Somaiya Vidyavihar University
K.J. Somaiya College of Engineering
(A Constituent College of Somaiya Vidyavihar University)

BJT
concepts DC AC

MOSFET >95%
concept DC AC

Course Code	Course Title							
116U40C302	Analog Electronic Circuits (AEC)							
	TH			P		TUT		Total
Teaching Scheme (Hrs.)	03			–		–		03
Credits Assigned	03			–		–		03
Examination Scheme	Marks							
	CA		ESE	TW	O	P	P&O	Total
	ISE	IA						
	30	20	50	–	–	–	–	100

Course prerequisites:

- Elements of Electrical and Electronics Engineering

Course Objectives:

The objective of the course is to impart fundamental knowledge and applications of semi-conductor devices like BJT and MOSFET. This course aims to build a foundation for DC analysis, biasing circuits of BJT, FET and small signal analysis of mid, low and high frequency range amplifiers using hybrid models. The course imparts knowledge of frequency response of single stage amplifiers. It conveys the concept of different types of feedback used in amplifiers and oscillators. It explains the importance of Differential Amplifiers, current mirrors and its application. Analysis of the MOSFET based circuits provides the necessary foundation for Analog and digital VLSI design.

Course Outcomes:

At the end of successful completion of the course the student will be able to

CO 1. Analyze BJT transistor circuits for DC and AC operations
CO 2. Analyze MOSFET circuits for DC and AC operations
CO 3. Learn the dependency of the amplifier gain over the frequency range
CO 4. Understand the concept of feedback and apply it to amplifiers and oscillators
CO 5. Understand the need of Differential Amplifiers

Module No.	Unit No.	Details	Hrs.	CO
		Bipolar Junction Transistor (BJT)	**10**	**CO1**
concepts	**1.1**	BJT (npn and pnp) construction, Working, input and output characteristics, DC Load Line, Concept of Biasing	22%	
DC analysis	**1.2**	DC Analysis of BJT circuits, Basic Transistor Application: Amplifier and as a switch		
1 AC analysis	**1.3**	Basic BJT amplifier configuration, Small signal hybrid pi model of BJT, Small signal mid – frequency analysis of CE, CB and CC BJT amplifiers.		
		#Self learning topic: Stability factor S(Ico) for all BJT biasing circuits		
		The Field Effect Transistor	**10**	**CO2**
Concept	**2.1**	MOS Field-Effect Transistor: Construction, Working, transfer and output characteristics, Enhancement and Depletion MOSFETs	22%	
DC 2 analysis	**2.2**	MOSFET Biasing and DC Circuit Analysis, MOSFET application as Amplifier and Switch		
AC analysis	**2.3**	Basic MOSFET amplifier configuration, Small signal model of MOSFET, Small signal mid – frequency analysis of CS,CG and CD MOSFET amplifiers.		
		Frequency Response of Single Stage Amplifiers	**08**	**CO3**
20Hz - 20KHz **3**	**3.1**	**Low frequency Response:** Effect of coupling and bypass capacitor on frequency response of single stage Common Source ~~MOSFET~~ amplifier.	20%	
	3.2	**High frequency Response:** High frequency model of MOSFET, Miller effect and miller capacitance, Unity gain bandwidth f_T and beta-cutoff frequency f_β, high frequency response of single stage MOSFET amplifiers.		

Module No.	Unit No.	Details	Hrs.	CO
4	Feedback Circuits		08	CO4
	4.1	**Negative feedback:** Basic feedback theory, characteristics of negative feedback, Effect of negative feedback with derivation for input impedance, output impedance, gain and bandwidth for the four feedback topologies. (no numerical examples to be included)	20%	
	4.2	**Positive Feedback:** Introduction and classification of oscillators, Barkhausen criterion for sustained oscillations. **Audio frequency oscillators:** Transistorized RC phase shift oscillator and Wein bridge oscillator. (theoretical description only – no analysis or numerical examples to be included) **Radio frequency oscillators:** LC tank circuit, Hartley, Colpitt's and clapp's oscillators,(theoretical description only – no analysis or numerical examples to be included)		
		#Self learning topic: Crystal Oscillator		
5	Differential Amplifiers		09	CO5
"IC"	5.1	**Single ended and Differential signaling MOSFET Differential Amplifiers:** Terminology and qualitative description, DC transfers characteristics, differential gain, common mode gain, and CMRR. AC (small signal analysis) and DC analysis of MOSFET differential amplifier		
	5.2	**Current mirrors:** Basic two transistor MOSFET current mirror, Three transistor MOSFET current mirror		
		Total	**45**	

S.No.	Name/s of Author/s	Title of Book	Name of Publisher with country	Edition and Year of publication
1.	Donald A. Neamen	*Microelectronics: Circuit Analysis and Design*	McGraw Hill, India	4^{th} Edition, 2021
2.	Robert L. Boylestad, Louis Nashelesky	*Electronic Devices and Circuit theory* Dont do AC analysis for BJT from here	Pearson Education, India	11^{th} Edition, 2015
3.	Behzad Razhavi	*Fundamentals of Microelectronics*	Wiley, India	3^{rd} Edition, 2021
4.	S. Salivahanan, N. Suresh Kumar	*Electronic Devices and Circuit*	McGraw Hill, India	4^{th} Edition, 2017
5.	Jacob Millman and C. Halkias	*Millman's Electronic Devices and circuits*	McGraw Hill, India	4^{th} Edition, 2015

5.1 BASIC BIPOLAR JUNCTION TRANSISTOR

Objective: • Understand the physical structure, operation, and characteristics of the bipolar junction transistors (BJT), including the npn and pnp devices.

The **bipolar junction transistor (BJT)** has three separately doped regions and contains two pn junctions. A single pn junction has two modes of operation—forward bias and reverse bias. The bipolar transistor, with two pn junctions, therefore has four possible modes of operation, depending on the bias condition of each pn junction, which is one reason for the versatility of the device. With three separately doped regions, the bipolar transistor is a three-terminal device. The basic transistor principle is that *the voltage between two terminals controls the current through the third terminal*.

Our discussion of the bipolar transistor starts with a description of the basic transistor structure and a qualitative description of its operation. To describe its operation, we use the pn junction concepts presented in Chapter 1. However, the two pn junctions are sufficiently close together to be called interacting pn junctions. The operation of the transistor is therefore totally different from that of two back-to-back diodes.

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Current in the transistor is due to the flow of both electrons and holes, hence the name **bipolar.** Our discussion covers the relationship between the three terminal currents. In addition, we present the circuit symbols and conventions used in bipolar circuits, the bipolar transistor current–voltage characteristics, and finally, some non-ideal current–voltage characteristics.

5.1.1 Transistor Structures

Figure 5.1 shows simplified block diagrams of the basic structure of the two types of bipolar transistor: npn and pnp. The **npn bipolar transistor** contains a thin p-region between two n-regions. In contrast, the **pnp bipolar transistor** contains a thin n-region sandwiched between two p-regions. The three regions and their terminal connections are called the **emitter, base,** and **collector.**[1] The operation of the device depends on the two pn junctions being in close proximity, so the width of the base must be very narrow, normally in the range of tenths of a micrometer (10^{-6} m).

Read

The actual structure of the bipolar transistor is considerably more complicated than the block diagrams of Figure 5.1. For example, Figure 5.2 is the cross section of

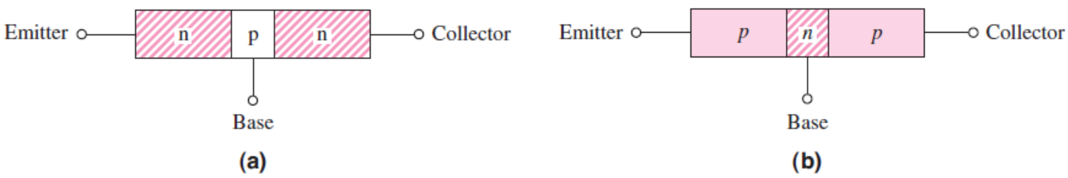
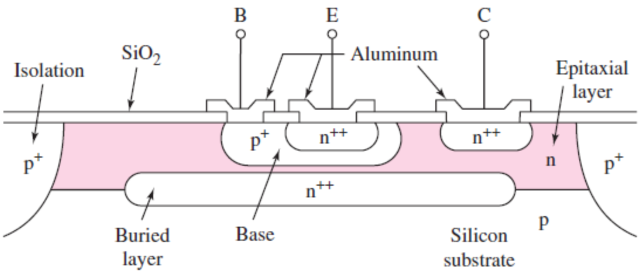


Figure 5.1 Simple geometry of bipolar transistors: (a) npn and (b) pnp

[1]The reason for the names **emitter** and **collector** for the terminals will become obvious as we go through the operation of the transistor. The term **base** refers to the structure of the original transistor.



Real structure

Figure 5.2 Cross section of a conventional integrated circuit npn bipolar transistor

a classic npn bipolar transistor fabricated in an integrated circuit. One important point is that the device is not symmetrical electrically. This asymmetry occurs because the geometries of the emitter and collector regions are not the same, and the impurity doping concentrations in the three regions are substantially different. For example, the impurity doping concentrations in the emitter, base, and collector may be on the order of 10^{19}, 10^{17}, and 10^{15} cm^{-3}, respectively. Therefore, even though both ends are either p-type or n-type on a given transistor, switching the two ends makes the device act in drastically different ways.

only Read

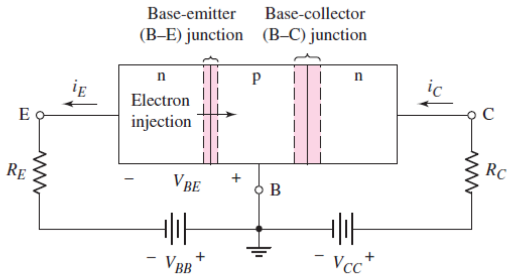
Although the block diagrams in Figure 5.1 are highly simplified, they are still useful for presenting the basic transistor characteristics.

5.1.2 npn Transistor: Forward-Active Mode Operation

Since the transistor has two pn junctions, four possible bias combinations may be applied to the device, depending on whether a forward or reverse bias is applied to each junction. For example, if the transistor is used as an amplifying device, the **base–emitter (B–E) junction** is forward biased and the **base–collector (B–C) junction** is reverse biased, in a configuration called the **forward-active operating mode,** or simply the **active region.** The reason for this bias combination will be illustrated as we look at the operation of such transistors and the characteristics of circuits that use them.

Transistor Currents

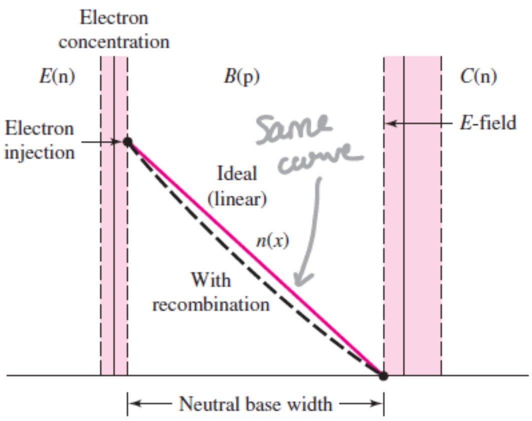
Figure 5.3 shows an idealized npn bipolar transistor biased in the forward-active mode. Since the B–E junction is forward biased, electrons from the emitter are injected across



In class, have not shown resistors for simplicity.

Resistors R_C & R_E = used for limiting current in BJT

Figure 5.3 An npn bipolar transistor biased in the forward-active mode; base–emitter junction forward biased and base–collector junction reverse biased



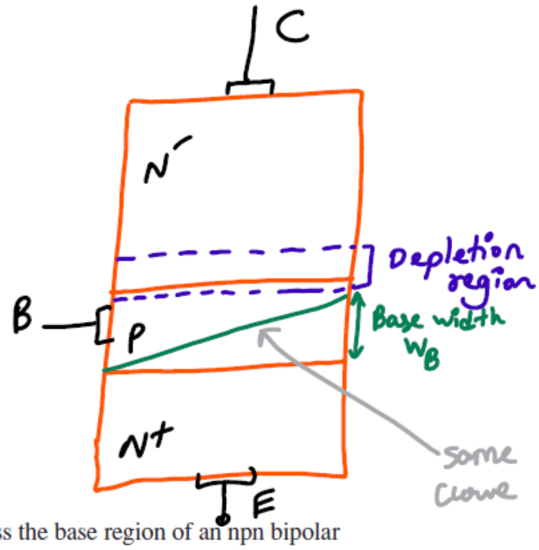


Figure 5.4 Minority carrier electron concentration across the base region of an npn bipolar transistor biased in the forward-active mode. Minority carrier concentration is a linear function versus distance for an ideal transistor (no carrier recombination), and is a nonlinear function versus distance for a real device (with carrier recombination).

the B–E junction into the base, creating an excess minority carrier concentration in the base. Since the B–C junction is reverse biased, the electron concentration at the edge of that junction is approximately zero.

The base region is very narrow so that, in the ideal case, the injected electrons will not recombine with any of the majority carrier holes in the base. In this case, the electron distribution versus distance through the base is a straight line as shown in Figure 5.4. Because of the large gradient in this concentration, electrons that are injected, or *emitted,* from the emitter region diffuse across the base, are swept across the base–collector space-charge region by the electric field, and are *collected* in the collector region creating the collector current. However, if some carrier recombination does occur in the base, the electron concentration will deviate from the ideal linear curve, as shown in the figure. To minimize recombination effects, the width of the neutral base region must be small compared to the minority carrier diffusion length.

$I_{EO} \approx \frac{I_S}{\alpha}$

I_S - reverse saturation current

Emitter Current: Since the B–E junction is forward biased, we expect the current through this junction to be an exponential function of B–E voltage, just as we saw that the current through a pn junction diode was an exponential function of the forward-biased diode voltage. We can then write the current at the emitter terminal as

$$i_E = I_{EO}[e^{v_{BE}/V_T} - 1] \cong I_{EO}e^{v_{BE}/V_T} \qquad i_E = \frac{I_S}{\alpha}\exp\left(\frac{V_{BE}}{V_T}\right) \tag{5.1}$$

where the approximation of neglecting the (-1) term is usually valid since $v_{BE} \gg V_T$ in most cases.[2] The parameter V_T is the usual thermal voltage. The emission coefficient n that multiplies V_T is assumed to be 1, as we discussed in Chapter 1 in considering the ideal diode equation. The flow of the negatively charged electrons is through the emitter into the base and is opposite to the conventional current direction. The conventional emitter current direction is therefore out of the emitter terminal.

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[2]The voltage notation v_{BE}, with the dual subscript, denotes the voltage between the B (base) and E (emitter) terminals. Implicit in the notation is that the first subscript (the base terminal) is positive with respect to the second subscript (the emitter terminal).

We will assume that the ideality factor n in this diode equation is unity (see Chapter 1).

The multiplying constant, I_{EO}, contains electrical parameters of the junction, but in addition is directly proportional to the active B–E cross-sectional area. Therefore, if two transistors are identical except that one has twice the area of the other, then the emitter currents will differ by a factor of two for the same applied B–E voltage. Typical values of I_{EO} are in the range of 10^{-12} to 10^{-16} A, but may, for special transistors, vary outside of this range.

$I_{EO} = \frac{I_S}{\alpha}$

Collector Current: Since the doping concentration in the emitter is much larger than that in the base region, the vast majority of emitter current is due to the injection of electrons into the base. The number of these injected electrons reaching the collector is the major component of collector current.

The number of electrons reaching the collector per unit time is proportional to the number of electrons injected into the base, which in turn is a function of the B–E voltage. To a first approximation, the collector current is proportional to e^{v_{BE}/V_T} and is independent of the reverse-biased B–C voltage. The device therefore looks like a **constant-current source.** The collector current is controlled by the B–E voltage; in other words, the current at one terminal (the collector) is controlled by the voltage across the other two terminals. *This control is the basic transistor action.*

$\beta : 100-300$

$\beta = \frac{I_C}{I_B} \; (\beta > 1)$

We can write the collector current as

$$i_C = I_S e^{v_{BE}/V_T} \qquad I_C = I_S \exp\left(\frac{V_{BE}}{V_T}\right) \tag{5.2}$$

α – Common emitter current gain

The collector current is slightly smaller than the emitter current, as we will show. The emitter and collector currents are related by $i_C = \alpha i_E$. We can also relate the coefficients by $I_S = \alpha I_{EO}$. The parameter α is called the **common-base current gain** whose value is always slightly less than unity. The reason for this name will become clearer as we proceed through the chapter.

β – Common base current gain

$\boxed{\alpha = \frac{I_C}{I_E}}$ usually close to 1 (0.9 to 1)

Base Current: Since the B–E junction is forward biased, holes from the base are injected across the B–E junction into the emitter. However, because these holes do not contribute to the collector current, they are not part of the transistor action. Instead, the flow of holes forms one component of the base current. This component is also an exponential function of the B–E voltage, because of the forward-biased B–E junction. We can write

$$i_{B1} \propto e^{v_{BE}/V_T} \tag{5.3(a)}$$

A few electrons recombine with majority carrier holes in the base. The holes that are lost must be replaced through the base terminal. The flow of such holes is a second component of the base current. This "recombination current" is directly proportional to the number of electrons being injected from the emitter, which in turn is an exponential function of the B–E voltage. We can write

$$i_{B2} \propto e^{v_{BE}/V_T} \tag{5.3(b)}$$

The total base current is the sum of the two components from Equations (5.3(a)) and (5.3(b)):

$$i_B \propto e^{v_{BE}/V_T} \qquad i_B = i_{B1} + i_{B2} \tag{5.4}$$

Figure 5.5 shows the flow of electrons and holes in an npn bipolar transistor, as well as the terminal currents.[3] (Reminder: the conventional current direction is the

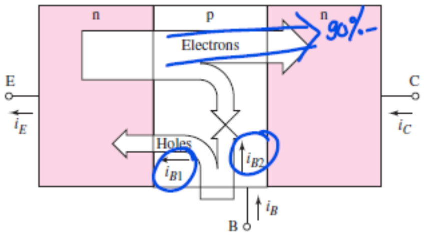

Figure 5.5 Electron and hole currents in an npn bipolar transistor biased in the forward-active mode. Emitter, base, and collector currents are proportional to e^{v_{BE}/V_T}.

same as the flow of positively charged holes and opposite to the flow of negatively charged electrons.)

If the concentration of electrons in the n-type emitter is much larger than the concentration of holes in the p-type base, then the number of electrons injected into the base will be much larger than the number of holes injected into the emitter. This means that the i_{B1} component of the base current will be much smaller than the collector current. In addition, if the base width is small, then the number of electrons that recombine in the base will be small, and the i_{B2} component of the base current will also be much smaller than the collector current.

Common-Emitter Current Gain

In the transistor, the rate of flow of electrons and the resulting collector current are an exponential function of the B–E voltage, as is the resulting base current. This means that the collector current and the base current are linearly related. Therefore, we can write

$$\frac{i_C}{i_B} = \beta \tag{5.5}$$

or

$$i_B = I_{BO} e^{v_{BE}/V_T} = \frac{i_C}{\beta} = \frac{I_S}{\beta} e^{v_{BE}/V_T} \tag{5.6}$$

The parameter β is the **common-emitter current gain**[4] and is a key parameter of the bipolar transistor. In this idealized situation, β is considered to be a constant for any given transistor. The value of β is usually in the range of $50 < \beta < 300$, but it can be smaller or larger for special devices.

The value of β is highly dependent upon transistor fabrication techniques and process tolerances. Therefore, the value of β varies between transistor types and also between transistors of a given type, such as the discrete 2N2222. In any example or problem, we generally assume that β is a constant. However, it is important to realize that β can and does vary.

Figure 5.6 shows an npn bipolar transistor in a circuit. Because the emitter is the common connection, this circuit is referred to as a **common-emitter configuration.** When the transistor is biased in the forward-active mode, the B–E junction is forward

End of AEC Lecture 1