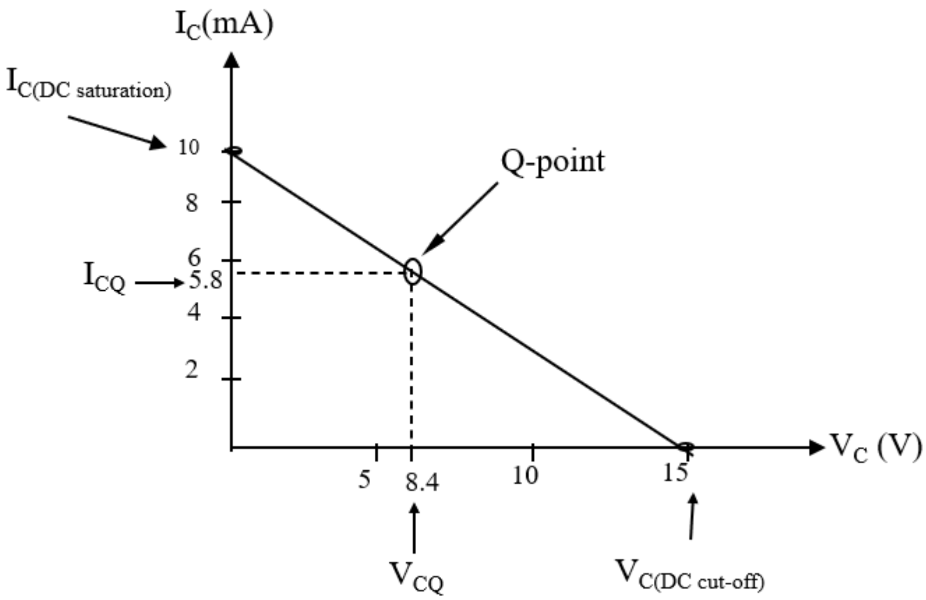
$$= \mathbf{10\ mA}_{\#}$$

Solution: Cut − off point

$$I_C = 0$$

$$V_{C(DC\ cut-off)} = V_{CC} = \mathbf{15\ V}_{\#}$$

Solution: DC Load Line



- The Operations of a Common Emitter Amplifier Circuit with AC Input Signal
    - A coupling capacitor must be used to connect an amplifier circuit in order to apply an AC signal.
    - For a DC source, the capacitor is open, while for an AC source, it is short.
    - The circuit's goal is to generate an output signal with a larger amplitude with the same waveform.
    - AC signal can pass through a capacitor since the load at the output section is:

$$r_L = R_C // R_L$$

$$\checkmark\ \frac{1}{r_L} = \frac{1}{R_C} + \frac{1}{R_L}$$

**r_L is total resistance at output section*

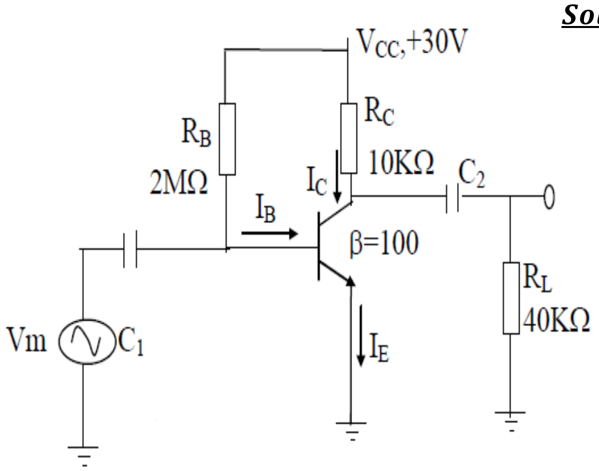
- The collector current value may have a new line ***(AC load line)*** in the AC analyzer since it cannot be dropped at the load line. Additionally, it may have a new cut-off region and saturation region.
- The equation for calculating the ac saturation and cut-off regions:

$$I_{C(AC\ Saturation)} = I_{CQ} + \frac{V_{CQ}}{r_L}$$

$$V_{C(AC\ cut-off)} = V_{CQ} + I_{CQ} \cdot r_L$$

- Example 3.2:

- Draw the circuit's DC and AC load lines based on figure given. Point to the Q-point. **Disregard V_{BE}.**



Solution: Operation point (Q – point)

$$I_B = \frac{V_{BB} - V_{BE}}{R_B}$$

$$= \frac{30\ V - 0}{2\ M\Omega} = 15\ \mu A_{\#}$$

$$I_C = \beta \cdot I_B$$

$$= (100)(15\ \mu A) = 1.5\ mA_{\#}$$

$$V_C = V_{CC} - I_C \cdot R_L$$

$$= 30\ V - (1.5\ mA)(10\ k\Omega)$$

$$= 30\ V - 15\ V = 15\ \ V_{\#}$$

$$V_{CQ} = V_C = \mathbf{15\ V}_{\#}$$

$$I_{CQ} = I_C = \mathbf{1.5\ mA}_{\#}$$

Solution: DC Saturation point

$$I_{C(DC\ Saturation)} = \frac{V_{CC}}{R_L} = \frac{30\ V}{10\ k\Omega}$$

$$= \mathbf{3\ mA}_{\#}$$

Solution: Cut − off point

$$I_C = 0$$

$$V_{C(DC\ cut-off)} = V_{CC} = \mathbf{30\ V}_{\#}$$

Solution: AC Load line

$$r_L = R_C // R_L \left(\frac{1}{r_L} = \frac{1}{10\ k\Omega} + \frac{1}{40\ k\Omega}\right)$$

$$= \mathbf{8\ k\Omega}_{\#}$$

$$V_{C(AC\ cut-off)} = V_{CQ} + I_{CQ} \cdot r_L$$

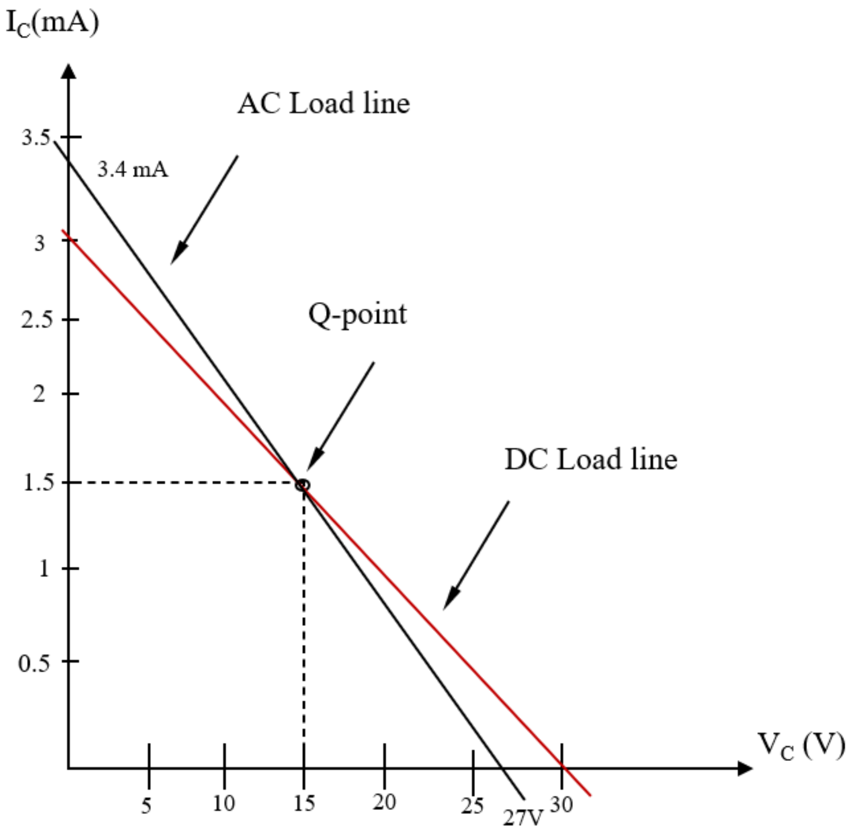
$$= 15\ V + (1.5\ mA \times 8\ k\Omega)$$

$$= \mathbf{27\ V}_{\#}$$

$$I_{C(AC\ Saturation)} = I_{CQ} + \frac{V_{CQ}}{r_L}$$

$$= 1.5\ mA + \frac{15\ V}{8\ k\Omega}$$

$$= \mathbf{3.4\ mA}_{\#}$$



- The Amplitude and Phase Shift of the Input and Output Waveforms
    - Output voltage may become more positive when input voltage oscillates during the second half of a negative cycle.
    - The phase difference between the input and output voltages is 180°, as shown in Figure 3.22.

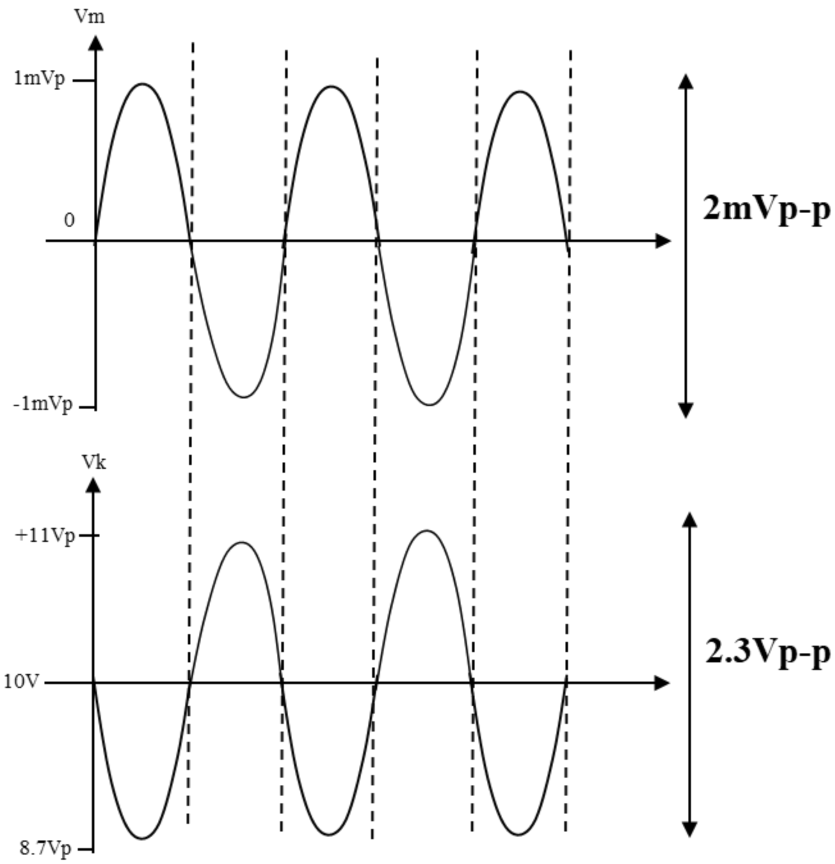


Figure 3.22: Input and Output Voltage Phase Difference

- Voltage Gain
  - The comparison of the input and output voltage values is known as the Voltage gain (A_v).
  - Example 3.3:
    - Referring to Figure 3.22 :

$$A_v = \frac{Output\ Voltage, V_o}{Input\ Voltage, V_i}$$

$$= \frac{2.3\ V_{pp}}{2\ mV_{pp}}$$

$$= 1150$$

  - Another formula that may be used to find the voltage gain circuit value is "first approximated" and "ideal transistor concept." In this approach, the circuit's tiny values are all ignored, and voltage gain is calculated by dividing the input resistance by the output resistance.
  - From this idea, the voltage gain equation is :

$$A_v = \frac{r_L}{re'}$$

  - while the equation for re' is :

$$re' = \frac{25\ mV}{I_E}$$

$I_E = I_C$ (current circuit operation)
$25\ mV$ = trasnsistor voltage value

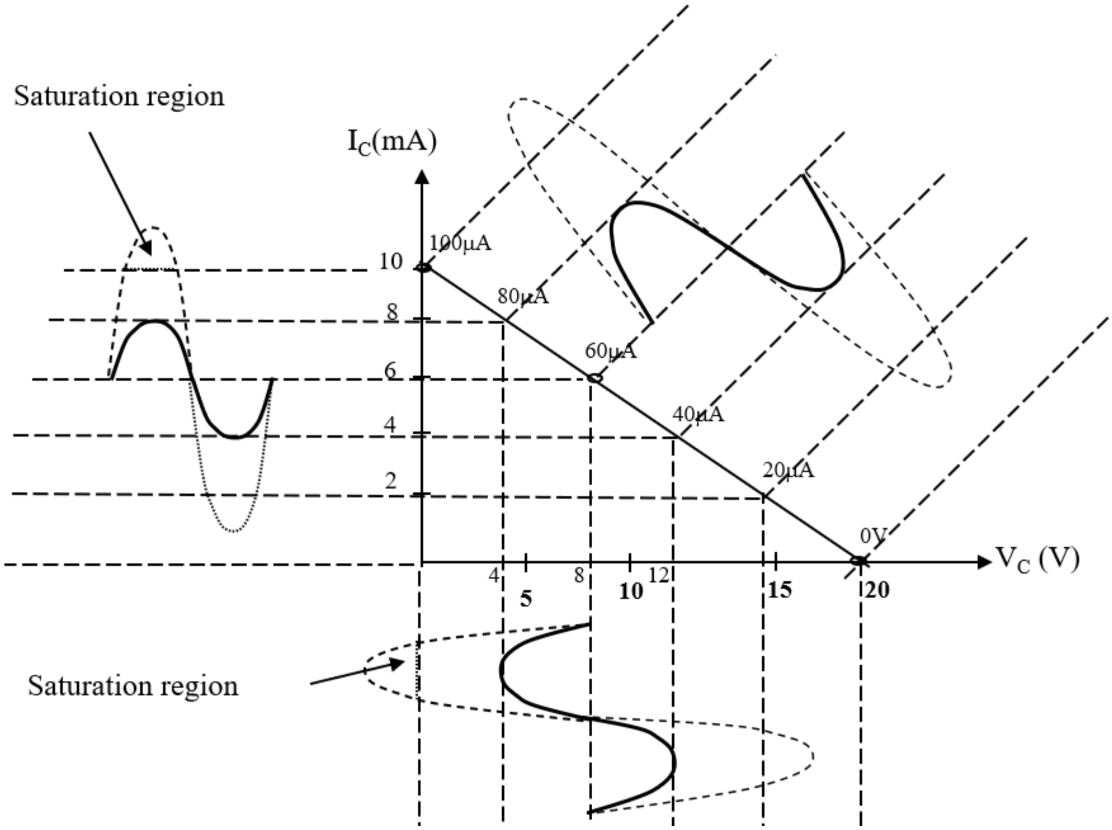


Figure 3.23: The Occurrence of Amplitude Distortion *(high input signal)*

- One of the factors that can affect I_B value is the AC input signal, thus its value shouldn't be too high as this could cause the I_B oscillation to become quite large.
- With the reference to Figure 3.23:
  - Q-point position during I_B = 60 μA, I_C = 6 mA, and V_C = 8 V is shown.
  - I_B oscillates between 40 μA to 80 μA, causing the V_C to oscillate between 4 V to 12 V while I_C oscillate between 4 mA to 8 mA.
- The voltage is measured at V_C *(the output value of the AC voltage)* and oscillate in one complete cycle 8 V_{P-P}.
- An excessively strong ac input signal may result in a large oscillation in the I_B *(waveform at the break line)*. As a result, I_C oscillate value follows

V_C and is similarly large. We discovered that the saturation area is where the I_C and V_C oscillate. There is no further gain value possible at this point. Thus, there is a chance of waveform **breakdown** or **distortion** across this area.

- As a result, every amplifier output has a piece that breaks; this leads us to believe that the amplifier circuit is incomplete and therefore to be avoided. Therefore, to identify a large and complete oscillation, the Q-point position is typically chosen near the middle of the load line.

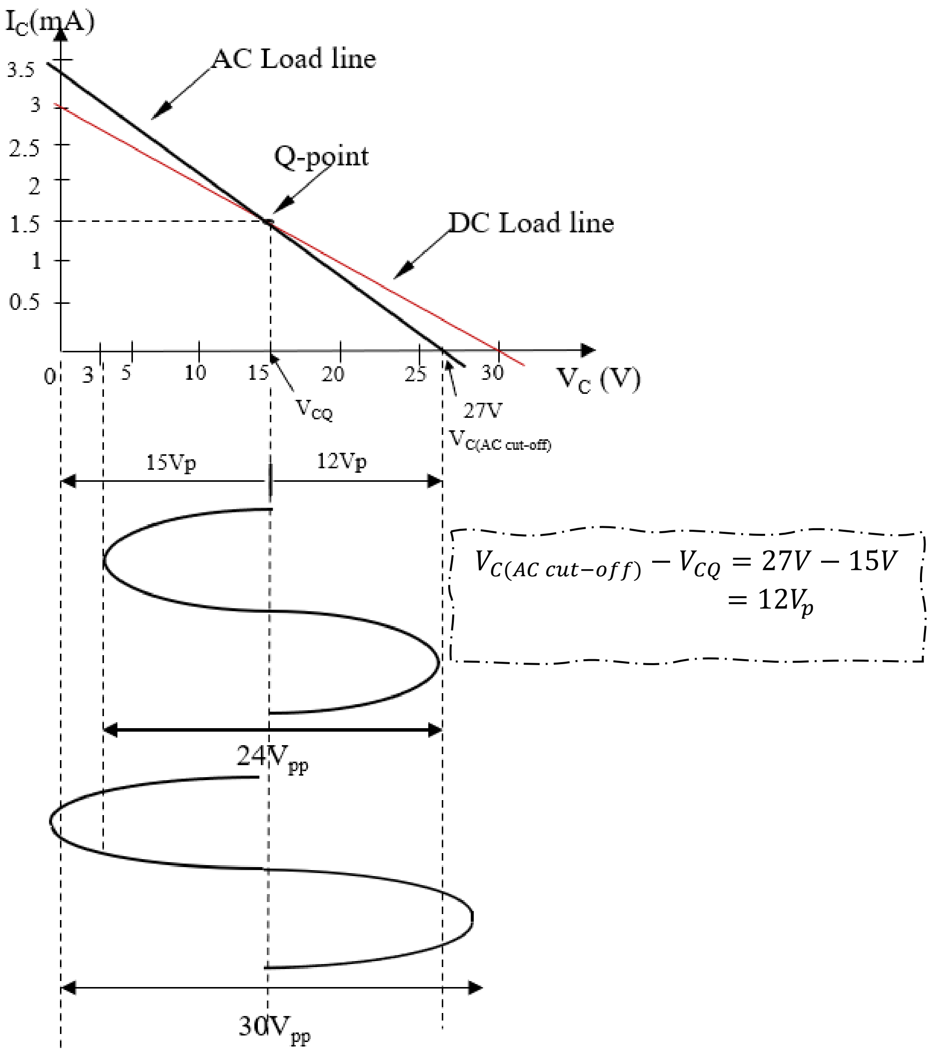


Figure 3.24: Max Input Signal *(Undistorted Output Signal Amplitude)*

- Example 3.4:
  - Referring to the value of maximum output voltage without distortion ($V_{o(max)}$) in Figure 3.24, determine the value of the maximum input voltage without distortion ($V_{i(max)}$) for the amplifier if the voltage gain of the A_v circuit is 100.

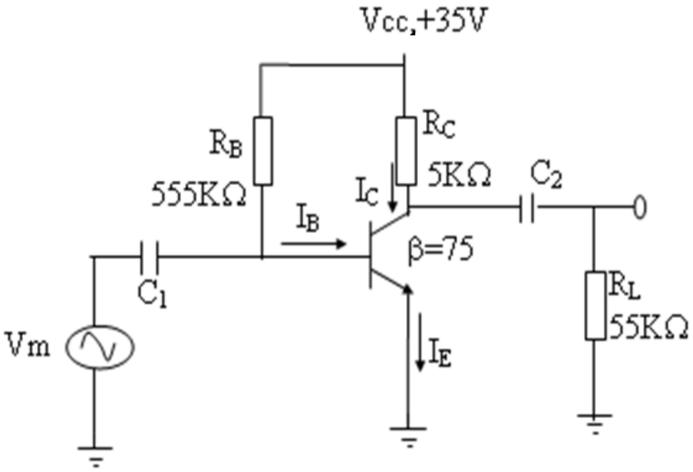
$$A_v = \frac{V_o}{V_i}, \quad V_i = \frac{V_o}{A_v}$$

$$V_i = \frac{24\ V_{pp}}{100}$$

$$= 240\ mV_{pp_{\#}}$$

  - The maximum input voltage without distortion value (Vi(max without distortion)) is the input voltage under these conditions since the output voltage that is being used is the maximum output voltage without distortion value (Vo(max without distortion)).
- The output signal that oscillates symmetrically and without distortion is called **Maximum Output Voltage without Distortion.**
- As previously mentioned, an AC load line may terminate if the load value at the circuit output's AC voltage differs from the load value at the circuit output's DC voltage.
- Maximum output voltage without distortion, $V_{o\ (max)}$ normally drawn referring to AC load line since the AC load line exits the circuit when an AC input signal is applied.
- Try to figure out which signal requires the highest output voltage possible for the following load line without distortion.
- To obtain the largest output voltage with the least amount of distortion, we can select the region with the fewest peak voltage counts.

- For example, one peak at the output voltage causes distortion if we use the large peak voltage value as the output voltage. The maximum output voltage without distortion is not met by this circumstance.
- Example 3.5:
  - Determine:
    - (i) All the values needed to draw the AC and DC load lines from the following figure. Ignore V_{BE}.
    - (ii) Sketch the maximum output voltage without distortion and determine the maximum input voltage without distortion using the graph.



$$I_B = \frac{V_{BB}}{R_{BB}} = \frac{35\ V}{555\ k\Omega} = 63.06\ \mu A_{\#}$$

$$I_C = \beta \cdot I_B = (75)(63.06\mu) = 4.73\ mA_{\#}$$

$$V_C = V_{CC} - I_C \cdot R_C$$

$$= 35\ V - 33.65\ V = 11.35\ V_{\#}$$

$$I_{CQ} = I_C = 4.73\ mA_{\#}$$

$$V_{CQ} = V_C = 11.35\ V_{\#}$$

1

DC Load Line

$$I_{C(DC)} = \frac{V_{CC}}{R_C} = \frac{35\ V}{5\ k\Omega} = 7\ mA_{\#}$$

$$V_{C(DC)} = V_{CC} = 35\ V_{\#}$$

2

AC Load Line

$r_L = R_C // R_L = 5\ k\Omega // 55 k\Omega$

$= 4.583\ k\Omega_{\#}$

$V_{C(AC)} = V_{CQ} + I_{CQ} \cdot r_L$

$= 11.35\ V + (4.73\ mA)(4.583\ k\Omega)$

$= 33.028\ V_{\#}$

$$I_{C(DC)} = I_{CQ} + \frac{V_{CQ}}{r_L}$$

$$= (4.73\ mA) + \frac{11.35\ V}{4.583\ k\Omega}$$

$= 7.21\ mA_{\#}$

3

$V_{in\ (max)}$ without distortion

$$r_e' = \frac{25\ mV}{i_E} = \frac{25\ mV}{4.73\ mA} = 5.29\ \Omega_{\#}$$

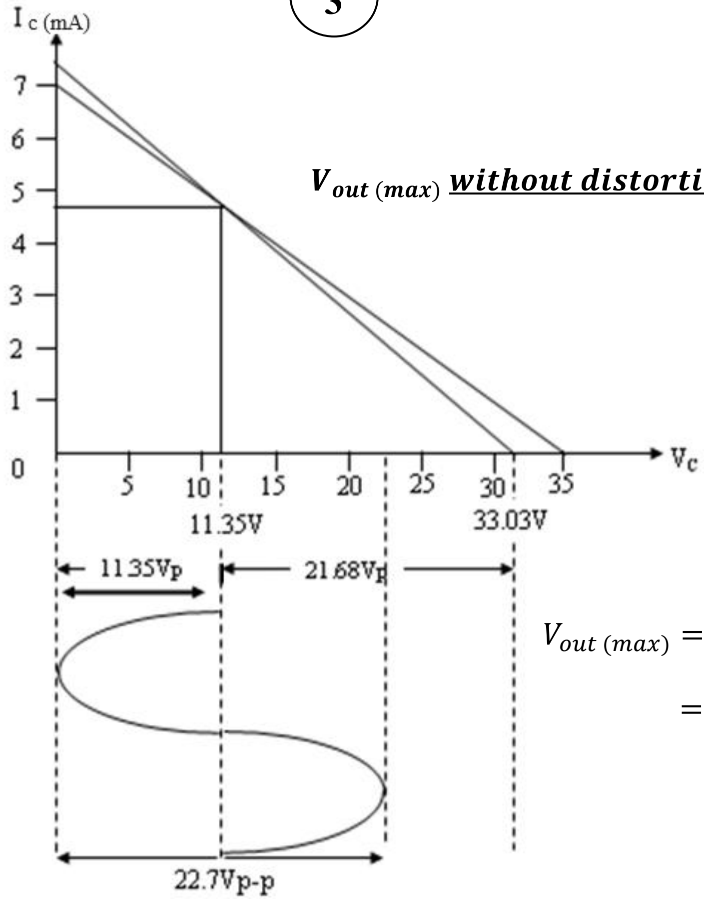
$$A_V = \frac{V_{out}}{V_{in}} = \frac{r_L}{r_e'} = \frac{4.58\ k\Omega}{5.29\ \Omega} = 867_{\#}$$

$$V_{in} = \frac{V_{out}}{A_V} = \frac{22.7\ V_{pp}}{867} = 26\ mV_{\#}$$

$* \ I_C = I_E$

$* \ V_{in} = V_{in(without\ distortion)}$

5



$V_{out\ (max)}$ without distortion

$V_{out\ (max)} = 11.35\ V_p \times 2$

$= 22.7\ V_{pp}$

4

3.6 Frequency Response Curve

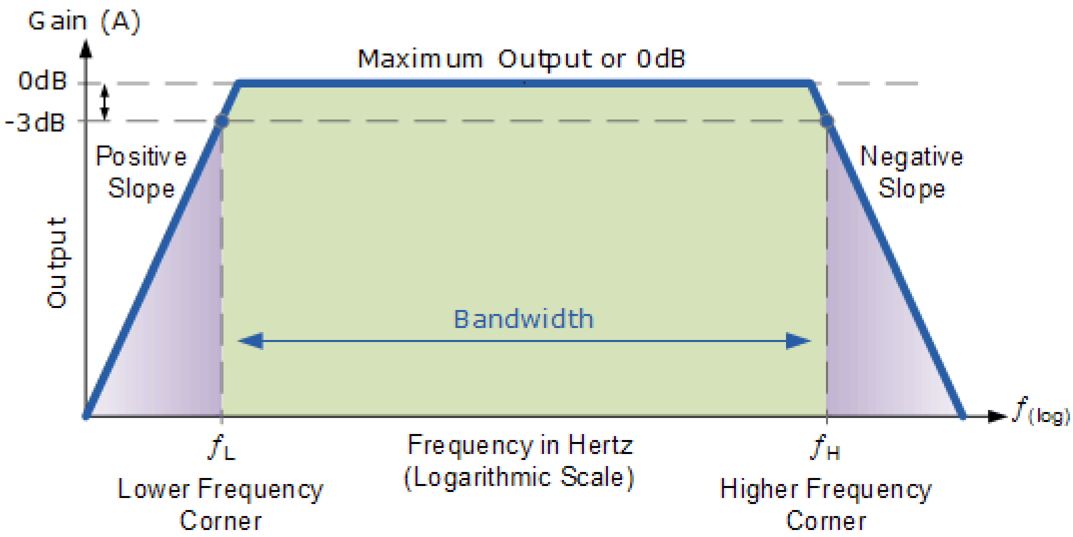


Figure 3.25: Frequency Response of An Amplifier or Filter

- The frequency response is the measure of any system's output spectrum in response to an input signal.
- The frequency response curves are often used to indicate the accuracy of electronic components or system.
- The **horizontal axis (x)** is labeled as **the frequency**, or the vibration that is detected by your ear and is measured in **hertz (Hz)**, while the **vertical axis (y)** is typically labeled as **the sound intensity**, also known as **amplitude**, in **decibels (dB)**.

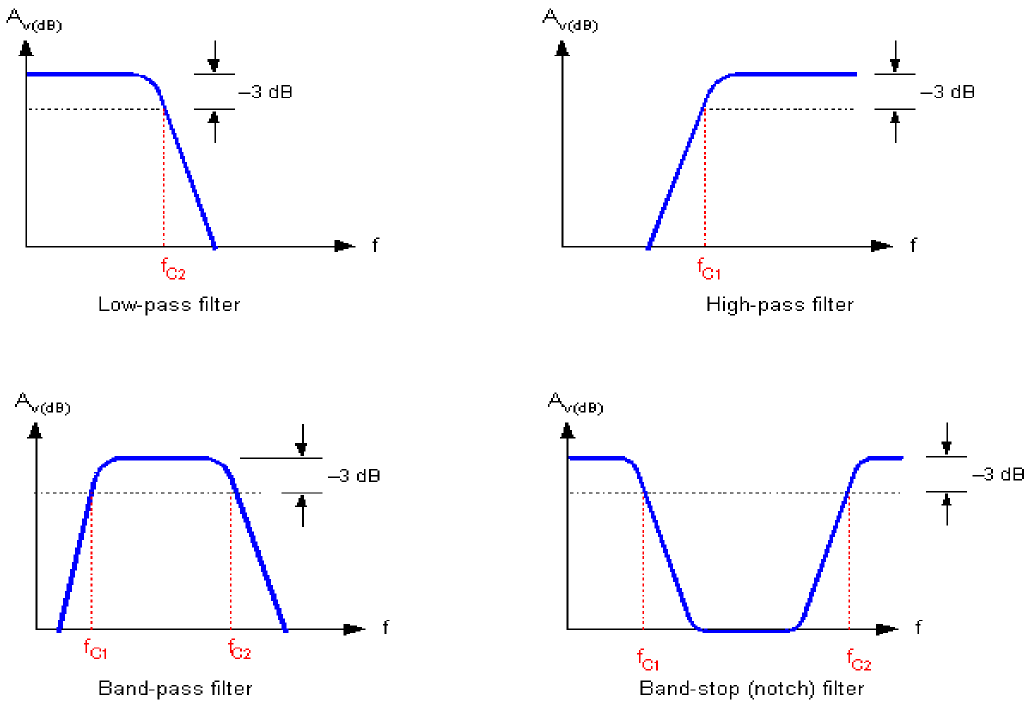


Figure 3.26: Filters

- Important parameters of a frequency response curve:

1. Maximum voltage gain, A_{Vmax} (dB)

- In order to reduce a huge measurement to a considerably smaller and more useful range, use A_{Vmax} (dB) rather than Av_{max} (V).
- A circuit's dB voltage gain can be calculated by multiplying the common log of A_V by twenty. The formula:

$$A_{V(dB)} = 20 \log \frac{V_{out}}{V_{in}}$$

2. Cut-off frequency

- At this frequency, a device will stop functioning efficiently or even stop functioning at all, which will cause it to shut down or be disconnected.
- The change in dB voltage gain is -3 dB when it falls to 70.7% of its maximum value.

- There exist a frequency range; 'lower cut-off frequency (f_H) and higher cut-off frequency (f_L).

3. ***Frequency bandwidth***

   i. **Bandwidth *(BW)*** is the difference between the upper and lower frequencies in a contiguous set of frequencies. It is typically measured in hertz.

$$BW = f_H - f_L$$

- deciBel (dB)
  - Decibel (dB) is the standard unit of measurement for the ratio of circuit output amplitude to input amplitude. Decibel is utilized in measurement because decibel make it simple to represent both extremely big and very small numbers.
  - Since 'bel' was deemed too big to be measured in units, decibel (dB) was defined so that **10 decibel = 1 bel**.

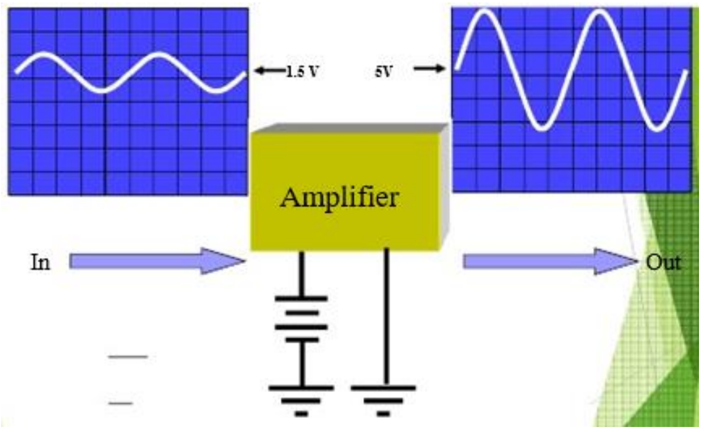
$$A_{P\ (dB)} = 10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

or

$$A_{V\ (dB)} = 20 \log_{10}\left(\frac{V_{out}}{V_{in}}\right)$$

- Frequency response characteristics of an amplifier
  - Calculate the maximum voltage gain in decibel, **$A_{Vmax(dB)}$**, using the formula:

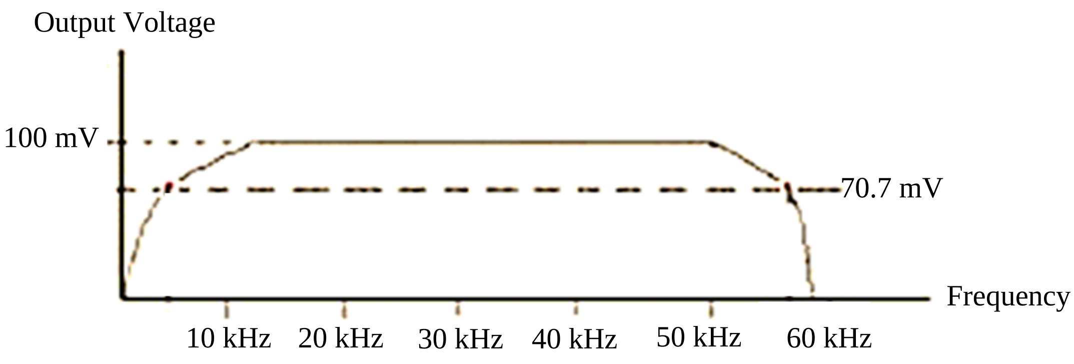
$$A_{Vmax(dB)} = 20\log_{10}(A_{Vmax})$$



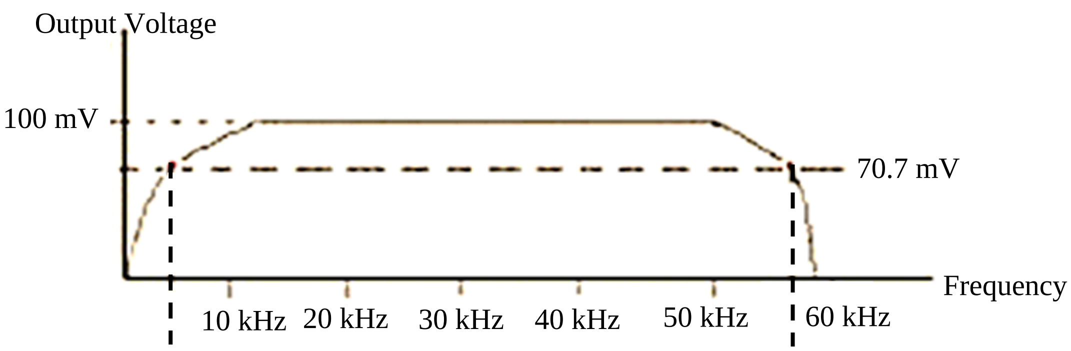
$$A_{Vmax} = \frac{V_{out}}{V_{in}} = \frac{5\ V}{1.5\ V} = 3.33$$

$$A_{Vmax(dB)} = 20\log_{10}(A_{Vmax}) = 20\log_{10}(3.33) = 10\ dB_{\#}$$

  - Example 3.6:
    - Determine the cut-off frequencies (f_{C1} and f_{C2}) and the frequency bandwidth from the frequency response diagram.



- Solution:
  - ✓ The amplifier's output has decreased to 70.7% of its maximum output, as indicated by the two spots on the response curve.
  - ✓ This indicates that at these frequencies, the output of 100 mV has decreased to 70.7 mV. We refer to these as the -3 dB points.



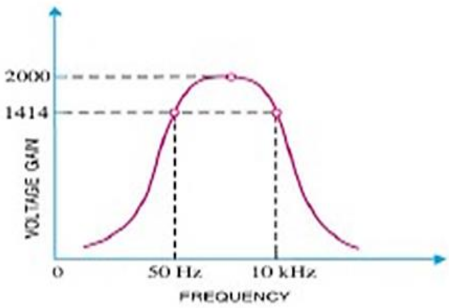
$f_{C1} = 5\ kHz_{\#}$ $f_{C2} = 58\ kHz_{\#}$

$$BW = f_{C2} - f_{C1}$$

$$= 58\ kHz - 5\ kHz$$

$$= 53\ kHz_{\#}$$

- Example 3.7:
  - The highest voltage gain of an amplifier is 2000, and it happens at 2 kHz. Between 51 Hz and 10 kHz, it drops to 1414. Calculate:
    - i. Bandwidth
    - ii. Lower cut-off frequency
    - iii. upper cut-off frequency
  - Solution:
    - ✓ the maximum gain is 2000.
    - ✓ Then 70.7% of the gain is 0.707 x 2000 =1414.
    - ✓ It is given that gain is 1414 at 50Hz and 10kHz.
    - i. Bandwidth = 10kHz – 50Hz = 9950Hz



ii. Lower cut-off frequency = 50 Hz

iii. Upper cut-off frequency = 10 kH

3.7 The Classification of Amplifier

- We believed that the amplifier produced an output for each component of the incoming signal. Only a portion of the input signal should be conducted by the transistor if needed.

- The amplifier's class of operation is determined by the portion of the input for which there is an output. Four types exist for operations on amplifiers.

- They are classified as class A, class AB, class B, class C

- Amplifier Types:
  - **Class A Amplifiers** are the simplest in design, and probably the best sounding of all the amplifier classes due to their low signal distortion.
  - **Class B amplifiers** were invented as a solution to the efficiency and heating problems associated with the class A amplifiers.
  - **Class AB Amplifier** is a combination of the two class A and class B type amplifiers above and is currently one of the most common types of power amplifier design.
  - **Class C Amplifier** design has the greatest efficiency but the poorest linearity of the classes of amplifiers.

- Class A Amplifier
    - The output of a class A amplifier conducts for the full 360° of the cycle.
    - The Q-point is set at the middle of the load line so that the AC signal can swing a full cycle.

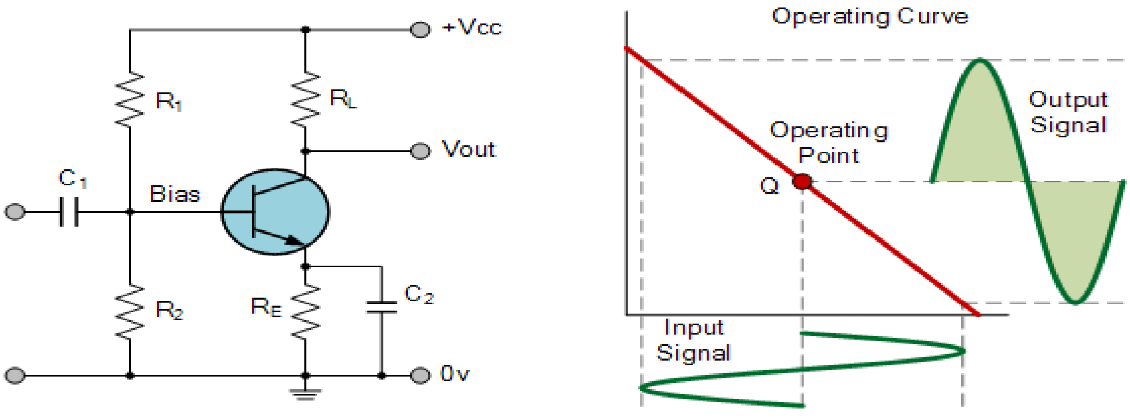


Figure 3.27: Class A Amplifier

- Class B Amplifier
    - The output of a class B amplifier only conducts 180°, or half of the AC input signal.
    - The Q-point is at 0V on the load line, so that the AC signal can only swing for one-half cycle.

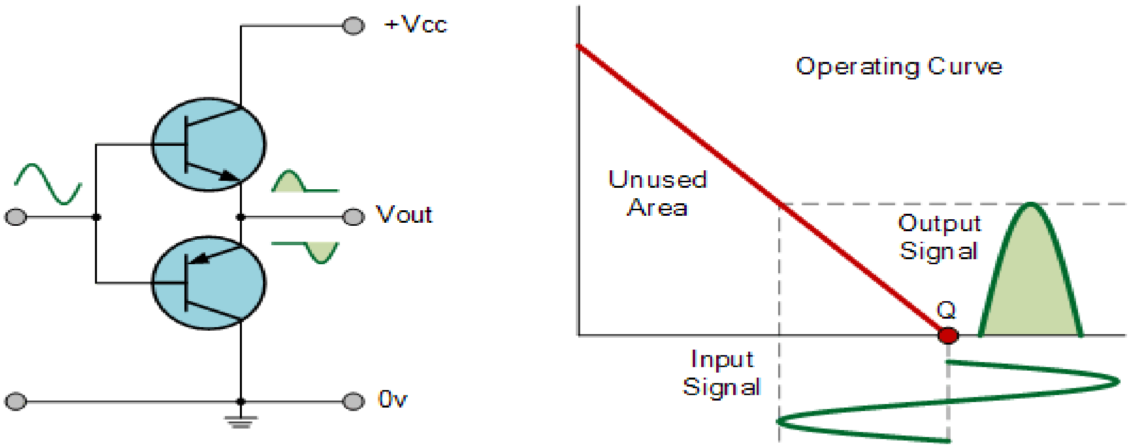


Figure 3.28: Class B Amplifier

- Class AB Amplifier
  - The Q-point of this amplifier is below the class A but above the class B, representing a compromise between the two types of amplifiers.
  - The output conducts between 180° and 360° of the AC input signal.

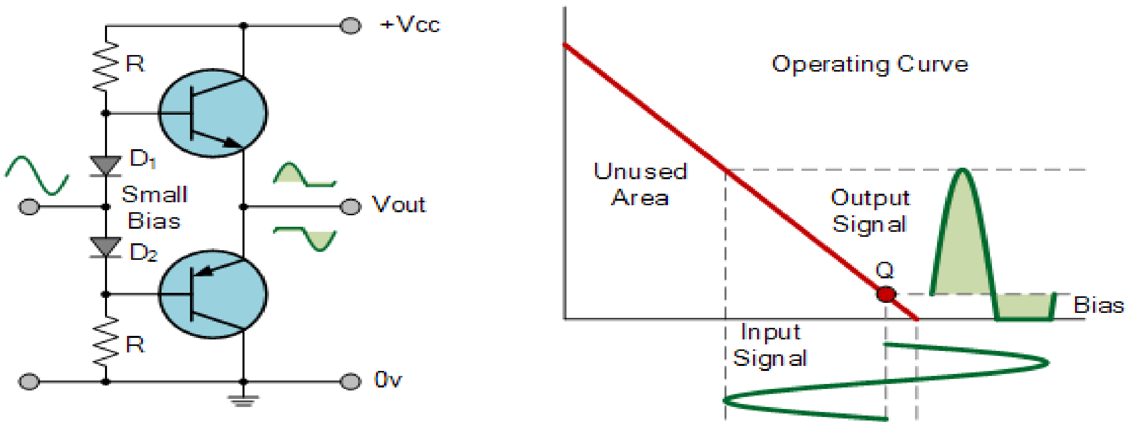


Figure 3.29: Class AB Amplifier

- Class C Amplifier
  - The output of the class C conducts for less than 180° of the AC cycle. The Q-point is below cutoff.

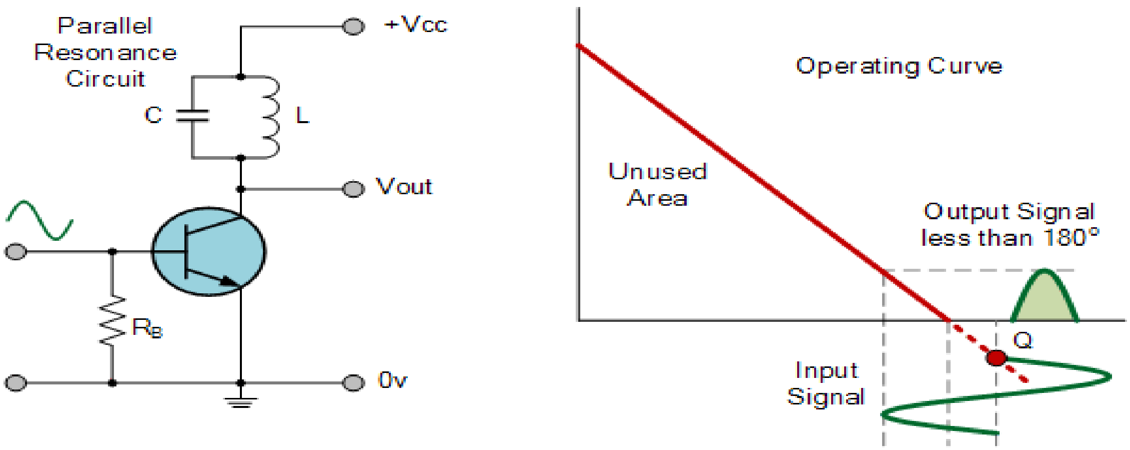


Figure 3.30: Class C Amplifier

- Amplifier Classes Comparison

Table 3.4: Comparison of Amplifier Classes

Class	**A**	**AB**	**B**	**C**
Operating cycle	360°	180° to 360°	180°	less than 180°
Power efficiency	**25% to 50%**	**between 25% and 78.5% (50%)**	**78.5%**	**90%**

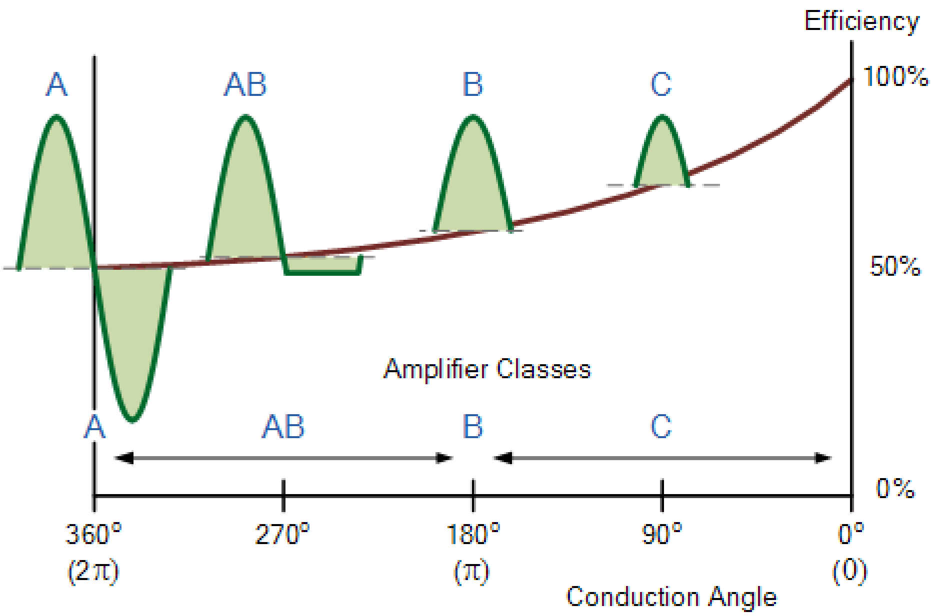


Figure 3.31: Efficiency of Amplifier Classes

- Application
  - **Class A** – practically all small signal amplifiers. A few moderate power amplifiers in audio applications.
  - **Class AB** – high power stages in both audio and radio frequency applications.

- **Class B** - extensively for audio amplifiers that require high-power outputs. It is also used as the driver- and power-amplifier stages of transmitters.
- **Class C** – generally limited to radio-frequency amplifier in transmitters, megaphones. Also called a 'tuned' amplifier.

3.8 Understand Other Biasing Techniques of Common Emitter Transistor Configuration

- Biasing Techniques of Common Emitter Transistor Configuration
  - Applying DC voltages to maintain a constant amount of voltage and current is known as ***biasing***.
  - Determining and preserving the appropriate levels of quiescent current and voltage in the circuit is one of the fundamental issues with transistor amplifiers.
  - As a result, a technique to correctly bias the transistor amplifier and stabilize its DC operating point *(the values of the collector voltage and collector current when there is no signal)* is required.
  - 2 types biasing techniques of common emitter:
    - **base biased with emitter feedback technique**
    - **biased voltage divider technique**

- Emitter Feedback Technique
  - Connecting resistor R_E to the transistor's emitter.
  - The stability level will be higher with the emitter resistor R_E compared to the fixed bias arrangement.
  - When the temperature rises, I_C starts to rise.
  - When I_C rises, I_E rises as well, which causes V_E toget higher.
  - Although V_{BE} (or V_B – V_E) is fixed, V_{BE} decreases as V_E rises. Lowering V_{BE} has the overall effect of lowering I_C, which stabilizes the circuit.

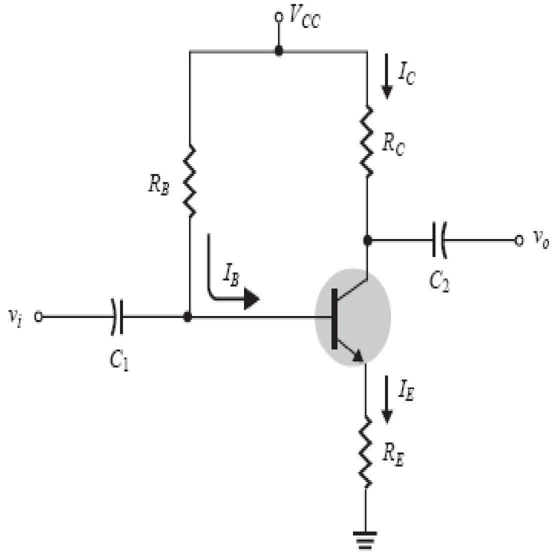


Figure 3.32: Base Biased with Emitter Feedback Technique

- Voltage Divider Technique
    - This technique differs from the emitter feedback technique with the existence of divider resistors R_1 and R_2.
    - These resistors provide a bias connection to the transistor base terminal which tries to balance the level of I_{BQ} with the change in beta.
    - If proper circuit parameters are employed, any change of beta will change the level of I_{BQ} but the operating point defined by I_{CQ} and V_{CEQ} can remain fixed.
    - Capacitor C_1 is added to bypass AC signal. *(to ground)*

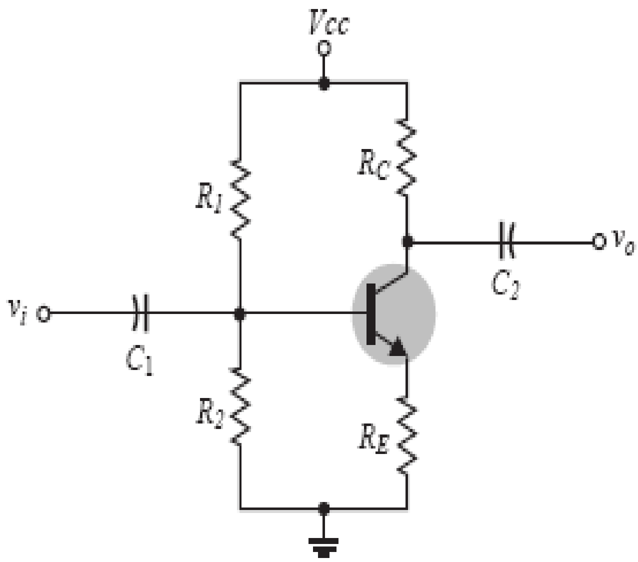


Figure 3.33: Biased Voltage Divider Technique

- Advantages of Biasing Technique
  - The voltage divider bias is widely used because reasonably **good stability** is achieved with a single supply voltage.

3.9 Concept of Feedback

- Definition of Feedback
  - A feedback amplifier is the process of sending part of the output signal of an amplifier, back to the input of the amplifier.
  - This partial dependence of amplifier output on its input helps to control the output. A feedback amplifier consists of two parts:

    i. An amplifier

    ii. A feedback circuit.

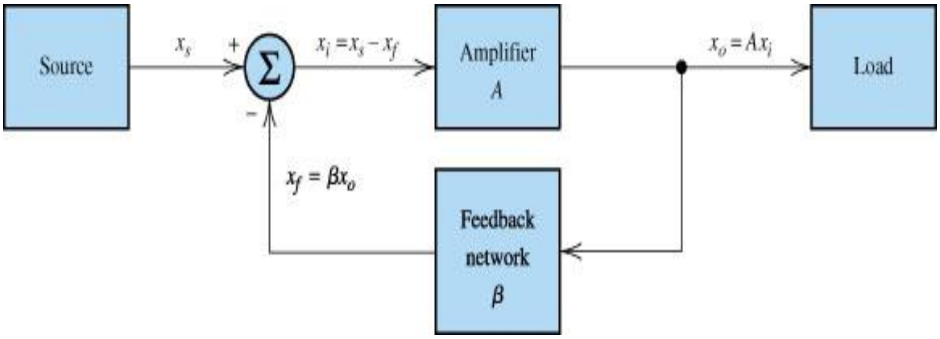


Figure 3.34: Block Diagram of Feedback

- The amplifier gain A *(amplifier A)* is often called **open-loop gain.**
- The term 'βA' is called **feedback factor** whereas β is known as **feedback ratio**.
- The expression (1 ± βA) is called **loop gain**.

- Types of Feedback
  - There are 2 types of feedback.
    i. Positive feedback

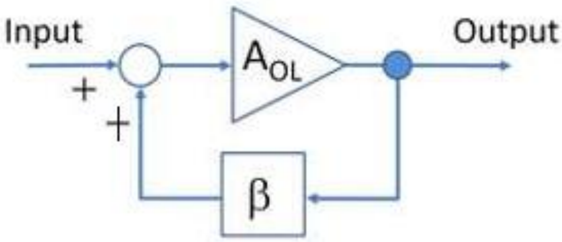


Figure 3.35: Positive Feedback

ii. Negative feedback

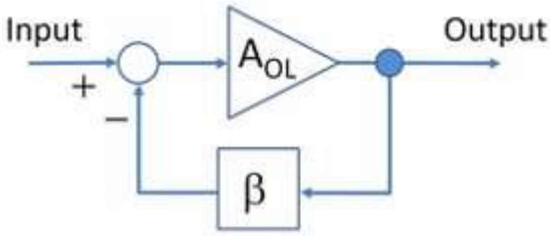


Figure 3.36: Negative Feedback

- Positive Feedback
  - It's also known as:
    - ***regenerative*** *or*
    - ***direct feedback.***
  - Positive feedback occurs when the feedback signal is in phase with the input signal. This indicates that the input signal will be enhanced or "regenerated" by the feedback signal.
  - As a result, the output signal has a higher amplitude than it would have without the feedback.
  - Positive feedback is rarely utilized in amplifiers because it causes too much distortion. Nonetheless, oscillator circuits use it because it boosts the original signal's power.

- Negative Feedback
  - It's also known as:
    - ***degenerative*** *or*
    - ***inverse feedback.***

- Amplifier with negative feedback, the feedback signal is out of phase with the input signal. This means that the feedback signal will subtract from or "degenerate" the input signal.
- As a result, the output signal has a less amplitude than it would have without the feedback.
- Negative feedback is frequently used in amplifier circuits.

- The Amplifier Gain A´ With Feedback is Given by

$$A' = \frac{V'_o}{V_i} = \frac{A}{1 - \beta A}$$

  - Positive feedback

$$A' = \frac{A}{1 - \beta A}_{\#}$$

  - Negative feedback

$$A' = \frac{A}{1 - (-\beta A)}$$

$$A' = \frac{A}{1 + \beta A}_{\#}$$

- Advantages of Negative Feedback
  - The voltage gain is more stable.
  - Increased bandwidth/ better frequency response.
  - Eliminates distortion and reduce the noise.
  - The input impedance increases.
  - Less dependent on temperature, manufacturing differences or other external properties of the devices.

- Disadvantages of Negative Feedback
  - Could result in instability if not properly constructed.
  - Reduction in the amplifier's gain.

CHAPTER 4

FIELD EFFECT TRANSISTORS (FET)

4.1 What would you get?

- Understand basic principles of JFET
- Understand basic principles of MOSFET
- Understand basic of JFET Amplifier
- Apply application of MOSFET as a switch

4.2 Basic Principles of Junction Field Effect Transistors (JFET)

- Introduction: The Field Effect Transistor (FET) is a THREE (3) terminal unipolar semiconductor device that has very similar characteristics to those of their *Bipolar Junction Transistor* (BJT) such as:
  - high efficiency,
  - instant operation,
  - robust and cheap,
  - can be used in most electronic circuit applications to replace BJT
- Differences
  - FET's are **voltage controlled devices** whereas BJT's are **current controlled devices.**
  - FET's also have a higher input impedance, but BJT's have higher gains.
  - FET's are less sensitive to temperature variations and because of there construction they are more easily integrated on IC's.
  - FET's are also generally more static sensitive than BJT's.

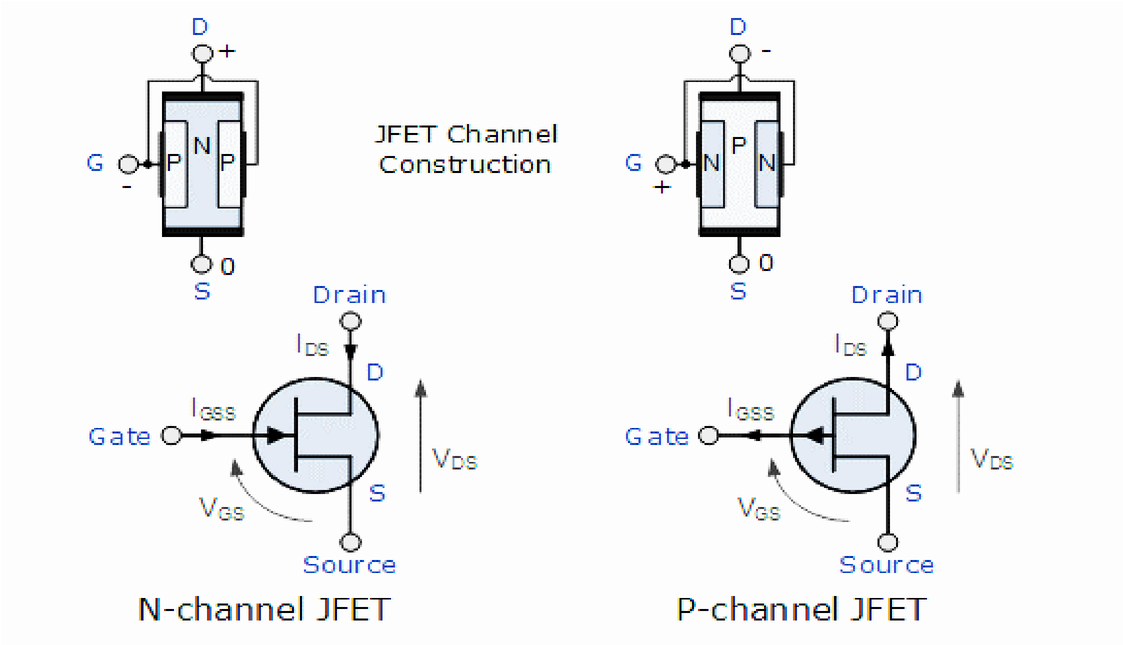


Figure 4.1: Physical Structure and Schematic Symbol of JFET

- Physical Structure
    - The Field Effect Transistor (FET) is a THREE (3) terminal device that is constructed with no PN-junctions within the main current carrying path between the Drain and the Source terminals.
    - The current path between these two terminals is called the "channel" which may be made of either a P-type or an N-type semiconductor material.
    - The control of current flowing in this channel is achieved by varying the voltage applied to the Gate.
    - The Field Effect Transistor is a "Unipolar" device that depends only on the conduction of electrons (N-channel) or holes (P-channel).

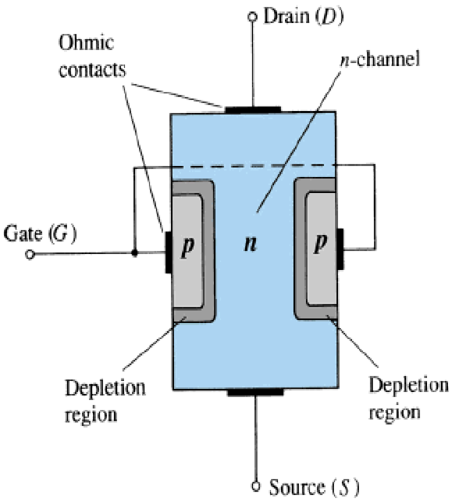


Figure 4.2: Physical Structure in Details

- Basic Operation of JFET
  - The way a JFET operates is like a water spigot:
    i. The source of water pressure – accumulated electrons at the negative pole of the applied voltage from drain to source
    ii. The drain of water – electron deficiency (or holes) at the positive pole of the applied voltage from drain to source.
    iii. The control of flow of water – Gate voltage that controls the width of the n-channel, which in turn controls the flow of electrons in the n-channel from source to drain.

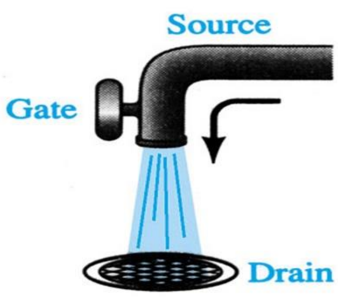
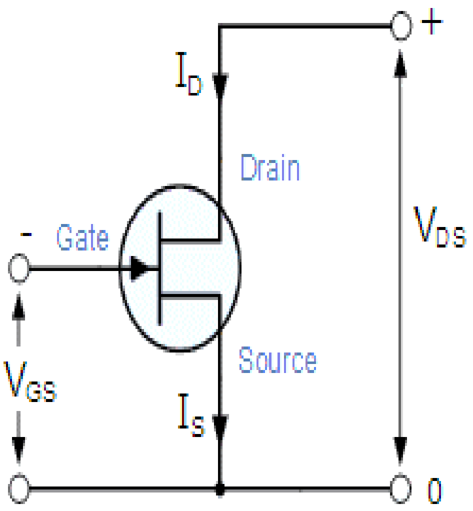


Figure 4.3: Water Spigot vs JFET Operation



- V_{GS} = the voltage applied between the Gate and the Source
- V_{DS} = the voltage applied between the Drain and the Source.

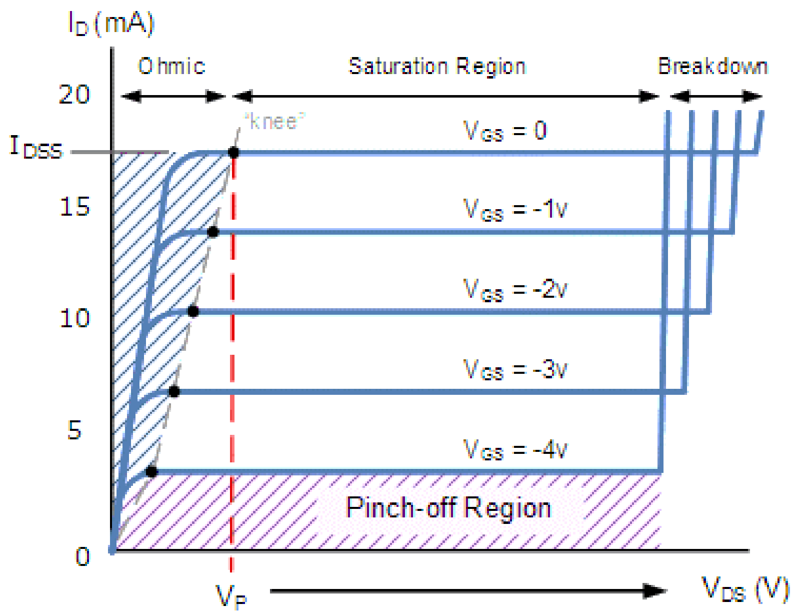


Figure 4.4: Output Characteristic V-I Curves of a Typical Junction FET

- The current that flows between the Drain and Source terminals is controlled by the voltage V_{GS} that is applied to the Gate.
- Since the JFET is a voltage-controlled device, meaning that "NO current flows into the gate!", the device's source current (I_S) that flowing out and its drain current (I_D) is equal ($I_D = I_S$).

- Operating Regions of JFET
  1. Linear/Ohmic Region
     - When VGS = 0, the depletion layer of the channel is very small and the JFET acts like a voltage-controlled resistor.
  2. Cut-off Region
     - Often referred to as the pinch-off region, this area is where the JFET operates as an open circuit when the channel resistance is at its highest because of the gate voltage, or V_{GS}.
  3. Saturation or Active Region
     - The Gate-Source voltage (V_{GS}) transforms the JFET into a good conductor, and it is largely or completely insensitive to the Drain-Source voltage (V_{DS}).
  4. Breakdown Region
     - The voltage between the Drain and the Source, (V_{DS}) is high enough to cause the JFET's resistive channel to break down and allows uncontrolled maximum current.

4.3 Basic Principles of Metal Oxide Semiconductor FET (MOSFET)

- Introduction: MOSFET is the second categorized of FET. MOSFET also have 3 terminals same as JFET. There are:
  - Source
  - Drain
  - Gate.
- Differences
  - The MOSFET is different from the JFET in that the channel is isolated from the gate by silicon oxide (SiO_2).
  - This leads to an even smaller gate current than that of a JFET. Insulated-Gate FET (IGFET) is another name for the MOSFET.

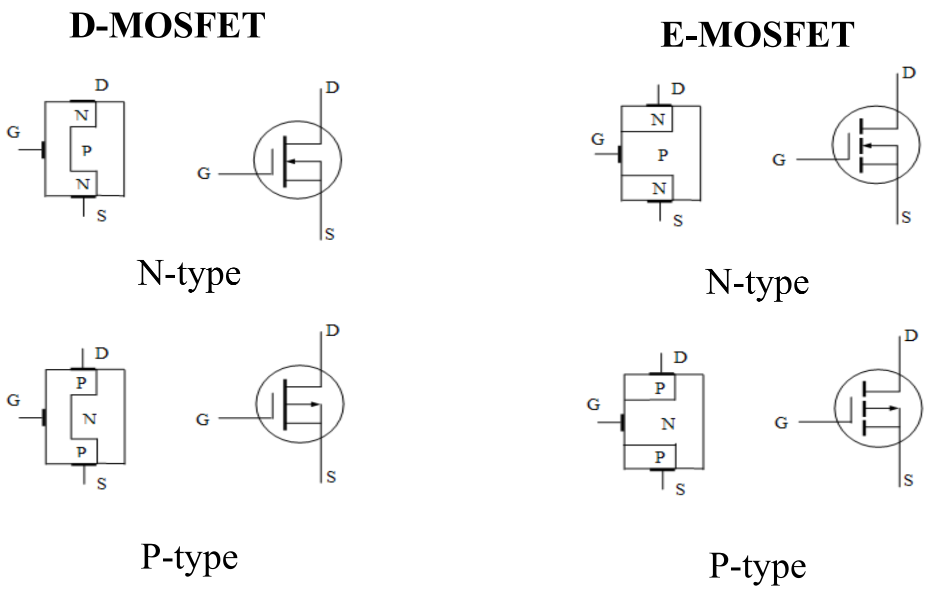


Figure 4.4: Physical Structures and Schematic Symbol

- D-MOSFET
  - They are **MOSFETs with depletion (D-MOSFET).** It's interesting to note that they can be biased to function as D-MOSFETS in the enhancement mode.
  - Take a look at the construction structure; the source and drain are connected to the channel. As a result, even when $V_{GS} = 0$, the drain current (I_D) can flow.

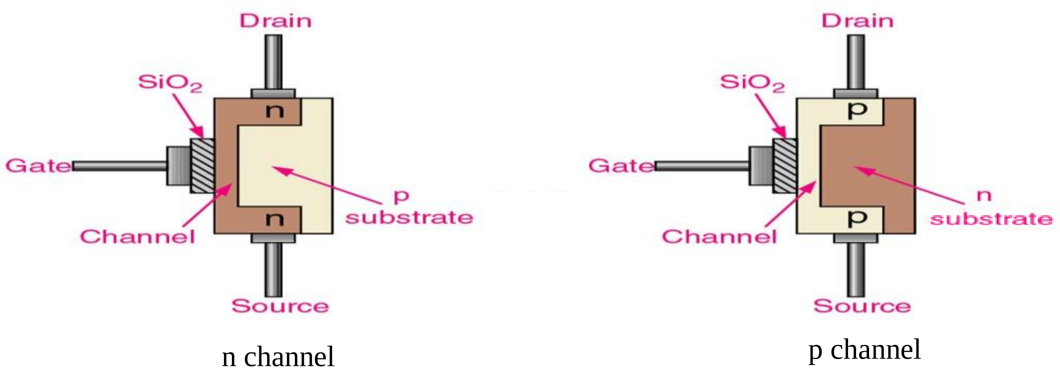


Figure 4.5: D-MOSFET Construction Structure

- There are two operating modes for the D-MOSFET:
  - i. Enhancement Mode
  - ii. Depletion Mode
- Enhancement Mode

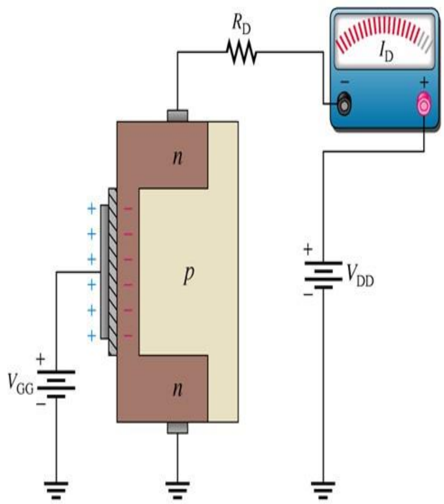
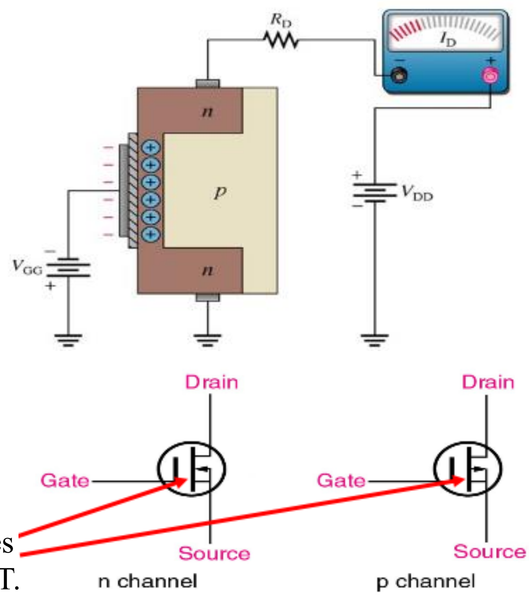


Figure 4.6: D-MOSFET Enhancement Mode (V_{GS} positive)

- The gate is made more positive while in the enhancement mode to improve current flow by drawing more electrons into the channel.
- For discussion purposes, n channel MOSFETs are being used. Polarities would shift for MOSFETs with p channels.

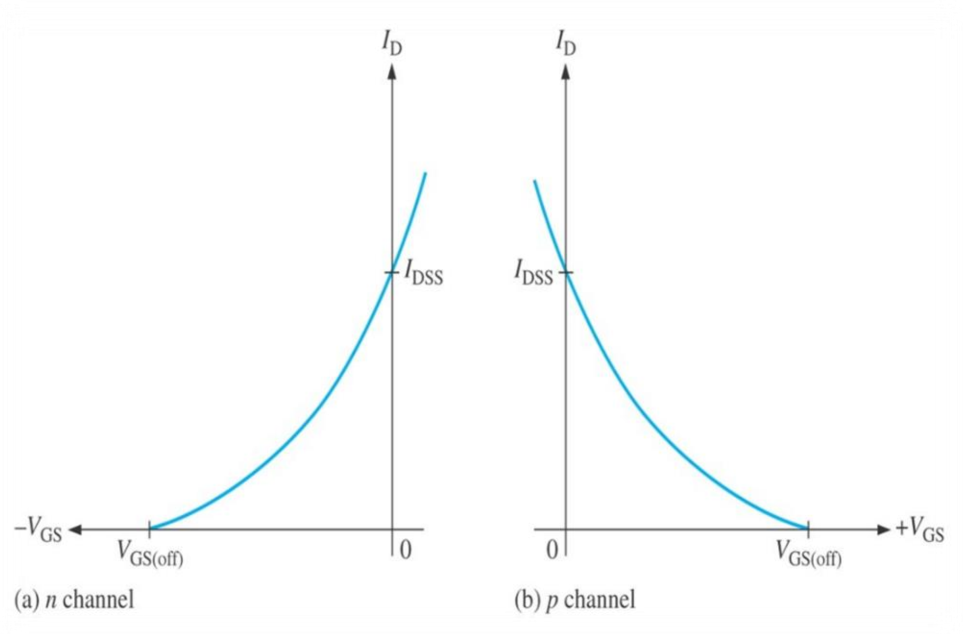
- Depletion Mode
  - The gate must be set more negatively in order to operate in the **depletion mode**, which narrows or empties the channel of electrons.



Note: The "solid" lines indicating D-MOSFET.

Figure 4.7: D-MOSFET Depletion Mode (V_{GS} negative and less than $V_{GS(off)}$)

- I-V Characteristic



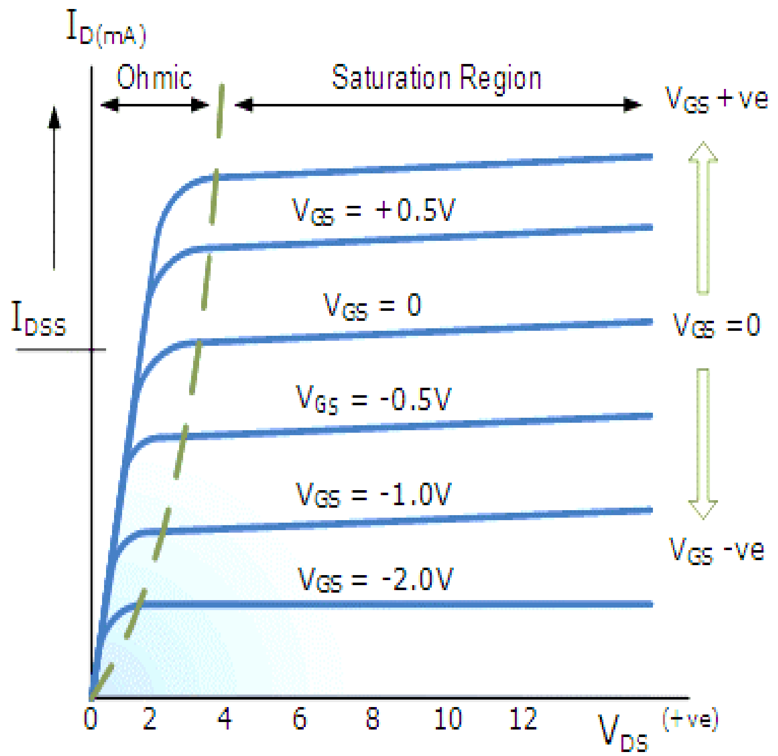


Figure 4.8: I-V Characteristic for D-MOSFET

- E-MOSFET
  - The **enhancement MOSFET (E-MOSFET)** has no structural channel. The channel is "induced" thru biasing. For an n-channel device, a **+V_G** induces a channel to form *(must exceed a threshold voltage).*
  - It is possible to say that the channel between the source and drain is disconnected, referring to the construction structure. As a result, if $V_{GS} = 0$, the drain current (I_D) cannot flow.

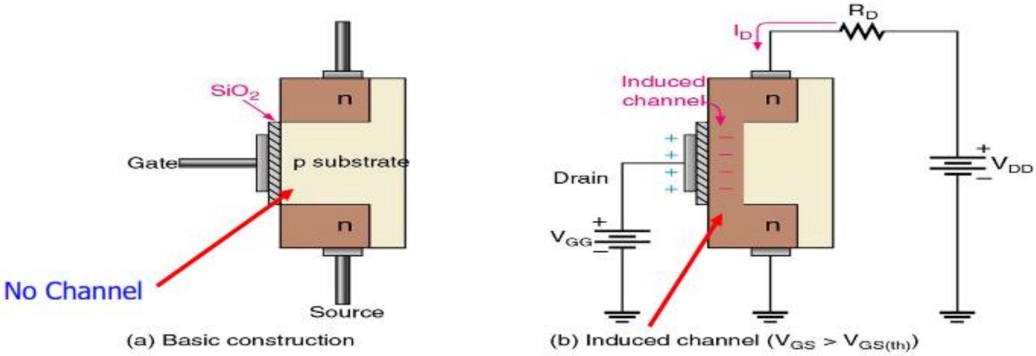
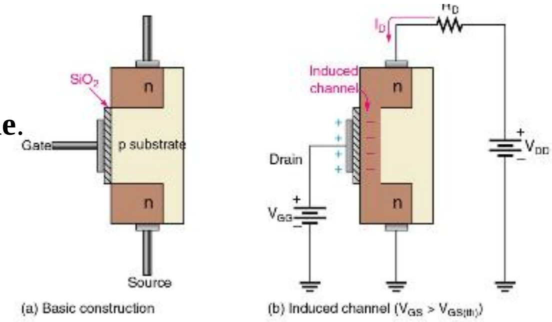
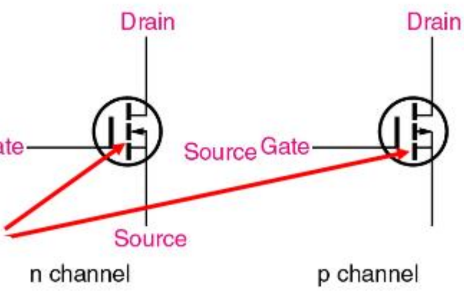


Figure 4.9: E-MOSFET Construction Structure

  - The E-MOSFET can operate in **only the enhancement mode**. With a positive voltage on the gate the p substrate is made more conductive.



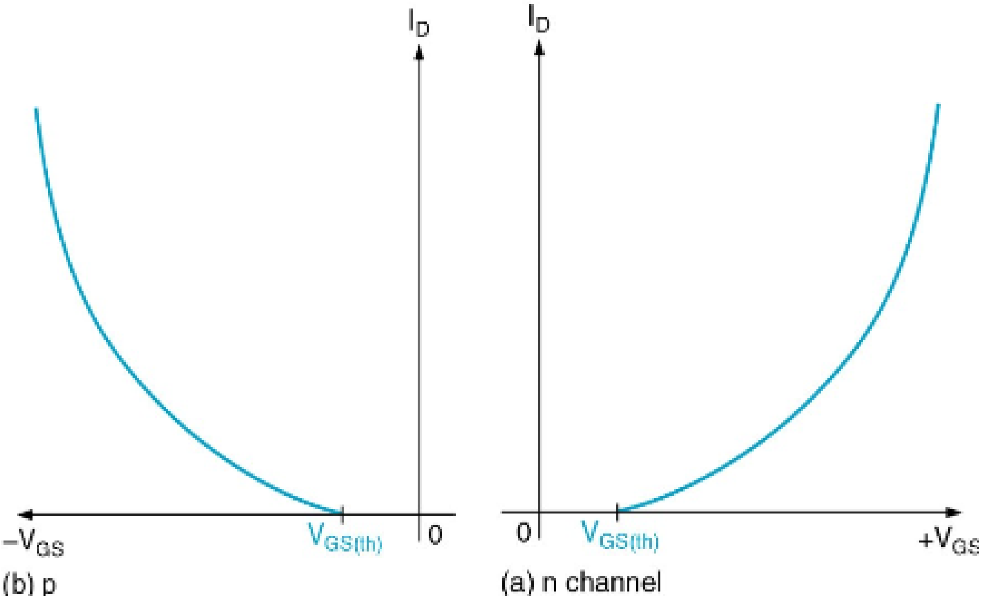


Note: The "broken" lines indicates E-MOSFET

Figure 4.10: E-MOSFET Enhancement Mode

- It is possible to say that E-MOSFET is the reverse of the D-MOSFET's depletion-mode type. The device being normally "OFF" when the gate bias voltage is equal to zero.
- A drain current will only flow when a gate voltage (V_{GS}) is applied to the gate terminal greater than the threshold voltage (V_{TH}) level in which conductance takes place making it a transconductance device.
- By pushing the holes in the channel aside, the positive (+ve) gate voltage thickens the channel and let current to pass by drawing electrons to the oxide layer. Due to the gate voltage's ability to improve the channel, this type of transistor is also known as an enhancement mode device.
- Raising the positive gate voltage will result in a further decrease in channel resistance and an increase in the drain current (ID) flowing through the channel. To put it another way, an N-channel enhancement mode MOSFET is turned "ON" by a zero or -VGS, and "OFF" by a zero or +VGS. In that case, a "normally open" switch is the same as an enhancement-mode MOSFET.

- IV-Characteristic



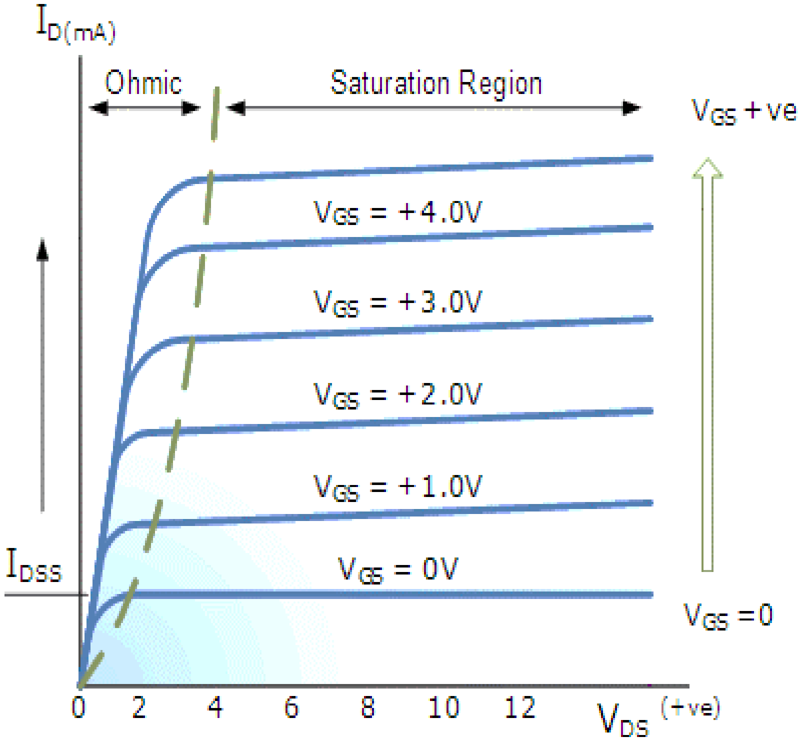
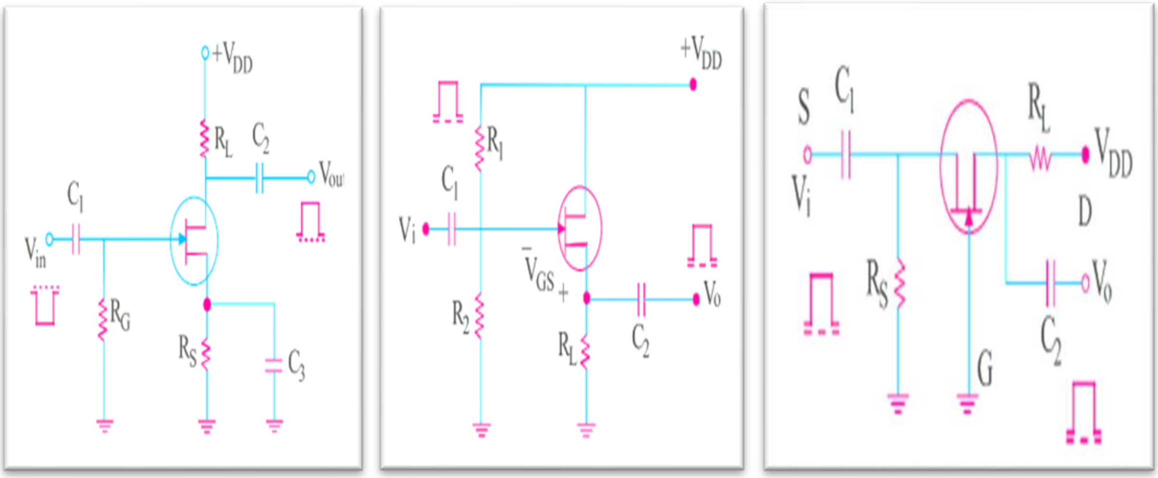


Figure 4.11: I-V Characteristic for E-MOSFET

4.4 Basic of Junction FET (JFET) Amplifier

- JFET Amplifier
  - FET amplifier is an amplifier which uses a field-effect transistor (FET). The main advantages of a FET when it comes to amplification are:
    i. Extremely high input impedance
    ii. Low output impedance

    These are the TWO (2) primary prerequisites for an amplifier.
  - Amplifiers normally operate the JFET in the saturation region.
    FET amplifiers can be classified into THREE (3) categories based on the common terminal (Comparable with an amplifier using Bipolar Junction Transistors (BJTs)) that is utilized for both input and output :
    i. Common Source (CS),
    ii. Common Drain (CD) or Source Follower (SF)
    iii. Common Gate (CG)



i. Common Source ii. Common Drain iii. Common Gate

Figure 4.12: Types of Amplifiers

Table 4.1: The Characteristics

Types	**Common Source**	**Common Drain (Source Follower)**	**Common Gate**
Power	Relatively low voltage gain (<100)	Low voltage gain (<1)	Relatively low voltage gain (<100)
Impedance	**High input impedance and output impedance**	**High input impedance** **Low output impedance**	**Low input impedance** **Relatively high output impedance**
Function	Typically used as a voltage amplifier	Typically used as a buffer or as a current amplifier	Typically used as a buffer

- DC Load Line
  - A common emitter amplifier and a common source JFET amplifier have a very similar fundamental circuit and set of features.
  - The DC load line for a JFET can be easily drawn by remembering the following two points:
    1. at $I_D = 0, V_{DS} = V_{DD}$
    2. at $V_{DS} = 0$, $I_D = \frac{V_{DD}}{R_L}$
  - The Q-point is generally situated at the middle point of the load line (for class-A operation) so that:
    1. $V_{DSQ} = \frac{1}{2} V_{DD}$
    2. $I_{DSQ} = \frac{\frac{1}{2}V_{DD}}{R_S+R_L}$

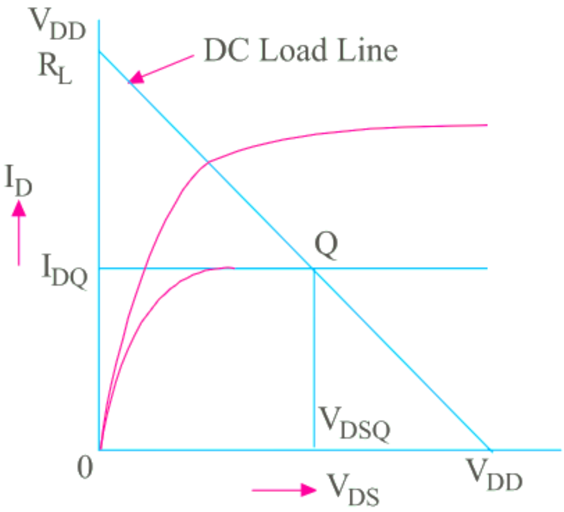
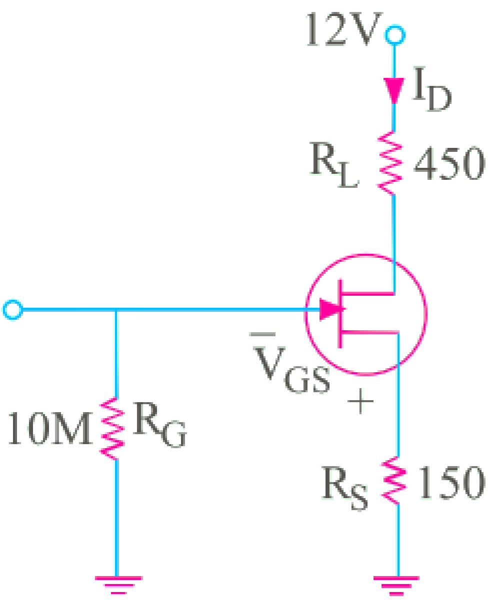


Figure 4.13: The Q-Point for Class A Operation

- Example:
  For the circuit of figure below, find the values of V_{DSQ} and V_{GS} assuming centrally located Q-point and zero gate current, I_G



Solution:

Since $I_G = 0$, *DC circuit is not disturbed.*

$$V_{DS} = \frac{1}{2} V_{DD} = \frac{1}{2} \times 12V$$

$$= \mathbf{6V}_{\#}$$

The balance of 6V drops across series combination of R_L *and* R_S

$$I_D = \frac{V_{DS}}{R_L + R_S}$$

$$I_D = \frac{6V}{450\Omega + 150\Omega} = 10mA$$

$$V_{GS} = -I_D \times R_S$$

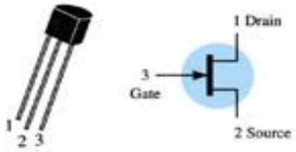
$$= -10mA \times 150\Omega$$

$$= \mathbf{1.5V}_{\#}$$

- Data Sheets

2N5457

CASE 29-04, STYLE 5
TO-92 (TO-226AA)



JFETs
GENERAL PURPOSE
N-CHANNEL—DEPLETION

Refer to 2N4220 for graphs.

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Drain-Source Voltage	V_{DS}	25	Vdc
Drain-Gate Voltage	V_{DG}	25	Vdc
Reverse Gate-Source Voltage	V_{GSR}	−25	Vdc
Gate Current	I_G	10	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	310 2.82	mW mW/°C
Junction Temperature Range	T_J	125	°C
Storage Channel Temperature Range	T_{stg}	−65 to +150	°C

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

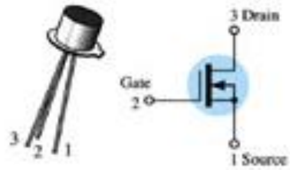
Characteristic		Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS						
Gate-Source Breakdown Voltage (I_G = −10 μAdc, V_{DS} = 0)		$V_{(BR)GSS}$	−25	–	–	Vdc
Gate Reverse Current (V_{GS} = −15 Vdc, V_{DS} = 0) (V_{GS} = −15 Vdc, V_{DS} = 0, T_A = 100°C)		I_{GSS}	 – –	 – –	 −1.0 −200	nAdc
Gate Source Cutoff Voltage (V_{DS} = 15 Vdc, I_D = 10 nAdc)	2N5457	$V_{GS(off)}$	−0.5	–	−6.0	Vdc
Gate Source Voltage (V_{DS} = 15 Vdc, I_D = 100 μAdc)	2N5457	V_{GS}	–	−2.5	–	Vdc
ON CHARACTERISTICS						
Zero-Gate-Voltage Drain Current* (V_{DS} = 15 Vdc, V_{GS} = 0)	2N5457	I_{DSS}	1.0	3.0	5.0	mAdc
SMALL-SIGNAL CHARACTERISTICS						
Forward Transfer Admittance Common Source* (V_{DS} = 15 Vdc, V_{GS} = 0, f = 1.0 kHz)	2N5457	$\|y_{fs}\|$	1000	–	5000	μmhos
Output Admittance Common Source* (V_{DS} = 15 Vdc, V_{GS} = 0, f = 1.0 kHz)		$\|y_{os}\|$	–	10	50	μmhos
Input Capacitance (V_{DS} = 15 Vdc, V_{GS} = 0, f = 1.0 MHz)		C_{iss}	–	4.5	7.0	pF
Reverse Transfer Capacitance (V_{DS} = 15 Vdc, V_{GS} = 0, f = 1.0 MHz)		C_{rss}	–	1.5	3.0	pF

*Pulse Test: Pulse Width ≤ 630 ms; Duty Cycle ≤ 10%

Figure 4.14: JFETs Data Sheets

2N3797

CASE 22-03, STYLE 2
TO-18 (TO-206AA)



MOSFETs
LOW POWER AUDIO

N-CHANNEL – DEPLETION

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Drain–Source Voltage 2N3797	V_{DS}	20	Vdc
Gate–Source Voltage	V_{GS}	±10	Vdc
Drain Current	I_D	20	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	200 1.14	mW mW/°C
Junction Temperature Range	T_J	+175	°C
Storage Channel Temperature Range	T_{stg}	–65 to +200	°C

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS					
Drain Source Breakdown Voltage (V_{GS} = –7.0 V, I_D = 5.0 μA) 2N3797	$V_{(BR)DSX}$	20	25	–	Vdc
Gate Reverse Current (1) (V_{GS} = –10 V, V_{DS} = 0) (V_{GS} = –10 V, V_{DS} = 0, T_A = 150°C)	I_{GSS}	– –	– –	1.0 200	pAdc
Gate Source Cutoff Voltage (I_D = 2.0 μA, V_{DS} = 10 V) 2N3797	$V_{GS(off)}$	–	–5.0	–7.0	Vdc
Drain-Gate Reverse Current (1) (V_{DG} = 10 V, I_S = 0)	I_{DGO}	–	–	1.0	pAdc
ON CHARACTERISTICS					
Zero-Gate-Voltage Drain Current (V_{DS} = 10 V, V_{GS} = 0) 2N3797	I_{DSS}	2.0	2.9	6.0	mAdc
On-State Drain Current (V_{DS} = 10 V, V_{GS} = +3.5 V) 2N3797	$I_{D(on)}$	9.0	14	18	mAdc
SMALL-SIGNAL CHARACTERISTICS					
Forward Transfer Admittance (V_{DS} = 10 V, V_{GS} = 0, f = 1.0 kHz) 2N3797 (V_{DS} = 10 V, V_{GS} = 0, f = 1.0 MHz) 2N3797	$\|y_{fs}\|$	1500 1500	2300 –	3000 –	μmhos
Output Admittance (I_{DS} = 10 V, V_{GS} = 0, f = 1.0 kHz) 2N3797	$\|y_{os}\|$	–	27	60	μmhos
Input Capacitance (V_{DS} = 10 V, V_{GS} = 0, f = 1.0 MHz) 2N3797	C_{iss}	–	6.0	8.0	pF
Reverse Transfer Capacitance (V_{DS} = 10 V, V_{GS} = 0, f = 1.0 MHz)	C_{rss}	–	0.5	0.8	pF
FUNCTIONAL CHARACTERISTICS					
Noise Figure (V_{DS} = 10 V, V_{GS} = 0, f = 1.0 kHz, R_S = 3 megohms)	NF	–	3.8	–	dB

(1) This value of current includes both the FET leakage current as well as the leakage current associated with the test socket and fixture when measured under best attainable conditions.

Figure 4.15: MOSFETs Data Sheets

4.5 Application of MOSFET as a Switch

- MOSFET as a Switch
  - The operation of the E-MOSFET can best be described using its I-V characteristics curves shown in Figure 4.16.
  - When the input voltage, V_{in} to the gate of the transistor is zero, the MOSFET conducts virtually no current and the output voltage, V_{out} is equal to the supply voltage V_{DD}. So, the MOSFET is "fully-OFF" and in its "cut-off" region.

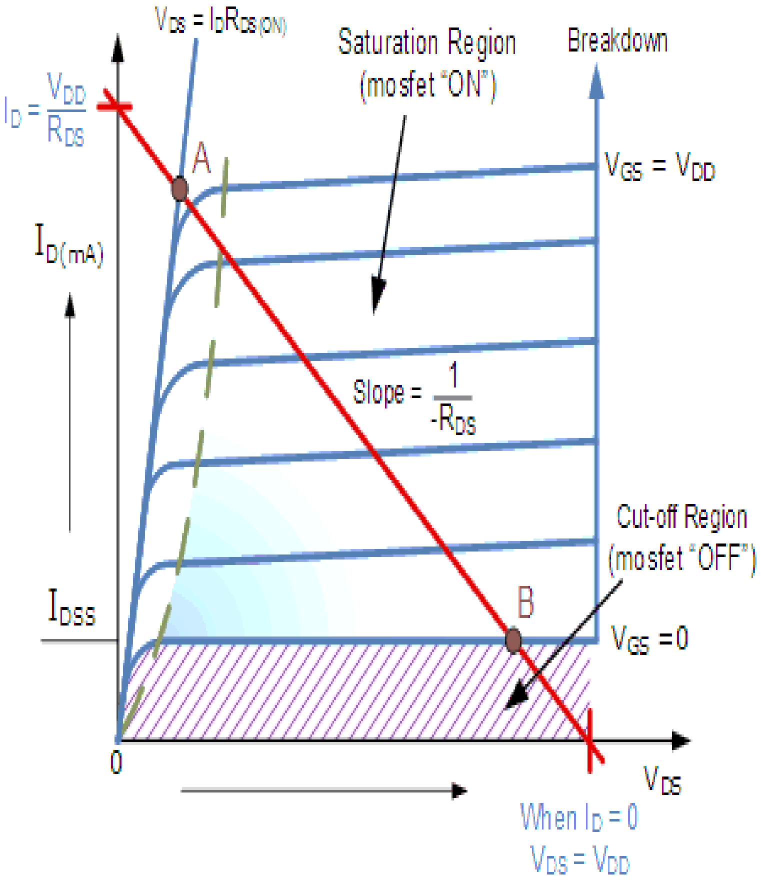


Figure 4.16: MOSFET's I-V Characteristics

- The V-I transfer curves can be used to calculate the minimal ON-state gate voltage needed to guarantee that the MOSFET stays fully-ON while carrying the chosen drain current.
- The MOSFET Q-point shifts to point A along the load line when VIN is HIGH or equal to VDD.
- A decrease in the channel resistance causes the drain current I_D to rise to its maximum value. I_D turns into a constant value that is solely reliant on V_{GS} and not on V_{DD}.
- As a result, the transistor functions similarly to a closed switch, but because of its R_{DS} (ON) value, the channel ON-resistance only very slightly decreases to zero.
- The MOSFET Q-point travels from point A to point B along the load line when V_{IN} is LOW or decreased to zero.
- Because of the extremely high channel resistance, the transistor functions as an open circuit and no current passes through the channel.
- The MOSFET will function as a "single-pole single-throw" (SPST) solid state switch if its gate voltage alternates between two values, HIGH and LOW.

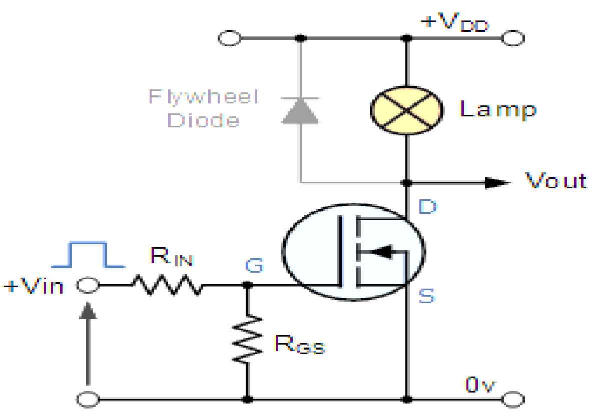


Figure 4.17: MOSFET as a Switch *(example)*

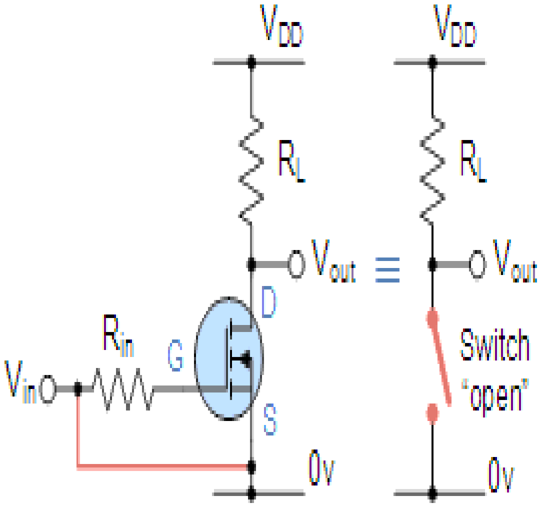


Figure 4.18: MOSFET Operates as an "Open Switch"

- Cut-off Characteristics
  - The *Input* and *Gate* are grounded (0V)
  - Gate-source voltage less than threshold voltage, $V_{GS} < V_{TH}$
  - MOSFET is "fully-OFF" (Cut-off region)
  - No Drain current flows ($I_D = 0$)
  - $V_{OUIT} = V_{DS} = V_{DD} =$ "1"
  - MOSFET operates as an "open switch”

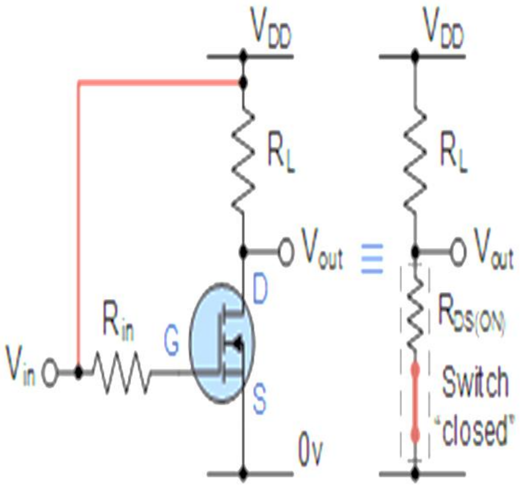


Figure 4.19: MOSFET Operates as a "Closed Switch"

- Saturation Characteristics
  - The input and Gate are connected to V_{DD}.
  - Gate-source voltage is much greater than threshold voltage, VGS > VTH
  - MOSFET is "fully-ON" (Saturation region)
  - Max Drain current flows, $\left(I_D = \frac{V_{DD}}{R_L}\right)$
  - V_{DS} = 0V (ideal saturation)
  - Min Channel resistance, $R_{DS(ON)} < 0.1\ \Omega$
  - $V_{OUT} = V_{DS}$ = 0.2V ($R_{DS}.I_D$)
  - MOSFET operates as a “closed switch”

CHAPTER 5

INTRODUCTION TO OTHER ELECTRONIC COMPONENTS

5.1 What would you get?

- Understand the construction of other electronic components
- Understand the characteristics of other electronic components

5.2 Construction of Other Electronic Components

- Silicon Controlled Rectifier (SCR)
  - A four layer p-n-p-n structure with the outer layers are referred to as the anode (p-type) and cathode (n-type).
  - The SCR's gate (control terminal) is attached to the p-type layer, which is situated adjacent to the cathode.

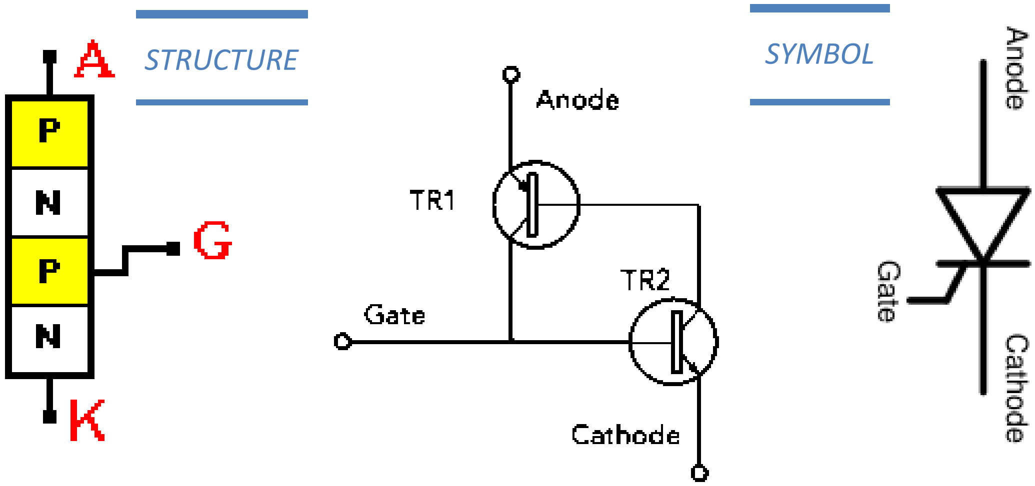


Figure 5.1: Silicon Controlled Rectifier (SCR) Structure and Symbol

- Triode for Alternating Current (TRIAC)
    - The structure is made up of several areas, usually two p-type regions and four n-type areas, as indicated.
    - Since it conducts by terminal, it lacks a cathode terminal; the other two are A1 (MT1, or main terminal) and A2 (MT2). One of the three is a gate.

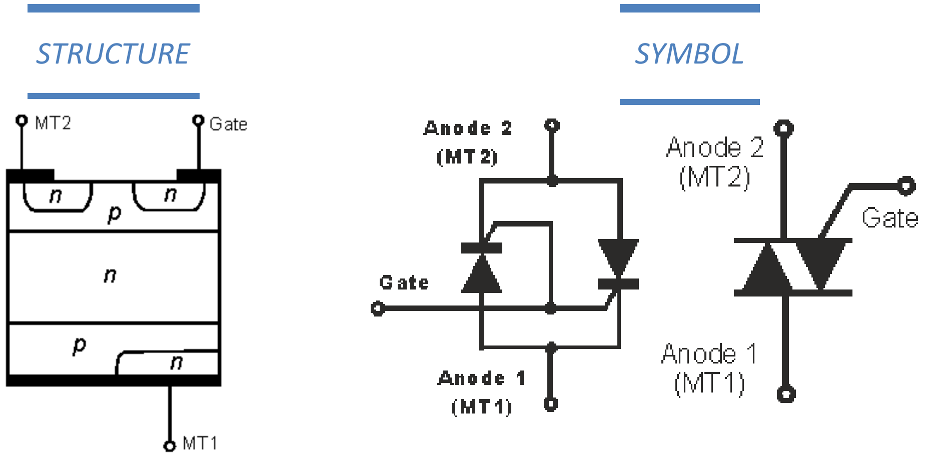


Figure 5.2: Triode for Alternating Current (TRIAC) Structure and Symbol

- Diode for Alternating Current (DIAC)
    - DIAC is a bi-directional or full-wave semiconductor switch that has the ability to be activated in both forward and reverse polarities.
    - The term DIAC does really refer to a diode AC switch.

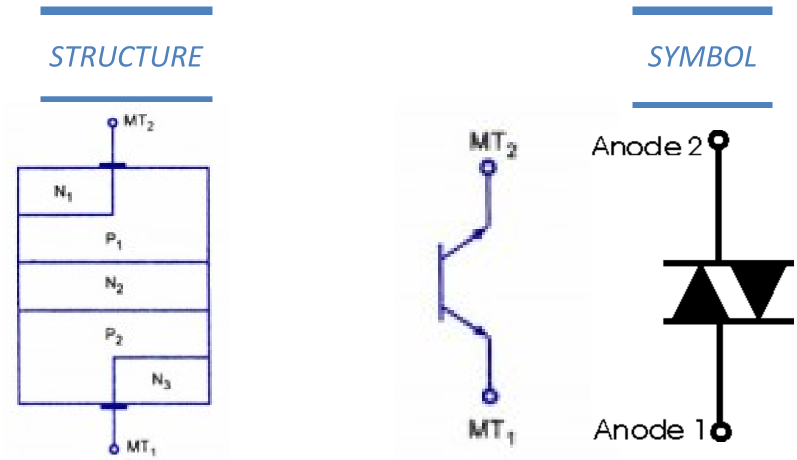


Figure 5.3: Diode for Alternating Current (DIAC) Structure and Symbol

- Uni-junction Transistor (UJT)
    - UJT has three terminals: two bases (B1 and B2) and an emitter (E). An n-type silicon bar that has been gently doped forms the base. Its ends are connected to two ohmic contacts, B1 and B2.
    - The emitter is extensively doped and of the p-type.

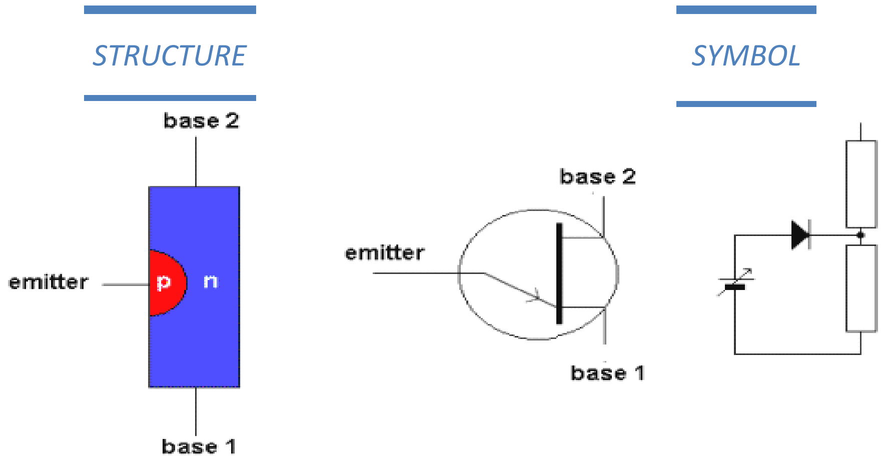


Figure 5.4: Uni-junction Transistor (UJT) Structure and Symbol

5.3 Characteristics of Other Electronic Components

- Characteristics of Silicon Controlled Rectifier (SCR):
    - In the normal "OFF" state, the device restricts current to the leakage current.
    - When the gate-to-cathode voltage exceeds a certain threshold, the device turns "ON" and conducts current.
    - As long as the current flowing through the device is higher than the holding current, the device will stay in the "ON" state even after the gate current is cut. Once current falls below the holding current for an appropriate period of time, the device will switch "OFF".
    - If the gate is pulsed and the current through the device is below the holding current, the device will remain in the "OFF" state.

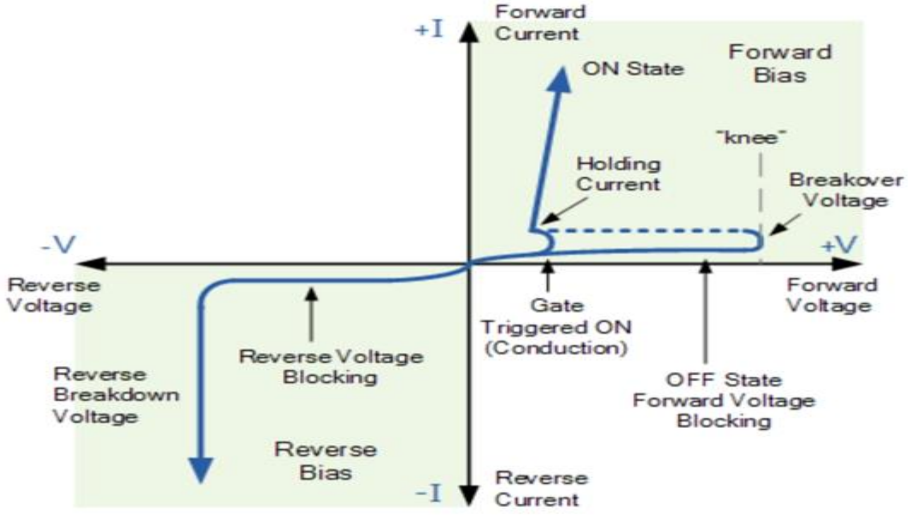


Figure 5.5: V-I Characteristics of Silicon Controlled Rectifier (SCR)

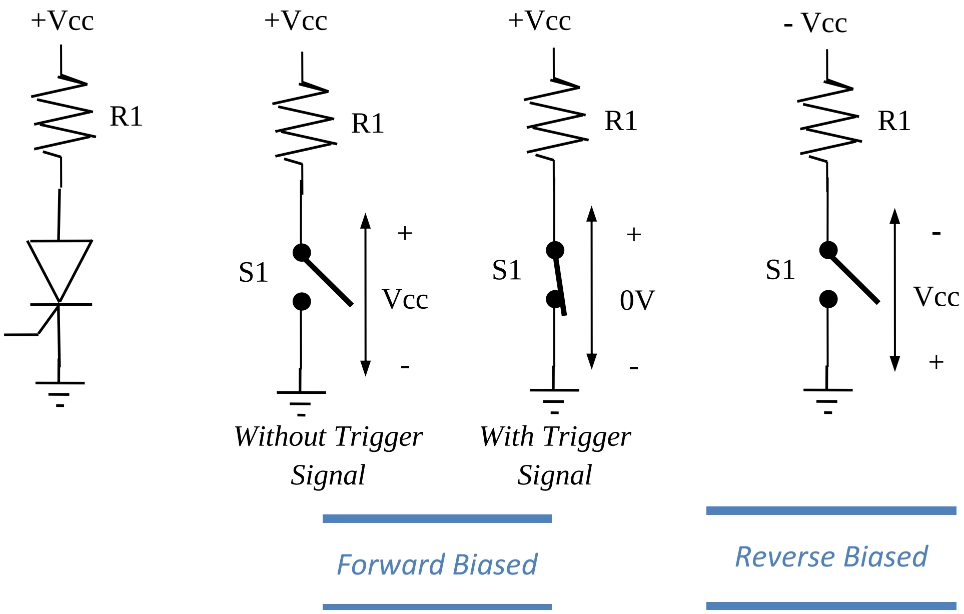


Figure 5.6: SCR Stage While Forward and Reverse Biased

- ***SCR Applications*** - SCRs are employed in numerous fields of electronics and have a wide range of applications. The following lists a few of the more popular uses for SCR:
  - AC power control (including lights, motors, etc).
  - Overvoltage protection crowbar for power supplies.
  - AC power switching.
  - Control elements in phase angle triggered controllers.
  - Within photographic flashlights, where they act as the switch to discharge a stored voltage through the flash lamp and then cut it off at the required time.
  - SCRs are able to switch high voltages and withstand reverse voltages making them ideal for switching applications, especially within AC scenarios.

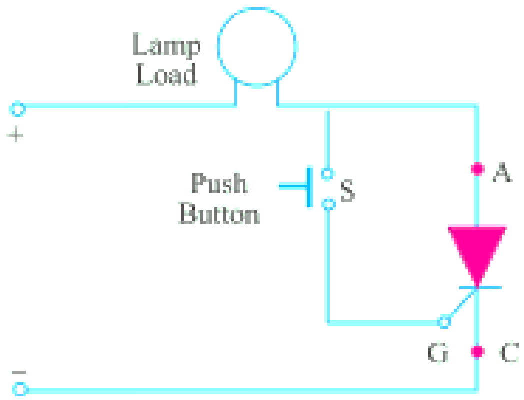


Figure 5.7: Example Circuit Using SCR

  - In Figure 5.7 the lamp is off when S is open because the SCR does not conduct. A positive voltage is delivered to the gate when S is momentarily closed, forward-biasing the center P-N junction.
  - As a result, SCR is pulsed into conduction and the lamp lights up. SCR will remain in the conducting state until the supply voltage is removed or reversed.

- Characteristics of Triode for Alternating Current (TRIAC)
  - It can be considered as two SCRs connected in antiparallel with a common gate connection.
  - A TRIAC can conduct in both directions and is normally used in AC-phase control.
  - Current can flow in either direction between MT1 and MT2 terminals when a small gate current is applied between MT1 and the gate terminal.
  - It is turned ON by triggering a positive or negative current between MT1 and the gate.
  - The holding current is the minimum current required to hold it on.

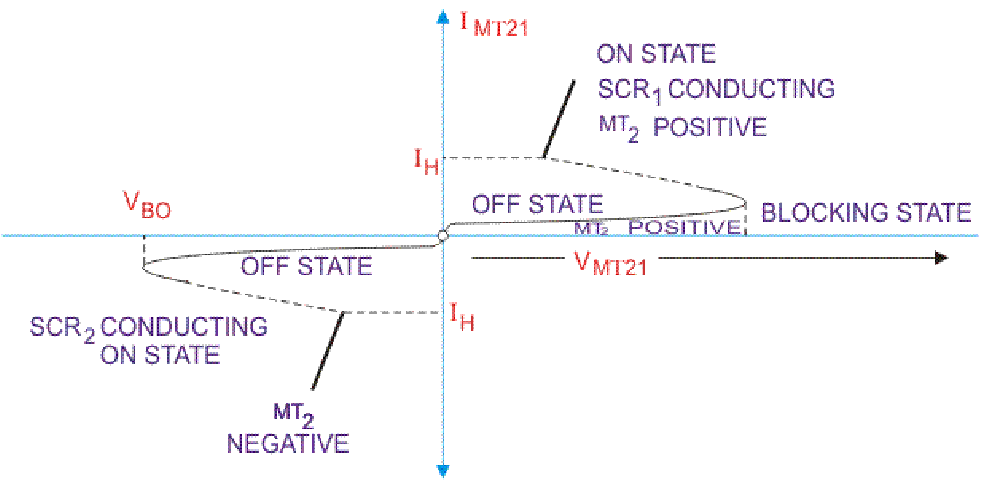


Figure 5.8: V-I Characteristics of Triode for Alternating Current (TRIAC)

  - ***TRIAC Applications*** - There are several applications for TRIACs. However, their non-symmetrical switching properties are one of the reasons they are rarely utilized in high power switching applications.
  - This causes a lot of problems for high power applications, particularly with electromagnetic interference.

- TRIACs are still utilized, meanwhile, in a variety of electrical switching applications:
  - Domestic light dimmers
  - Electric fan speed controls
  - Small motor controls
  - Control of small AC powered domestic appliances
- The TRIAC is an electronic component that is widely used in many circuit applications, ranging from light dimmers through to various forms of AC control. It is generally only used for lower power applications.

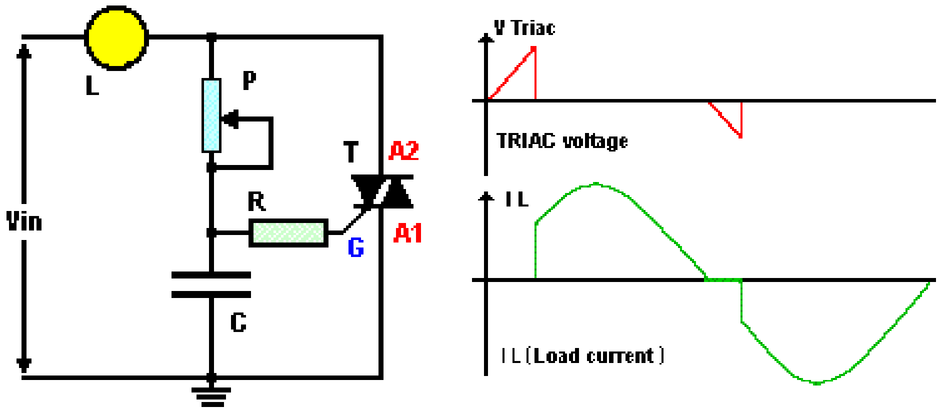


Figure 5.9: Example Circuit Using TRIAC

- The TRIAC controls the flow of the alternating current that passes through the lamp (load), moving continuously between the "ON" state (when the current flows through the TRIAC) and the "CUT OFF" state (when the current does not run through the TRIAC)
- If we move the potentiometer knob, we can change the charging time of the capacitor making the phase difference between the power supply voltage and the voltage applied to the gate to increase or decrease.

- Characteristics of Diode for Alternating Current (DIAC)
    - The DIAC is a bidirectional trigger diode which is designed specifically to trigger a TRIAC or SCR. Basically the DIAC does not conduct (except for a small leakage current) until the breakover voltage is reached.
    - The operation of a DIAC can best be explained by imaging it as two diodes connected in series. Voltage applied across it in either direction turns ON one diode, reverse biasing the other. Hence, it can be switched from OFF to ON state for either polarity of the applied voltage.

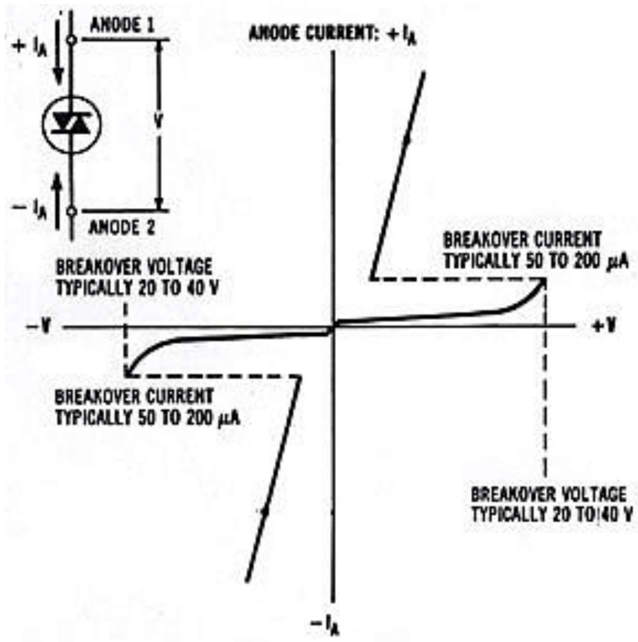


Figure 5.10: V-I Characteristics of Diode for Alternating Current (DIAC)

- ***DIAC Applications*** - DIAC has symmetrical bi-directional switching characteristics.
- Because of this feature, DIACS are frequently used as triggering devices in TRIAC phase control circuits used for light dimming, universal motor speed control and heat control etc.

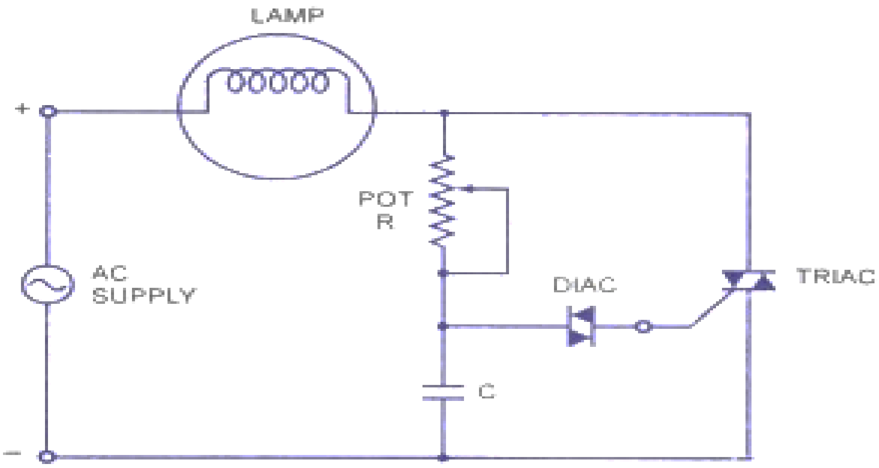


Figure 5.11: Example Circuit Using DIAC

- The circuit for a TRIAC controlled by an R-C phase-shift network and a DIAC is given in Figure 5.11.
- This circuit is an example of a simple lamp dimmer. The TRIAC conduction angle is adjusted by adjusting the potentiometer R. The longer the TRIAC conducts, the brighter the lamp will be.
- The DIAC acts like an open-circuit until the voltage across the capacitor exceeds its breakover or switching voltage (and the TRIAC's required gate trigger voltage).

- Characteristics of Uni-junction Transistor (UJT)
  - Cut off region - Initially the emitter voltage increase from zero, a small leakage current flows in the emitter circuit due to minority carries. This continues up to the peak point. The UJT is in OFF condition.
  - Negative resistance region – the region between the peak point and valley point. When the VE reaches the peak point voltage, IE starts flowing. After the peak point to increase the VE furthers leads to sudden increase the IE with corresponding decrease in VE.
  - Saturation region - after the valley point, the current becomes saturation. The UJT is ON condition. The VE almost constant with increasing IE

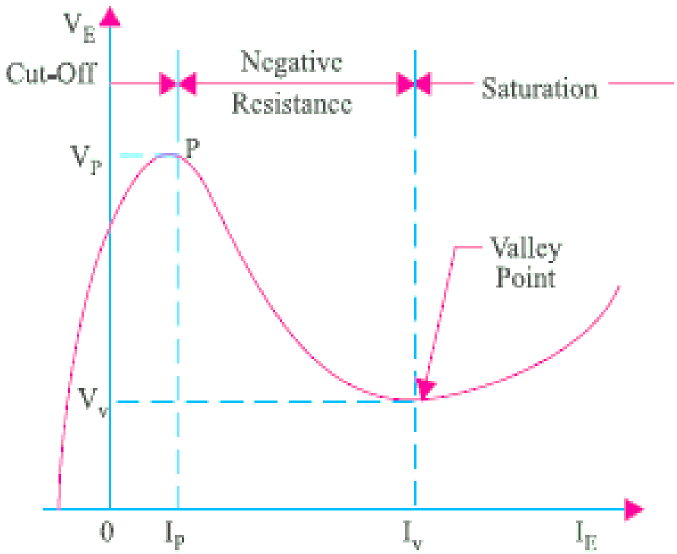
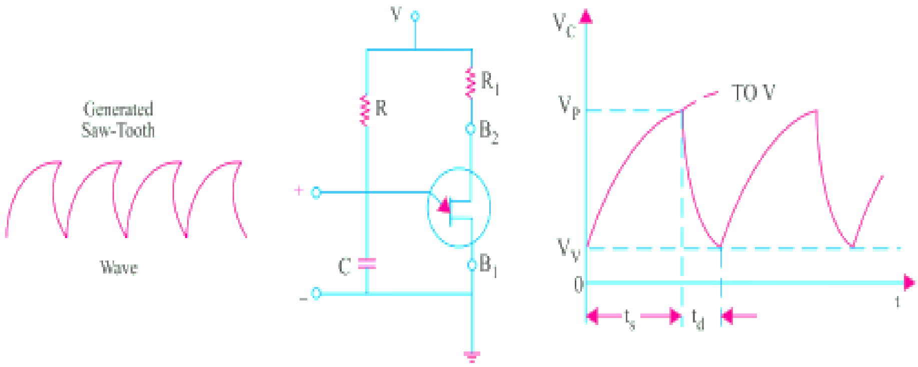


Figure 5.12: V-I Characteristics of Uni-junction Transistor (UJT)

- ***UJT Applications*** - One unique property of UJT is that can be triggered by any one of its three terminals. Once triggered, the emitter current IE of the UJT increases regeneratively till it reaches a limiting value determined by the external power supply.
- Because of this particular behavior, UJT is used in a variety of circuit applications. Some of which are:
    - phase control
    - switching
    - pulse generation
    - sine wave generator
    - sawtooth generator



5.13: Example Circuit Using UJT

- The relaxation oscillator consists of a UJT and a capacitor C which is charged through R as VBB is switched on. When the capacitor voltage VC reaches in time ts the value of Vp, the UJT fires and rapidly discharges C via B1 till the voltage falls below the minimum value Vv. The device then cuts off and C starts to charge again.
- This cycle is repeated continuously thus generating a sawtooth waveform across C.

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