Application of Transistors

Objectives

After going through the module the learner will be able to :

- Understand transistor characteristics and their significance and applications.
- Study the characteristics of a common emitter n-p-n/ p-n-p transistor and to know the method of finding the values of current and voltage gains.
- Use the characteristics to see application of transistor as a switch
- Apply the characteristics to see working of transistor as an amplifier

Content Outline

- Unit Syllabus
- Module Wise Distribution of Unit Syllabus
- Words You Must Know
- Introduction
- Transistor Characteristics
- Transistor as a Device
- Input and Output Characteristic Curves and Transfer Characteristics
- Transistor as a Switch
- Transistor as an Amplifier
- Summary

Unit Syllabus

Unit-09: Electronic Devices

Chapter-14: Semiconductor Electronic Material, Devices and Simple Circuits.

Energy bands in conductors, semiconductors and insulators (qualitative only) semiconductors intrinsic and extrinsic

Semiconductor diode -IV characteristics in forward and reverse bias, application of diode as a rectifier

Special purpose p-n diodes LED, photodiode, solar cell and Zener diode and their characteristics, Zener diode as a voltage regulator

Junction transistor, transistor action, characteristics of a transistor and transistor as amplifier common emitter configuration

Basic idea of Analog and Digital signal, logic gates OR, AND, NOR, NOT, NAND

Keeping the needs of state boards in mind we have not changed the content

Module Wise Distribution of Unit Syllabus 10 Modules

Module 1	• Energy bands in solids • Forbidden gap • Fermi level • Energy bands in conductors, semiconductors and insulators
Module 2	• Uniqueness of semiconductors • Charge carriers in semiconductors electrons and holes • Intrinsic semiconductors • Extrinsic semiconductors p and n type • Why are *p* and *n* type semiconductors neutral?
Module 3	• *p-n* junction diode • Potential barrier • Depletion layer • Characteristics of *pn* junction diode • Forward and reverse bias, knee voltage, magnitude of bias voltages • To draw the IV characteristics curve for a *p-n* junction in forward bias and reverse bias

Module 4	• Application of diode
	• Rectifier meaning and need of such a devise
	• Half wave and full wave rectifier
	• Rectifier in our homes
	• Special purpose diode
	    ○ LED
	    ○ Photodiode
	    ○ Solar cells
	• Solar panels and future of energy

Module 5	• To identify a diode, an LED, a resistor and a capacitor
	• Use a multimeter to
	    ○ See the unidirectional flow of current in case of a diode and an LED
	    ○ Check whether a given diode is in working order

Module 6	• Zener diode • Characteristics of Zener diode • To draw the characteristic curve of a Zener diode and to determine its reverse breakdown voltage • How is a Zener diode different from other diodes? • Zener diode as a voltage regulator • Working of a Zener diode • Zener diodes in our homes

Module 7	• Junction transistor
	• Design of the transistor
	• *n-p-n* and *p-n-p*
	• Use a multimeter to
	    ○ identify base of transistor
	    ○ distinguish between *n-p-n* and *p-n-p* type transistor
	    ○ check whether a given electronic component (e.g. diode , transistor, or IC) is in working order
	• Transistor action
	• Characteristics of a transistor, *n-p-n* common emitter

Module 8	• Understanding transistor characteristics and its applications • To study the characteristics of a common emitter *n-p-n, p-n-p* transistor and to find the values of current and voltage gains.

	● Transistor as switch ● Transistor as amplifier
Module 9	● Transistor as an amplifier ● Circuit diagram and understanding bias ● Input and output waveforms ● Phase change
Module 10	● Analog signals ● Logic gates ● Truth tables ○ OR gate ○ AND gate ○ NOT gate ○ NAND gate ○ NOR gate

Module 8

Words You Must Know

- **Conductors:** These are the materials which conduct electricity easily. They have a very large number of free electrons. conductors: material capable of carrying electric current, i.e. material which has "mobile charge carriers" and are therefore capable of electric current (e.g. electrons, ions,.) e.g. metals, liquids with ions (water, molten ionic compounds), plasma !
- **Insulators:** These are the materials which do not conduct electricity because they do not have free electrons. Quartz, most covalent and ionic solids, plastics
- **Semiconductors:** These are the materials for which electrical conductivity values less than conductors but more than that of insulators. The conductivities of semiconductors are highly temperature sensitive.
- **Semiconductors Materials:** germanium Ge, silicon Si, GaAs, GaP, InP have useful characteristic properties.
- **Superconductors:** certain materials have zero resistivity at very low temperature, but are quite like normal conductors at room temperature

- **Energy Level:** As per Bohr's theory electrons revolve around the nucleus only in some specific orbits called stationary orbits. Energy of electrons in these orbits is constant and are termed as energy levels.
- **Energy Bands Theory:** in solid material, electron energy levels 'merge' to form bands of allowed energies. A band is a collection of a large number of close energies. The bands are separated by forbidden bands.
- **Valence Bands:** This band comprises energy of valence electrons. It is the outermost highest filled band with electrons. Electrons of this band do not contribute to conduction of electric current.
- **Conduction Band:** this is a higher band to valence band; it may be empty or partially filled. In metals or good conductors this band is filled
- **Forbidden Energy Gap (E_g):** It is the minimum energy required to take an electron from valence band to conduction band. Insulators have highest E_g and conductors have least Eg.
- **Intrinsic Semiconductors:** these are pure semiconductors without any impurity. They show very small electrical conductivity at room temperature.
  The gap between the valence band and conduction band is relatively small. These are covalent bonded materials such as Si and Ge the forbidden gap width in Si is 1.1 eV and for Ge it is 0.7 eV.
- Electrons moving to conduction band leave "hole" (covalent bond with missing electron) behind; under influence of applied electric field, neighbouring electrons can jump into the hole, thus creating a new hole, etc.
- holes can move under the influence of an applied electric field, just like electrons; both contribute to conduction., in pure Si and Ge, there are equally many holes as there are conduction electrons
- **Doping:** It is the deliberate and controlled addition of impurities in intrinsic semiconductors to enhance their electrical conductivity in a controlled manner.
- **Extrinsic Semiconductors** initially pure semiconductor to which an appropriate /designed impurities is added to increase its conductivity are known as extrinsic semiconductors or impurity semiconductors
- **Dopant :**two types of dopants used in doping the tetravalent Si or Ge element:

(i) Pentavalent dopants (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

(ii)Trivalent dopants (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.

- ***p*-type Semiconductors**, these are formed by doping elements like Si and Ge with trivalent atoms. Like B, Al, Ga ,In ,such that only 3 of the 4 covalent bonds get filled . A hole or vacancy is created because of the unfilled fourth covalent bond. There are more holes as compared to electrons in p type extrinsic semiconductor.
- ***n*-type semiconductors**, these are formed by doping elements like Si and Ge with pentavalent atoms. In this case impurity or dopant having 5 valence electrons like P, As Sb is added to a sample of initially pure semiconductor... of these 4 electrons get used by the covalent bond of the surrounding Si or Ge atoms. The fifth electron is unpaired or left loosely bound .Hence only a small amount of energy is needed to lift it into the conduction band (0.5 eV for Si) n-type semiconductors have more conduction electrons and fewer holes . For example; doping fraction of 1 in 10^8 Sb in Si yield about 5 x 10^{16} conduction electrons per cm^3 at room temperature which is a gain of 5×10^5 conduction electrons over intrinsic Si.
- **Advantage of doped semiconductors is we can alter conductivity by choice of doping fraction and choose majority carriers**
- **p-n junction** A *p-n* junction is a boundary, or interface, between the two types of semiconductors, (*p*-type and *n*-type), inside a single crystal
- **Diffusion current** holes diffuse from p-side to n-side ($p \rightarrow n$) and electrons diffuse from *n*-side to p-side ($n \rightarrow p$). diffusion means movement due to difference in concentration, from higher to lower concentration; in absence of electric field across the junction, holes "diffuse" towards and across boundary into n type and capture electrons diffuse across boundary, fall into holes ("recombination of majority carriers") which forms a depletion region, **(a region without free charge carriers)** around the boundary ,charged ions are left behind (cannot move): the negative ions left on p-side give a net negative charge on p-side of the junction; the positive ions left on n-side give a collection of net positive charge on n-side of the junction . The potential barrier, created as an electric field across the junction, prevents further diffusion.

- **Potential barrier:** Initially both the sides were electrically neutral. Now, because of diffusion of electrons and the holes, there are immobilised additional ions on both sides.

  From the n side, electrons have diffused to the p-side, so there are positive immobile ions on the n side, from the p side, holes have diffused to the n side, so there are negative immobile ions on the p side. These immobile ions near the junction create a potential difference across the junction.
- Due to the positive space-charge region on the n-side of the junction, and the negative space charge region on the *p*-side of the junction, an electric field, directed from positive charge towards negative charge develops.

  Due to this field, an electron on the p-side of the junction moves to the n-side and a hole on the n-side of the junction moves to p-side.

  The motion of charge carriers due to the electric field is called drift.
- **A drift current, which is opposite in direction to the diffusion current, is set up.**
- **Forward bias** when an external voltage V is applied across a semiconductor diode such that p-side is connected to the positive terminal of the battery and n-side to the negative terminal it is said to be forward biased.
- **Reverse Bias** The positive terminal of the battery is connected to the n-side of the semiconductor and negative terminal is connected to the *p*-side. This way of connecting a diode with a battery is called Reverse Biasing.
- **Characteristics of a *p-n* junction diode:** When a bias is placed across a conductor, its characteristic curves show the dependence of current on voltage placed across the conductor.
- **Knee Voltage** the special value of forward voltage beyond which the current increases with increase in the voltage is known as the knee Voltage.
- **Dynamic Resistance of a Junction Diode** I-V characteristics of a p-n junction diode during forward /reverse biasing is not a straight line. We therefore cannot have a unique (constant) value for the resistance of the diode. We can, however use the basic definition of resistance

  $$resistance = \frac{change\ in\ potential\ difference}{corresponding\ change\ in\ current}$$

  We can use it to define

Dynamic resistance of a junction diode (for a particular value of the applied /current flowing) is defined as the ratio of small change in the applied potential across the diode to the corresponding small change in the junction current.

$dynamic\,resistance = \frac{\Delta V}{\Delta I}$

- **Rectifier** is a device which converts an alternating current (AC) into a direct current (DC).
- **Filter Circuit** the ripples in the DC can be reduced by allowing the output to pass through a **filter circuit.**
- **Photodiodes** used for detecting optical signals (photodetectors).
- **Light Emitting Diodes (LED)** which convert electrical energy into light.
- **Photovoltaic Devices** which convert optical radiation into electricity (solar cells **)**
- **Transistors (bipolar) Transistor** combination of two diodes that share the middle portion, called "base" of the transistor; other two sections: "emitter" and "collector"; usually, the base is very thin and lightly doped. Two kinds of bipolar transistors: p-n-p and n-p-n transistors.
- **Transistor Action *p-n-p* Transistor** if emitter-base junction is forward biased, "holes flow" from battery into emitter, move into base, some holes annihilated with electrons in n-type base, but because base thin and lightly doped, most holes make it through base into collector, holes move through collector into negative terminal of battery; i.e. "collector current" flows whose size depends on how many holes have been captured by electrons in the base. This depends on the number of n type carriers in the base which can be controlled by the size of the base current, which is allowed to flow from the base to the emitter. The base current is usually very small. Small changes in base current can cause big differences in collector current.

  Since due to chosen biasing the emitter base junction has lower resistance as compared to base collector hence resistance increases so it is called transistor or transfer of resistance.
- **Common emitter *n-p-n* input characteristics of a transistor the variation of the base current I_B with the base-emitter voltage V_{BE} is called the input characteristic.**
- **Input resistance this is dynamic (ac resistance) and as can be seen from the input characteristic, its value varies with the operating current in the transistor**

$$r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}$$

The value of r_i can be anything from a few hundreds to a few thousand ohms.

- **Output characteristics of a transistor the variation of the collector current I_C with the collector-emitter voltage V_{CE} is called the output characteristic.**
- **Output Resistance (r_o):** This is defined as the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at a constant base current I_B.

$$r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B}$$

- **Current Amplification factor (β):** This is defined as the ratio of the change in collector current to the change in base current at a constant collector-emitter voltage (V_{CE}) when the transistor is in active state.

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

  This is also known as small signal current gain and its value is very large.
  If we simply find the ratio of I_C and I_B we get what is called βdc of the transistor.
  Hence

$$\beta_{dc} = \frac{I_C}{I_B}$$

  Since I_C increases with I_B almost linearly and $I_C = 0$ when $I_B = 0$, the values of both β_{dc} and β_{ac} are nearly equal.
  So, for most calculations β_{dc} can be used. Both β_{ac} and β_{dc} vary with V_{CE} and I_B (or I_C) slightly
- **Transfer Characteristics of a Transistor** plot transfer characteristics to show the variation of output voltage with input voltage called transfer as voltage is transferred from input to output.

Introduction

The seed of the development of modern solid-state semiconductor electronics goes back to the 1930's when it was realised that some solid-state semiconductors and their junctions offer the possibility of controlling the number and the direction of flow of charge carriers through them. Simple excitations like light, heat or small applied voltage can change the number of mobile charges in a semiconductor. Note that the supply and flow of charge carriers in the semiconductor devices are within the solid itself.

p-n junction diodes have many uses. The characteristic curves indicate the performance when the p-n junction is forward or reverse bias. We explained the behaviour in earlier modules of this unit.

The use of a *p-n* junction as a rectifier. (The purpose of a rectifier is to convert alternating current into unidirectional current). The use of *p-n* junctions with different bias and design as useful to electrical devices have been explained earlier. We learnt about photodiodes, LEDs and solar cells. We also learnt about the Zener effect and its applications.

Here we must understand that semiconductor material is being used in different ways for current control by using doping and biasing by design.All the devices are hence, invented.

The energy gap between the valence and conduction band in semiconductors helped inventors to make many useful devices. Perhaps the most revolutionary step, in the use of semiconductor devices, was the development of transistors.

Transistor can be used in several ways –

ts use as a switch without any mechanical movement and as an amplifier to enlarge a weak signal.

Our mobile handsets have a very large number of transistors. We use their ability to amplify a voice signal by just pressing on a button which in turn makes more transistors operational.

Let us in this module attempt to see details of these applications.

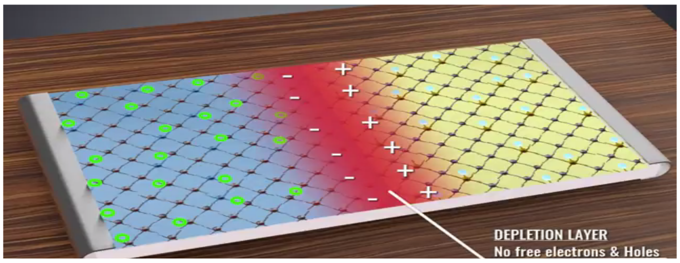
View the video it will recapitulate the ideas you have learnt in previous modules of this unit

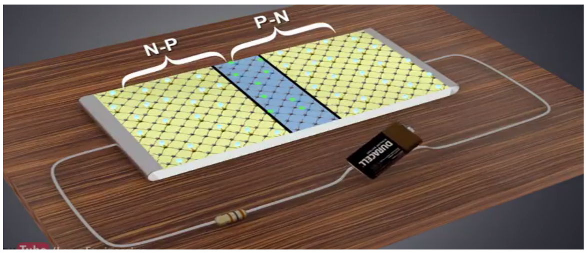
https://www.youtube.com/watch?v=7ukDKVHnac4\

About the video

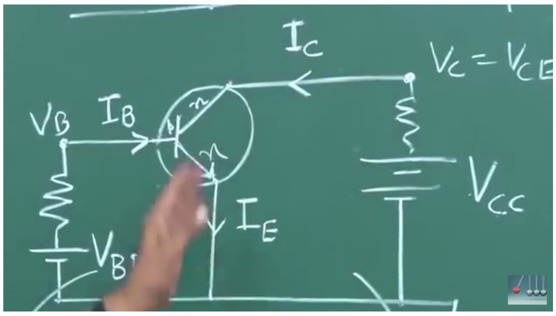
The invention of transistors revolutionised human civilization like no other technology. This video demonstrates working of a Bipolar Junction Transistor (BJT) with its practical applications such as transistors as an amplifier and as a switch with help of animation. Along with transistor working of diodes is also explained in this video. The video covers the following topics - structure of Silicon atom, doping, N type doping, P type doping, working of Diode, working of NPN transistor and dual stage amplification.

Some screen shots





Another interesting video



Series of videos on physics of semiconductors will cover following topics:-

- Energy levels in pure crystalline solids
- Conduction mechanism
- Fermi level and density of states

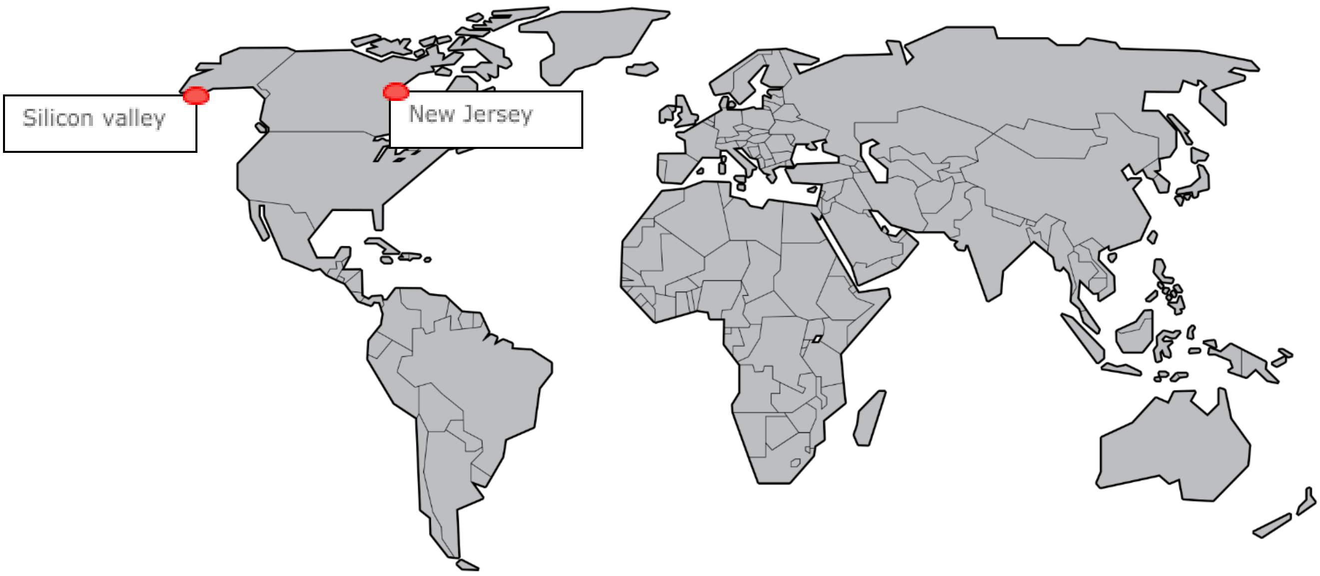
- Doping of acceptor and donor impurities p-n junctions, mechanism of current under different biasing conditions
- Special purpose p-n junctions (Zener diodes, photodetectors, solar cell, LED etc.)
- Theory of transistors
- Applications like amplification, switching, oscillator etc. Binary number system
- Logic gates

Transistors were invented at Bell Laboratories in New Jersey in 1947 by three brilliant US physicists: **John Bardeen** (1908–1991), **Walter Brattain** (1902–1987), and **William Shockley** (1910–1989).

The team, led by Shockley, had been trying to develop a new kind of amplifier for the US telephone system—but what they actually invented turned out to have much more widespread applications. Bardeen and Brattain made the first practical transistor (known as a point-contact transistor) on Tuesday, December 16, 1947. Shortly afterward, during a stay in a hotel, at a physics conference, he single-handedly figured out the theory of the junction transistor—a much better device than the point-contact transistor.

Shockley set up his own transistor-making company and helped to inspire the modern-day phenomenon the "Silicon Valley" (the prosperous area around Palo Alto, California where electronics corporations have congregated). Two of his employees, Robert Noyce and Gordon Moore, went on to establish Intel, the world's biggest micro-chip manufacturer.

Bardeen, Brattain, and Shockley shared the world's top science award, the 1956 Nobel Prize in Physics, for their discovery https://commons.wikimedia.org/wiki/File:Simple_world_map.svg



Transistors Characteristics

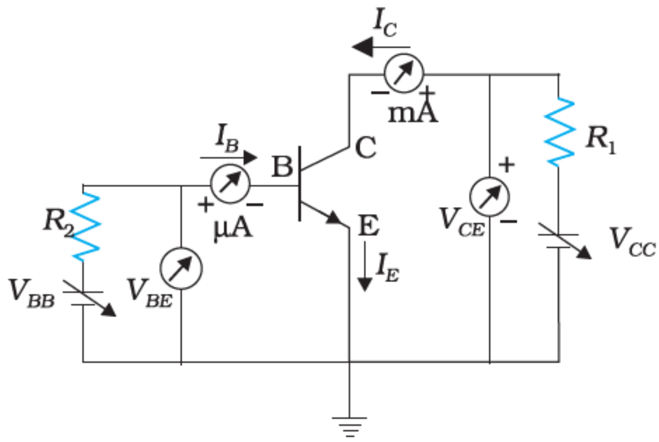
Common emitter transistor characteristics

- When a transistor is used in CE configuration, the input is between the base and the emitter and the output is between the collector and the emitter.
- The variation of the base current I_B with the base-emitter voltage V_{BE} is called the input characteristic.
- Similarly,The variation of the collector current I_C with the collector-emitter voltage V_{CE} is called the output characteristic.

he output characteristics are controlled by the input characteristics.

This implies that **the collector current changes with the base current.**

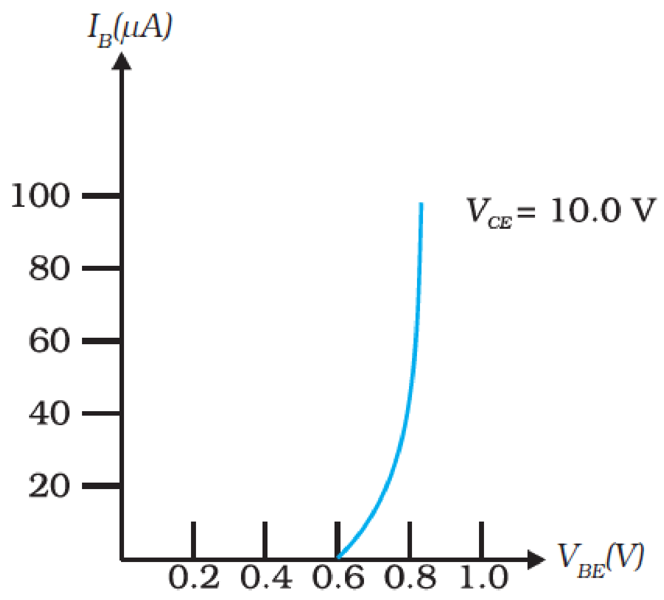
The input and the output characteristics of *n-p-n* transistors can be studied by using the circuit



Circuit arrangement for studying the input and output characteristics of n-p-n transistor in CE configuration

To study the input characteristics of the transistor in CE configuration, a curve is plotted between the base current I_B against the base-emitter voltage V_{BE}.

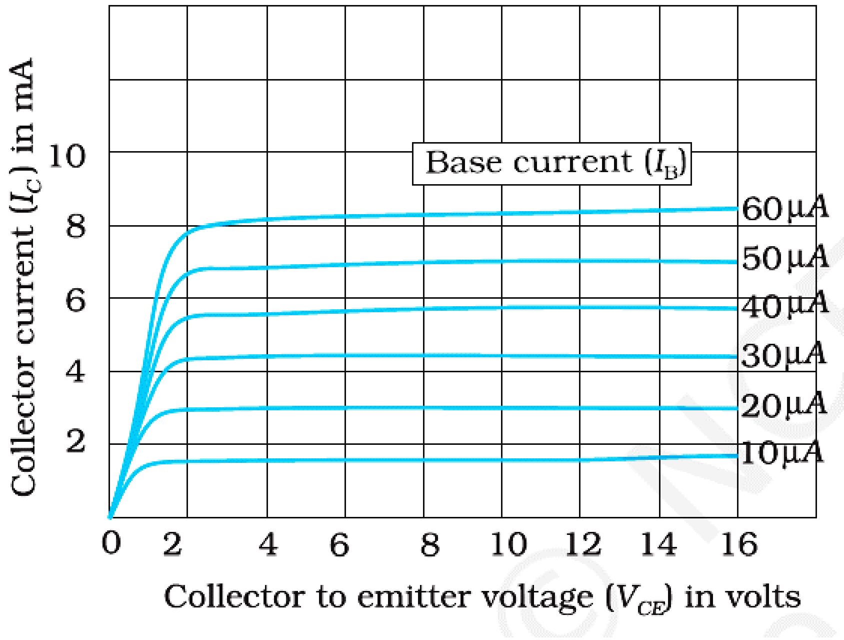
- The collector-emitter voltage V_{CE} is kept fixed while studying the dependence of I_B on V_{BE}.
- We are interested in obtaining the input characteristic when the transistor is in active state. So the collector-emitter voltage V_{CE} is kept large enough to make the **base collector junction reverse biased.**
- Since $V_{CE} = V_{CB} + V_{BE}$ and for Si transistor V_{BE} is 0.6 to 0.7 V, V_{CE} must be sufficiently larger than 0.7 V.
- Since the transistor is operated as an amplifier over a large range of V_{CE}, the reverse bias across the base collector junction is high most of the time.
- Therefore, the input characteristics may be obtained for V_{CE} somewhere in the range of 3 V to 20 V. Since the increase in V_{CE} appears as an increase in V_{CB}, its effect on I_B is negligible.
- As a consequence, input characteristics for various values of V_{CE} will give almost identical curves.
- Hence, it is enough to determine only one input characteristic. The input characteristics of a transistor is as shown



Typical input characteristics,

The **output characteristic is obtained by observing the variation of I_C as V_{CE} is varied keeping I_B constant**.

- It is obvious that if V_{BE} is increased by a small amount, both hole current from the emitter region and the electron current from the base region will increase. As a consequence both I_B and I_C will increase proportionately.
- This shows that when I_B increases I_C also increases. The plot of I_C versus V_{CE} for different fixed values of I_B gives us output characteristics.
- So there will be different output characteristics corresponding to different values of I_B as shown



Typical output characteristics

The linear segments of both the input and output characteristics can be used to calculate some important ac parameters of transistors.

Input resistance (r_i): This is defined as the ratio of change in base emitter voltage (ΔV_{BE}) to the resulting change in base current (ΔI_B) at constant collector-emitter voltage (V_{CE}).

This is dynamic (ac resistance) and as can be seen from the input characteristic, its value varies with the operating current in the transistor

$$r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)_{V_{CE}}$$

The value of r_i can be anything from a few hundreds to a few thousand ohms.

Output resistance (r_o): This is defined as the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at a constant base current I_B.

$$r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)_{I_B}$$

The output characteristics show that initially for very small values of V_{CE}, I_C increases almost linearly. This happens because the base-collector junction is not reverse biased and the transistor is not in active state.

In fact, the transistor is in the saturation state and the current is controlled by the supply voltage V_{CC} (=V_{CE}) in this part of the characteristic. When V_{CE} is more than that required to reverse bias the base-collector junction, I_C increases very little with V_{CE}.

The reciprocal of the slope of the linear part of the output characteristic gives the values of r_o. The output resistance of the transistor is mainly controlled by the bias of the base collector junction.

The high magnitude of the output resistance (of the order of 100 kW) is due to the reverse-biased state of this diode. This also **explains why the resistance at the initial part of the characteristic, when the transistor is in saturation state, is very low.**

Current amplification factor (β): This is defined as the ratio of the change in collector current to the change in base current at a constant collector-emitter voltage (V_{CE}) when the transistor is in active state.

$$\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_{CE}}$$

This is also known as small signal current gain and its value is very large. If we simply find the ratio of I_C and I_B we get what is called βdc of the transistor.

Hence

$$\beta_{dc} = \frac{I_C}{I_B}$$

Since I_C increases with I_B almost linearly and $I_C = 0$ when $I_B = 0$, the values of both β_{dc} and β_{ac} are nearly equal.

So, for most calculations β_{dc} can be used. Both β_{ac} and β_{dc} vary with V_{CE} and I_B (or I_C) slightly

Transistors as a Device

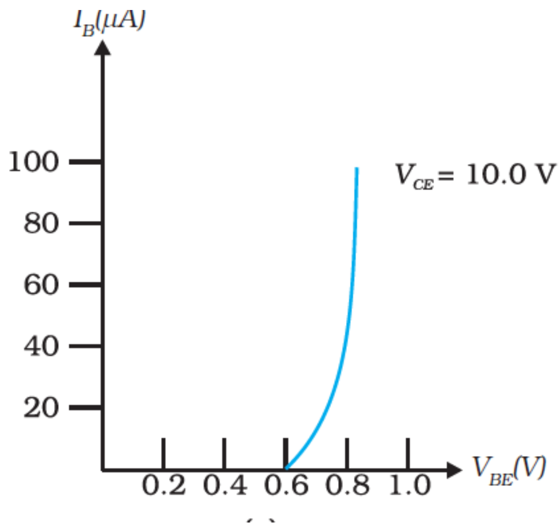
The transistor can be used as a device, its applications depend on the configuration used (namely CB-common base, CC-common collector and CE common emitter), the biasing of the E-B and B-C junction and the operation region namely

- cut-off,
- active region and

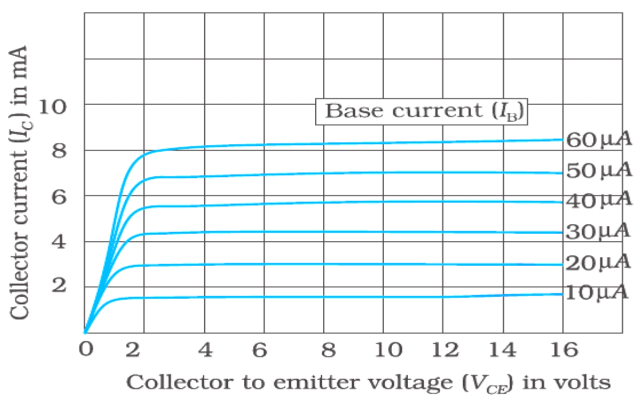
- saturation
- The common emitter configuration lends itself to voltage amplification and is the most commonly used configuration for transistor amplifiers.
- The emitter base junction is forward biased and the collector emitter junction is reverse biased. The transistor is operated in the active region.

As mentioned earlier we have confined only to the CE configuration and will be concentrating on the biasing and the operation region to understand the working of a device. When the transistor is used in the cut off or saturation state it acts as a switch. On the other hand, to using the transistor as an amplifier, it must operate in the active region.

Input and output Characteristics Curves and Transfer Characteristics

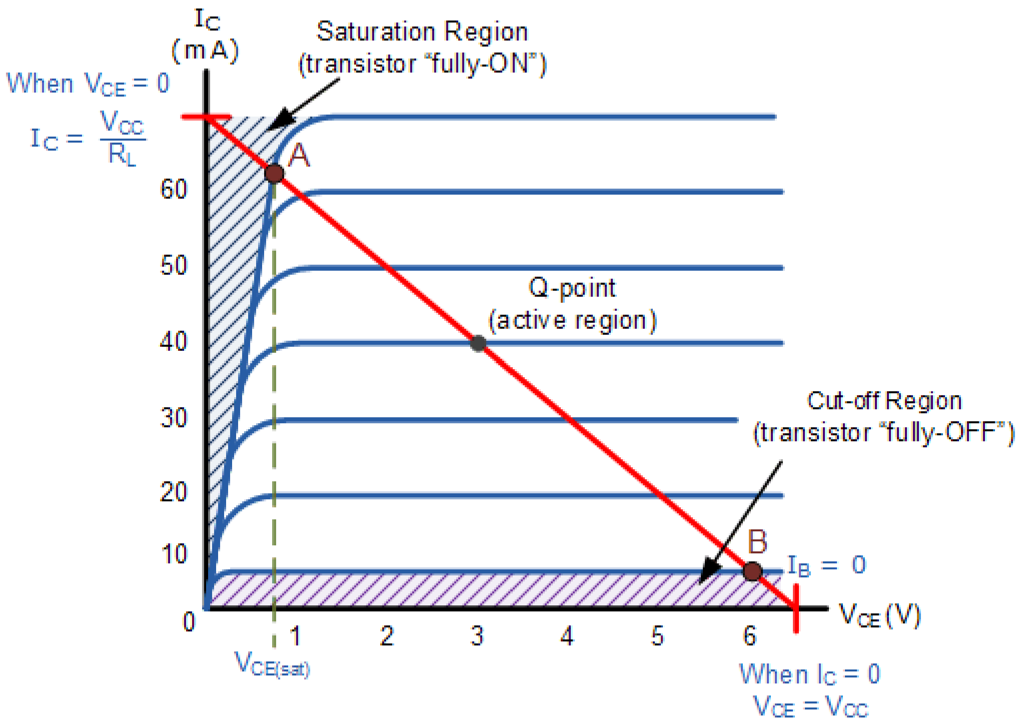


Input characteristic curves- shows the variation of base current due to changes in emitter base voltage



Output characteristic curves- shows the variation of collector current due to changes in emitter collector voltage

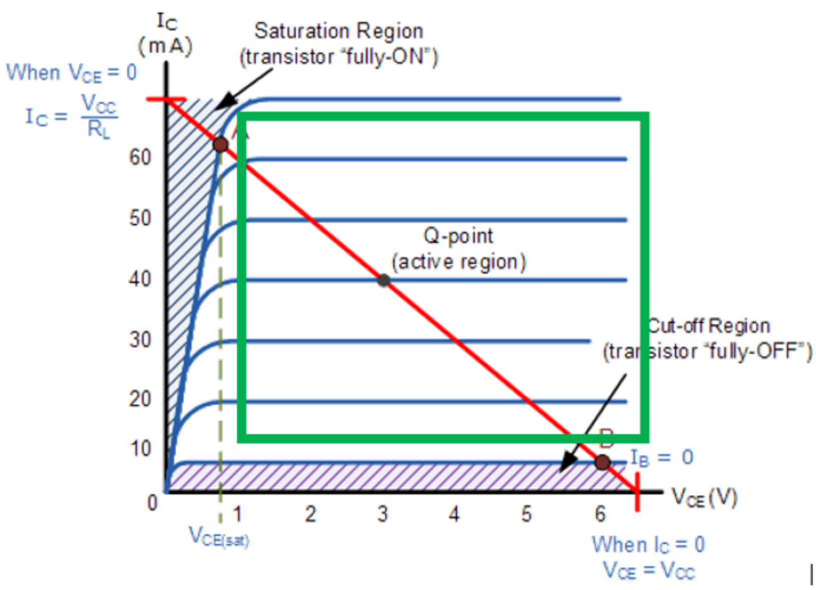
Study of the output characteristic graph



https://i.stack.imgur.com/UuO7V.gif

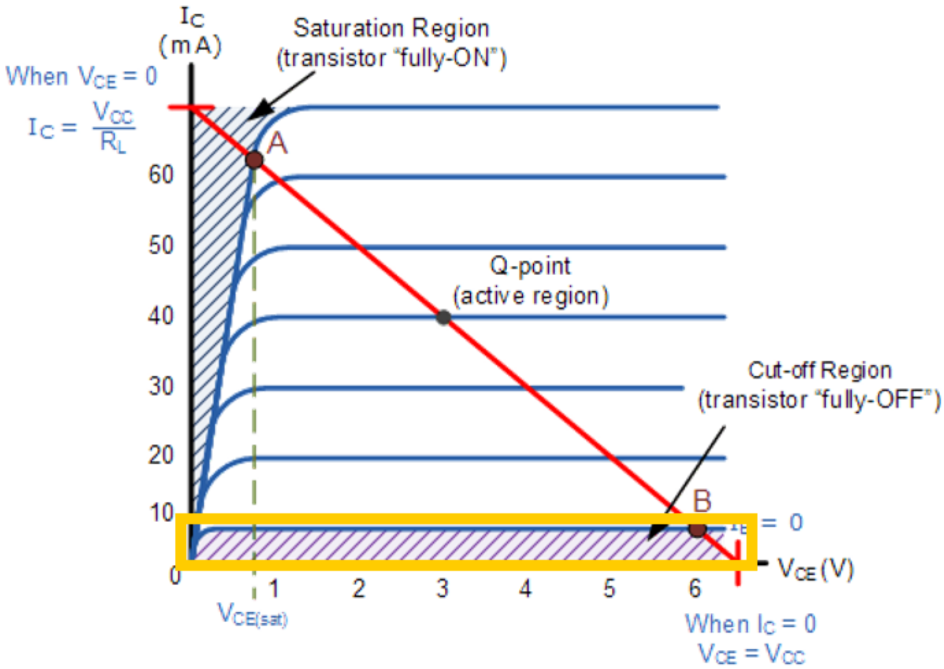
From the Graph

- **Region 1**-In linear portion of the graph for different I_B the transistor **active** region, The response is :$I_c = c_{on}$



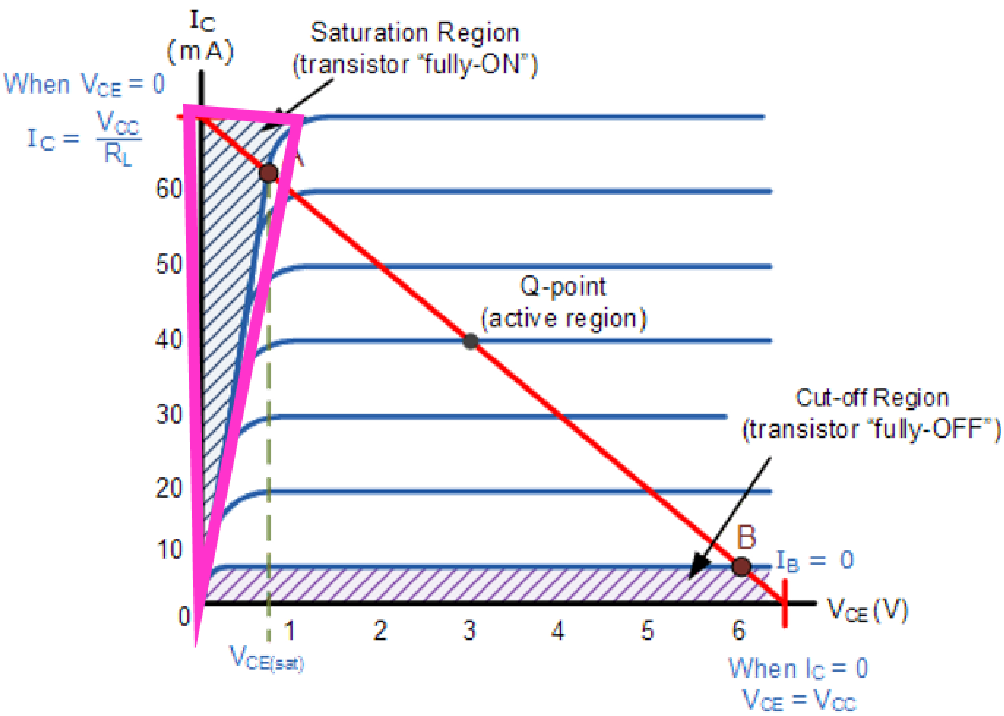
- **Region 2-** In **Cut off region**, Response is : $I_c = 0$.

  - No matter how large the increase in V_{CE}, Ic is still zero. It is Similar to Air gap in the plug type key in the laboratory.



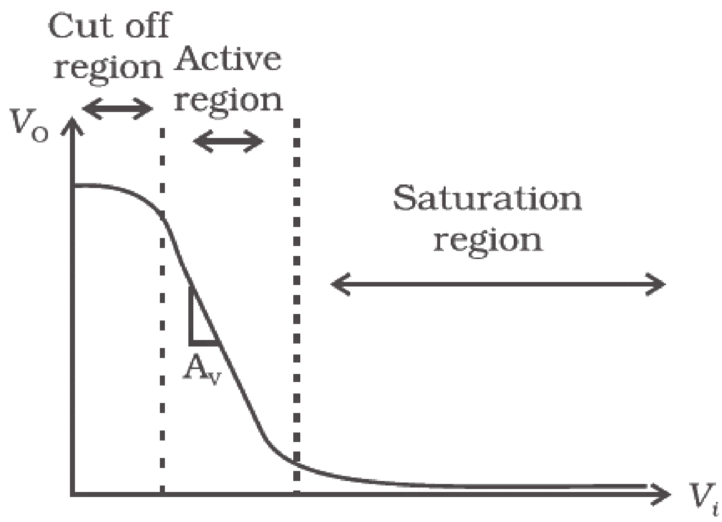
- **Region3-**In **Saturation region**, Response is : I_c = const. V_{CE} is constant, being the slope of the curve.

  We can plot a **Transfer Characteristic Curve**



The above graphs when plotted to show the variation of output voltage with input voltage give transfer characteristics, which means how the voltage is 'transferred' from input to output.This is called **transfer characteristics.**

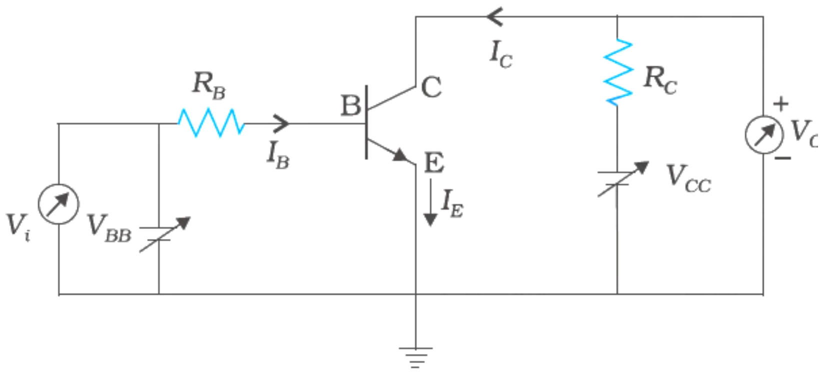
The cut off region corresponds to input voltages lower than knee voltage for the emitter base forward bias.



Transfer characteristic.

Transistor as Switch

We shall try to understand the operation of the transistor as a switch by focussing on the behaviour of the base-biased transistor in CE configuration as shown in the circuit diagram.



Base-biased transistor in CE configuration,

Applying **Kirchhoff's voltage rule** to the input and output sides of this circuit, we get

$V_{BB} = I_B R_B + V_{BE}$

And

$V_{CE} = V_{CC} - I_C R_C$

We shall treat V_{BB} as the dc input voltage Vi and V_{CE} as the dc output voltage V_O. So, we have

$V_i = I_B R_B + V_{BE}$

$V_O = V_{CC} - I_C R_C$

Let us see how Vo changes as Vi increases from zero onwards.

- In the case of Si transistors, as long as input Vi is less than 0.6 V, the transistor will be in a cut off state and current I_C will be zero.
  Hence $\mathbf{V_o = V_{CC}}$
- When Vi becomes greater than 0.6 V the transistor is in active state with some current I_C in the output path and the output Vo decreases as the term $I_C R_C$ increases.
- With increase of V_i, I_C increases almost linearly and so Vo decreases linearly till its value becomes less than about 1.0 V.
- Beyond this, the change becomes non-linear and transistor goes into saturation state.

- With further increase in V_i the output voltage is found to decrease further towards zero though it may never become zero.

From the V_o vs V_i curve (transfer characteristics of the base-biased Transistor), We see that between cut off state and active state and between active state and saturation state there are regions of non-linearity showing that the transition from cut-off state to active state and from active state to saturation state are not sharply defined.

Let us see now how the transistor is operated as a switch. As long as V_i is low and unable to forward-bias the transistor, Vo is high (at V_{CC}).

If V_i is high enough to drive the transistor into saturation, then Vo is low, very near to zero.

When the transistor is not conducting it is said to be switched off and **when it is driven into saturation it is said to be switched on.**

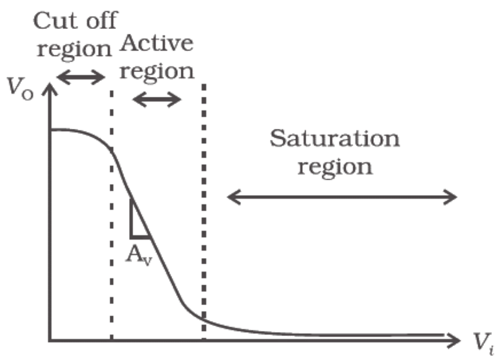
This shows that if we define low and high states as below and above certain voltage levels corresponding to cut off and saturation of the transistor, then we can say that a low input switches the transistor off and a high input switches it on.

Alternatively, we can say that a low input to the transistor gives a high output and a high input gives a low output.

The switching circuits are designed in such a way that the transistor does not remain in active state.

Transistors as a Amplifier

For using the transistor as an amplifier, **we will use the active region of the V_o versus V_i curve.**



Transfer characteristics

The **slope of the linear part of the curve represents the rate of change of the output with the input.**

It is negative because the output is $V_{CC} - I_C R_C$ and not $I_C R_C$.

That is why as input voltage of the CE amplifier increases its output voltage decreases and the output is said to be out of phase with the input.

If we consider ΔV_o and ΔV_i as small changes in the output and input voltages then $\frac{\Delta V_o}{\Delta V_i}$ is called **the small signal voltage gain A_V of the amplifier**.If the V_{BB} voltage has a fixed value corresponding to the mid-point of the active region, the circuit will behave as a CE amplifier with voltage gain = $\frac{\Delta V_o}{\Delta V_i}$.

We can express the voltage gain A_V in terms of the resistors in the circuit and the current gain of the transistor as follows.

We have, $V_o = V_{CC} - I_C R_C$

Therefore, $\Delta V_0 = 0 - R_C \Delta I_C$

Similarly, we have from

$V_i = I_B R_B + V_{BE}$

$\Delta V_i = R_B \Delta I_B + \Delta B_{BE}$

But ΔB_{BE} is negligibly small in comparison to $R_B \Delta I_B$ in this circuit.

So, the **voltage gain** of this **CE amplifier** is given by

$$A_V = -\frac{R_C \Delta I_C}{R_B \Delta I_B}$$

$$= -\beta_{ac}\left(\frac{R_C}{R_B}\right)$$

Now because of biasing arrangement the collector emitter resistance is >>base emitter resistance.Thus the linear portion of the active region of the transistor can be exploited for the use in amplifiers.

Example:

Calculate the β_{dc} gain if in a typical transistor $I_B = 10\ \mu A$ produces a large collector current = $500\ \mu A$

Solution:

$$\beta_{dc} = \frac{I_C}{I_B} = 50$$

Example:

Differentiate between β_{dc} current gain and β_{ac} current gain

Solution:

dc current gain is defined as the ratio of collector current to the base current , while ac current gain is the ratio of the change in collector current to the change in the base current at a constant collector to emitter voltage.

$$\beta_{dc} = \frac{I_C}{I_B} \text{ and } \beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right) at\ constant\ V_{CE}$$

Example:

What is meant by ac voltage gain?

Solution:

Ac voltage gain is defined as the ratio of the change in the output voltage to the change in input voltage, when the transistor is in the active region.

Suppose on placing an a-c signal in the input circuit the base current changes by ΔI_B and corresponding output collector current changes byΔI_C. If the R_i and R_o are resistances of input and output circuits

Then $A_v = \frac{\Delta I_C \times R_o}{\Delta I_B \times R_i} = \beta_{ac} \frac{R_o}{R_i} = current\ gain \times resistance\ gain$

Example:

Define ac power gain. Find a relation between power gain and current voltage gain.

Solution:

Power gain is defined as the ratio of change in output power to change in input power

Power = current × voltage

ac power gain = a-c current gain × a-c voltage gain

$= \beta_{ac} \times A_v = \beta_{ac} \times \beta_{ac} \frac{R_o}{R_i}$

$= \left(\beta_{ac}\right)^2 \times resistance\ gain$

For common emitter circuits the value of power gain is very high.

Example:

The base current of a transistor is 105 µA and the collector current is 2.05 m A. Compute the values of

a. β_{dc}

b. Ie

c. A change of 27 µA in the base current produces a change of 0.65 m A in the collector current find β_{ac}

Solution:

I_B = 105 µA

I_c = 2.05mA

a) $\beta_{dc} = \frac{I_C}{I_B} = \frac{2.05 \times 10^{-3}}{105 \times 10^{-6}} = 19.52$

b) $I_E = I_B + I_C = 0.105\ mA + 2.05\ mA = 2.155\ m\ A$

c) $\beta_{ac} = \left(\frac{\Delta I_C}{\Delta I_B}\right) = \frac{0.65 mA}{27 \mu A} = \frac{0.65 \times 10^{-3}}{27 \times 10^{-6}} = 24.07$

Example:

The current gain for a common emitter amplifier is 59. If the emitter-current is 6.0 mA find

a) Base current

b) Collector current

Solution:

$$\beta_{dc} = \frac{I_C}{I_B} = 59$$

$I_B + I_C = I_E = 6$ m A

Solving the two we get $I_B =$ 0.1 m A and $I_C = 5.9$ mA

Example:

Find the voltage gain and power gain in a transistor amplifier in common emitter configuration when current gain is 66 and input and output resistances are 0.5 k ohms and 50 k ohms respectively

Solution:

Voltage gain

$$A_v = \beta_{ac}\frac{R_o}{R_i} = 66\times\frac{50k\ ohms}{0.5k\ ohms} = 6600$$

Power gain

$$A_v \times \beta_{ac} = 6600\times66 = 4.356\times10^5$$

Think about These

- **Under normal use of transistors, the emitter is forward biased and the collector is reverse biased. Can either of these biasing's be changed?**

  No, the biasing's cannot be changed. If the emitter is reversing biased no current will flow and if the collector is forward biased there will be current due to the p-n junction between base and collector.

- **Why is the output resistance higher than the input resistance in a transistor?**

  The emitter of a transistor is forward biased and the collector is reverse biased, the smaller emitter voltage produces a large emitter current. This also means that a small voltage variation at the input of the transistor produces a large emitter current variation .In other words we can say that the input offers very low resistance to a small input voltage. The reverse bias collector collects all the charge carriers that diffuse into it through the base, a large change in collector voltage produces a small change in collector current or we can say it offers a large resistance.

- **Would the resistances be different even if the transistor has no bias?**

The doping and design is such that the potential barrier at emitter base junction is lower than the base collector barrier potential. But in the absence of bias the charge carriers do not flow across the junctions.

- **In a transistor the forward bias is always smaller than the reverse bias.**

This is done on purpose. If the forward bias is made large, the majority charge carriers would move from the emitter to the collector through the base with high energy. This could damage the transistor due to excessive heat.

- **Transistors are temperature sensitive**

In transistors electrons and holes are the charge carriers through the transistor. If temperature rises there would be more charge carriers as the covalent bonds break and set electrons and holes free in the conduction and valence bands respectively due to larger currents when biased the heat could damage the transistor.

- **Can we check whether a transistor is damaged or is in working order**

The forward biased emitter base junction should offer low resistance while the reverse biased base collector should give higher resistance. If the transistor is damaged both will show low resistance, unbiased transistor

- **Why is the base region of a transistor thin and slightly doped?**

The base controls the flow of majority charge carrier's holes in p-n-p and electrons in n-p-n, from the emitter to the collector. The base is made thinner and is lightly doped so that it has a small number of free electrons in p-n-p and holes in n-p-n. This minimises the recombination of holes and electrons in it .Most of the electrons or holes arriving from the emitter diffuse across the base to reach the collector. This is the reason why collector current is almost equal to the emitter current.

If the base region is made large as compared to a usual transistor will it affect the values of collector current, current gain?
The collector current will decrease. Hence the current gain will also be smaller.

- **Can two p-n junctions placed back to back act as a p-n-p transistor?**
  No, even if fused together the base region would be thick and with heavier than desired doping.

Summary

We have learnt in this module

- *p-n* junction is the 'key' to all semiconductor devices.
- When such a junction is made, a 'depletion layer' is formed consisting of immobile ion-cores devoid of their electrons or holes. This is responsible for a junction potential barrier.
- By changing the external applied voltage, junction barriers can be changed. In forward bias (*n*-side is connected to the negative terminal of the battery and *p*-side is connected to the positive), the barrier is decreased while the barrier increases in reverse bias. Hence, forward bias current is more (mA) while it is very small (μA) in a p-n junction diode.
- Transistor is an *n-p-n* or *p-n-p* junction device.
- The central block (thin and lightly doped) is called 'Base' while the other electrodes are 'Emitter' and 'Collectors'.
- The emitter-base junction is forward biased while the collector-base junction is reverse biased.
- The transistors can be connected in such a manner that either C or E or B is common to both the input and output. This gives the three configurations in which a transistor is used: CE-Common Emitter, CC- Common Collector and CB-Common Base
- The plot between I_C and V_{CE} for fixed I_B is called output characteristics
- The plot between I_B and V_{BE} with fixed V_{CE} is called input characteristics.

- The important transistor parameters for CE-configuration are:
- Input resistance $r_i = \left(\frac{\Delta V_{BE}}{\Delta I_B}\right)$ *keeping* V_{CE} *constant*
- Output resistance $r_o = \left(\frac{\Delta V_{CE}}{\Delta I_C}\right)$ *keeping* I_B *constant*
- Current amplification factor $\beta = \left(\frac{\Delta I_C}{\Delta I_B}\right)$ *keeping* V_{CE} *constant*
- Transistor can be used as an amplifier. The voltage gain of a transistor amplifier in common emitter configuration is:

  $$A_v = \left(\frac{v_0}{v_i}\right) = \beta\frac{R_C}{R_B}$$

  Where R_c and R_B are the resistances in collector and base sides of the circuit

- When the transistor is used in the cut-off or saturation state, it acts as a switch.