Unit-II BIPOLAR JUNCTION TRANSISTOR

INTRODUCTION

- The transistor was developed by Dr.Shockley along with Bell Laboratories team in 1951
- The transistor is a main building block of all modern electronic systems
- It is a three terminal device whose output current, voltage and power are controlled by its input current
- In communication systems it is the primary component in the amplifier
- An amplifier is a circuit that is used to increase the strength of an ac signal
- Basically there are two types of transistors
    - Bipolar junction transistor
    - Field effect transistor
- The important property of the transistor is that it can raise the strength of a weak signal
- This property is called amplification
- Transistors are used in digital computers, satellites, mobile phones and other communication systems, control systems etc.,
- A transistor consists of two P-N junction
- The junction are formed by sand witching either p-type or n-type semiconductor layers between a pair of opposite types which is shown below

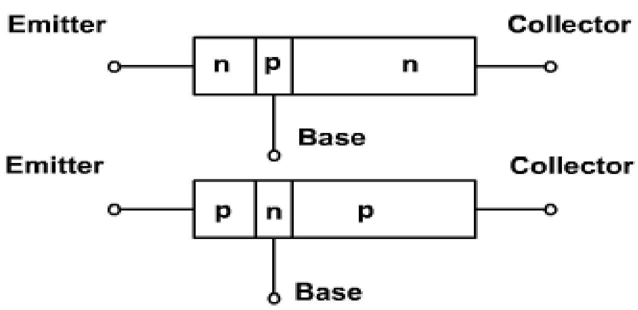


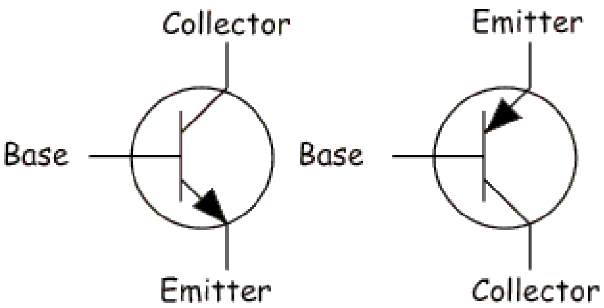
Fig: transistor

TRANSISTOR CONSTRUCTION

- A transistor has three regions known as emitter, base and collector

- **Emitter:** it is aregion situated in one side of a transistor, which supplies charge carriers (ie., electrons and holes) to the other two regions
- Emitter is heavily doped region
- **Base:** It is the middle region that forms two P-N junction in the transistor
- The base of the transistor is thin as compared to the emitter and is alightly doped region
- **Collector:** It is aregion situated in the other side of a transistor (ie., side opposite to the emitter) which collects the charge carrirs
- The collector of the transistor is always larger than the emitter and base of a transistor
- The doping level of the collector is intermediate between the heavy doping of emitter and the light doping of the base

TRANSISTOR SYMBOLS



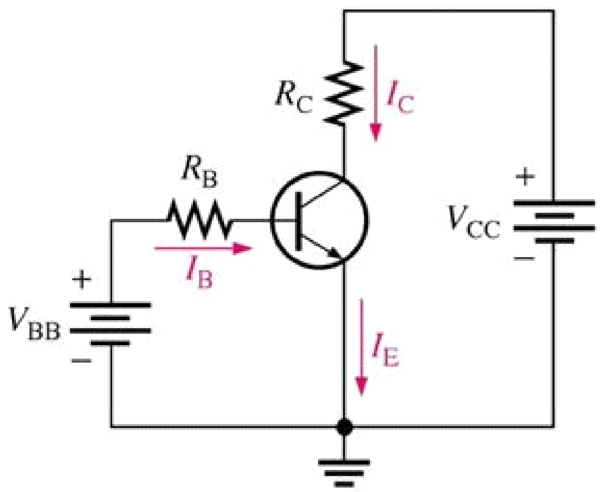
- The transistor symbol carries an arrow head in the emitter pointing from the P- region towards the N- region
- The arrow head indicates the direction of a conventional current flow in a transistor
- The direction of arrow heads at the emitter in NPN and PNP transistor is opposite to each other
- The PNP transistor is a complement of the NPN transistor
- In NPN transistor the majority carriers are free electrons, while in PNP

transistor these are the holes

UNBIASED TRANSISTORS

- A transistor with three terminals (Emitter, Base, Collector) left open is called an unbiased transistor or an open – circuited transistor
- The diffusion of free electrons across the junction produces two depletion layers
- The barrier potential of three layers is approximately 0.7v for silicon transistor and 0.3v for germanium transistor
- Since the regions have different doping levels therefore the layers do not have the same width
- The emitter base depletion layer penetrates slightly into the emitter as it is a heavily doped region where as it penetrates deeply into the base as it is a lightly doped region
- Similarly the collector- base depletion layer penetrates more into the base region and less into the collector region
- The emitter- base depletion layer width is smaller than the that of collector base depletion layer
- The unbiased transistor is never used in actual practice. Because of this we went for transistor biasing

OPERATION OF NPN TRANSISTOR

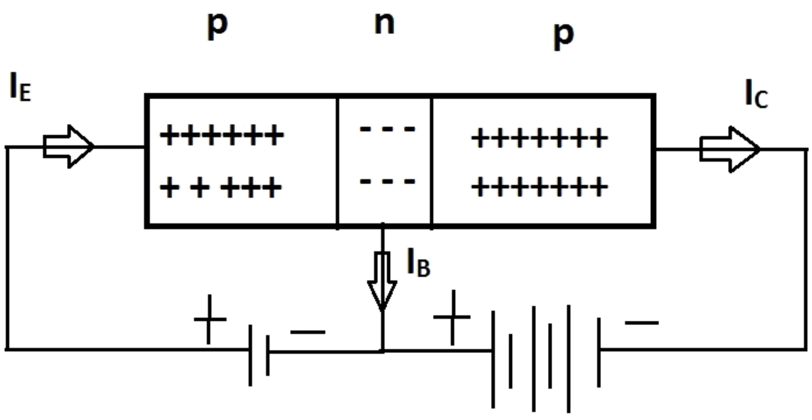


(a) *npn*

- The NPN transistor is biased in forward active mode ie., emitter – base of transistor is forward biased and collector base junction is reverse biased

- The emitter – base junction is forward biased only if V is greater than barrier potential which is 0.7v for silicon and 0.3v for germanium transistor
- The forward bias on the emitter- base junction causes the free electrons in the N –type emitter to flow towards the base region. This constitutes the emitter current . Direction of conventional current is opposite to the flow of electrons
- Electrons after reaching the base region tend to combine with the holes
- If these free electron combine with holes in the base, they constitute base current ().
- Most of the free electrons do not combine with the holes in the base
- This is because of the fact that the base and the width is made extremely small and electrons do not get sufficient holes for recombination
- Thus most of the electrons will diffuse to the collector region and constitutes collector current . This collector current is also called injected current, because of this current is produced due to electrons injected from the emitter region
- There is another component of collector current due to the thermal generated carriers.
- This is called as reverse saturation current and is quite small

OPERATION OF PNP TRANSISTOR



p-n-p transistor

- Operation of a PNP transistor is similar to npn transistor
- The current within the PNP transistor is due to the movement of holes where as, in an NPN transistor it is due to the movement of free electrons
- In PNP transistor, its emitter – base junction is forward biased and collector base junction is reverse biased.
- The forward bias on the emitter – base junction causes the holes in the emitter region to flow towards the base region
- This constitutes the emitter current ( ).
- The holes after reaching the base region, combine with the electrons in the base and constitutes base current.
- Most of the holes do not combine with the electrons in the base region
- This is due to the fact that base width is made extremely small, and holes does not get sufficient electrons for recombination.
- Thus most of the holes diffuse to the collector region and constitutes collector region
- This current is called injected current, because it is produced due to the holes injected from the emitter region
- There is small component of collector current due to the thermally generated carriers
- This is called reverse saturation current.

TRANSISTOR CURRENTS

- We know that direction of conventional current is always opposite to the electron current in any electronic device.
- However, the direction of a conventional current is same as that of a hole current in a PNP transistor
- Emitter current
- Base current
- Collector current

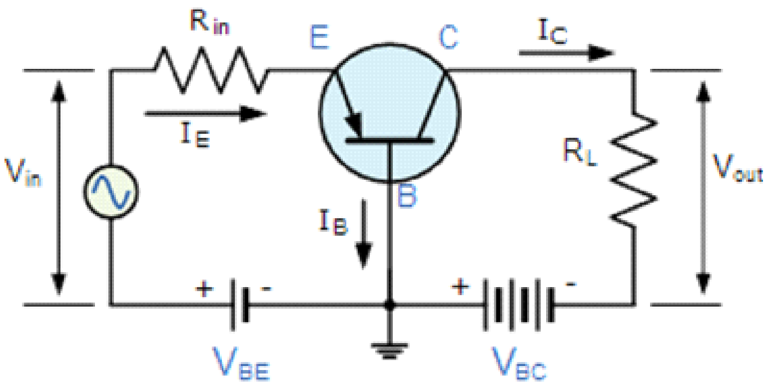
- Since the base current is very small

TRANSISTOR CONFIGURATIONS

- A transistor is a three terminal device, but we require four terminals (two for input and two for output) for connecting it in a circuit.
- Hence one of the terminal is made common to the input and output circuits.
- The common terminal is grounded
- There are three types of configuration for the operation of a transistor

  - **Common base configuration**
    - This is also called grounded base configuration
    - In this configuration emitter is the input terminal, collector is the output terminal and base is the common terminal
  - **Common emitter configuration(CE)**
    - This is also called grounded emitter configuration
    - In this configuration base is the input terminal, collector is the output terminal and emitter is the common terminal
  - **Common collector configuration(CC)**
    - This is also called grounded collector configuration
    - In this configuration, base is the input terminal, emitter is the output terminal and collector is the common terminal.

- **Common base configuration (CB)**



- The input is connected between emitter and base and output is connected across collector and base
- The emitter – base junction is forward biased and collector – base junction is reverse biased.
- The emitter current, flows in the input circuit and the collector current flows in the output circuit.
- The ratio of the collector current to the emitter current is called current amplification factor.
- If there is no input ac signal, then the ratio of collector current to emitter current is called dc alpha
- The ratio of change in the collector current to change in the emitter current is known as ac alpha
- = Common-emitter current gain = Common-base current gain

$$= \frac{I_C}{I_B} \qquad = \frac{I_C}{I_E}$$

- The input characteristics look like the characteristics of a forward-biased diode. Note that V_{BE} varies only slightly, so we often ignore these characteristics and assume:

- Common approximation: $V_{BE} = V_o = 0.65$ to $0.7V$

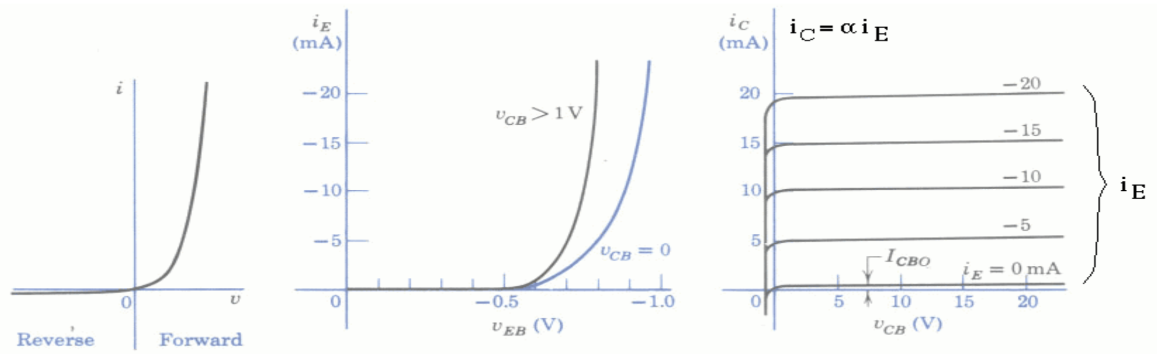
- The higher the value of better the transistor. It can be increased by making the base thin and lightly doped

- The collector current consists of two parts transistor action. Ie., component dependind upon the emitter current , which is produced by majority carriers

- The leakage current due to the movement of the minority carriers across base collector junction

CHARACTERISTICS OF CB CONFIGURATION

- The performance of transistors determined from their characteristic curves that relate different d.c currents and voltages of a transistor
- Such curves are known as static characteristics curves
- There are two important characteristics of a transistor
  - Input characteristics
  - Output characteristics



(a) Diode characteristic (b) Emitter characteristics (c) Collector characteristics

INPUT CHARACTERISTICS

- The curve drawn between emitter current and emitter – base voltage for a given value of collector – base voltage is known as input characteristics

Base width modulation (or) Early effect

- In a transistor, since the emitter – base junction is forward biased there is no effect on the width of the depletion region
- However, since collector – base junction is reverse biased as the reverse bias voltage across the collector – base junction

increase the width of the depletion region also increases

  - Since the base is lightly doped the depletion region penetrates deeper into the base region
  - This reduces the effective width of the base region
  - This variation or modulation of the effective base width by the collector voltage is known as base width modulation or early effect
  - The decrease in base width by the collector voltage has the following three effects

- It reduces the chances of recombination of electrons with the holes in the base region
  Hence current gain increases with increase in collector – base voltage

- The concentration gradient of minority carriers within the base increases. This increases the emitter current
- For extremely collector voltage , the effective base width may be reduced to zero, resulting in voltage breakdown of a transistor
- This phenomenon is known as punch through
  - The emitter current increases rapidly with small increase in which means low input resistance
  - Because input resistance of a transistor is the reciprocal of the slope of the input characteristics

Output characteristics

- The curve drawn between collector current and collector – base voltage, for a given value of emitter current is known as output characteristics

ACTIVE REGION

- There is a very small increase in with increase in
- This is because the increase in expands the collector – base depletion region and shorten the distance between two depletion region
- Hence due to the early effect does not increase very much with increase in
- Although, the collector current is independent of if is increased beyond a certain value, eventually increases rapidly because of avalanche effects
- This condition is called punch – through or reach – through
- When it occurs large current can flow destroying the device

CUT – OFF REGION

- small collector current flows even when emitter current
- this is the collector leakage current

SATURATION REGION

- collector current flows even when the external applied voltage is reduced to zero. There is a low barrier potential existing at the collector – base junction and this assists in the flow of collector current

(II) COMMON – EMITTER CONFIGURATION

- The input is connected between base and emitter, while output is connected between collector and emitter
- Emitter us common to both input and output circuits.
- The bias voltage applied are Vce and Vbe.
- The emitter-base junction is forward biased and collector-emitter junction is reverse biased.
- The base current Ib flows in the input circuit and collector current Ic flows sin the output circuit.
- CE is commonly used because its current, Voltage, Power gain are quite high nd output to input impedance ratio is moderate
- The rate of change in collector current to change in base current is called amplification factor B.
- The current gain in the common-emitter circuit is called BETA (b). Beta is the relationship of collector current (output current) to base current (input current).
- Two voltages are applied respectively to the base B and collector C with respect to the common emitter E.
- Same as the CB configuration, here in the CE configuration, the BE junction is forward biased while the CB junction is reverse biased. The voltages of CB and CE configurations are related by:

$$V_{CE} = V_{CB} + V_{BE}, \quad \text{or} \quad V_{CB} = V_{CE} - V_{BE}$$

- The base current is treated as the input current, and the collector current is treated as the output current:

$$I_C = \alpha I_E + I_{CB0} = \alpha(I_C + I_B) + I_{CB0} \approx \alpha(I_C + I_B)$$

- Solving this equation for collector current, we get the relationship between the output collector current and the input base current:

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CB0} = \beta I_B + (\beta+1) I_{CB0} = \beta I_B + I_{ce0} \approx \beta I_B$$

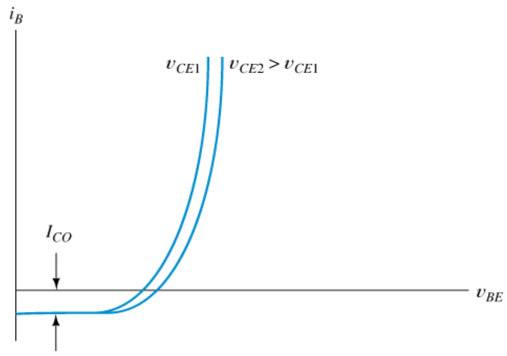
- Here we have also defined the CE *current gain* or *current transfer ratio*

$$\beta = \frac{\alpha}{1-\alpha} \approx \frac{I_C}{I_B}$$

- which is approximately the ratio of the output current and the input current . The two parameters α and β are related by:

$$\beta = \frac{\alpha}{1-\alpha}, \qquad \alpha = \frac{\beta}{1+\beta}, \qquad 1+\beta = \frac{1}{1-\alpha}, \qquad 1-\alpha = \frac{1}{1+\beta}$$

Characteristics of CE configuration



(a) Input characteristics

i) Input Characteristics

- Same as in the case of common-base configuration, the junction of the common-emitter configuration can also be considered as a forward biased diode, the current-voltage characteristics is similar to that of a diode:

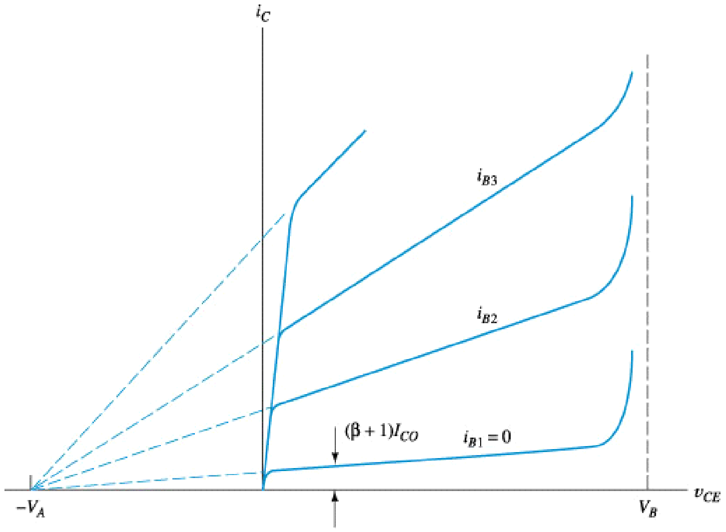
$$I_B = f(V_{BE}, V_{CE}) \approx f(V_{BE}) = I_0(e^{V_{BE}/V_T} - 1)$$

- The Curve drawn between base current and base-emitter voltage for a given value of collector-emitter voltage is known as input characteristics.
- The input characteristics of CE transistors are similar to those of a forward biased diode because the base-emitter region of the transistor is forward-biased.
- Input Resistance is larger in CE configuration than in CB configuration.

This is because the I/P current increases less rapidly with increase in Vbe.

- An increment in value of Vce causes the input current to be lower for a given level of Vbe.
- This is explained on the basis of early effect.
- As a result of early effect, more charge carriers from the emitter flows across the collector-base junction and flow out through the based lead.

ii) Output Characteristics



(b) Output characteristics

$$I_C = f(I_B, V_{CE}) \approx f(I_B) = \beta I_B \qquad \text{(in linear region)}$$

- It is the curve drawn between collector current Ic and collector-emitter voltage Vce for a given value of base current Ib.

- The collector current Ic varies with Vce and becomes a constant.
- Output characteristics in CE configuration has some slope while CB configuration has almost horizontal characteristics.
- This indicates that output resistance incase of CE configuration is less than that in CB configuration.

Active Region

- For small values of base current, the effect of collector voltage Vc over Ic is small but for large values of Ib, this effect increases.
- The shape of the characteristic is same as CB configuration
- The difference that Ic is larger than input current

- Thus, the current gain is greater than unity.

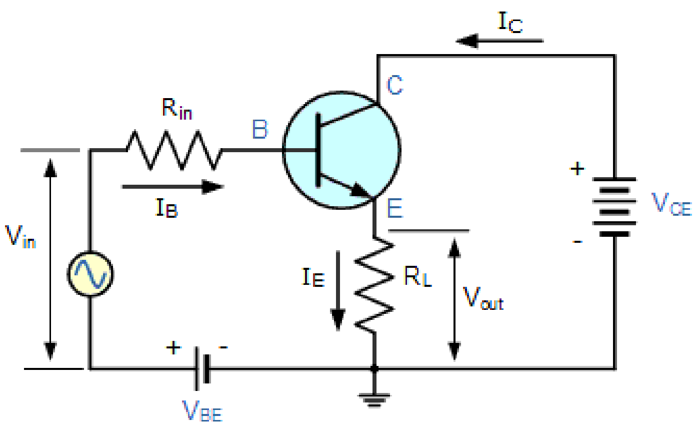
<u>Saturation Region</u>

- With low values of Vce, the transistor is said to be operated in saturation region and in this region, base current Ib does not correspond to Ic,

<u>Cut off Region</u>

- A small amount of collector current Ic flows even when Ib=0, This is called emitter leakage current.

iii) Common Collector Configuration:



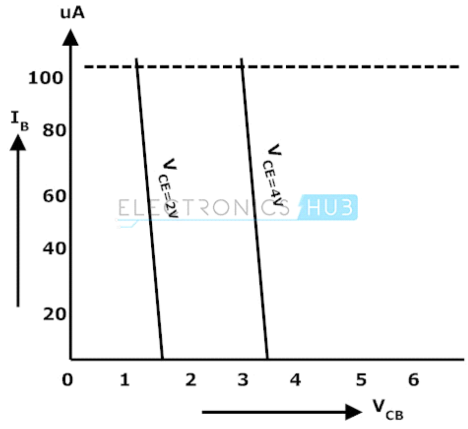
- Input is applied between base and collector while output is applied between emitter and collector.
- The collector forms the terminal common to both the input and output.
  GAIN is a term used to describe the amplification capabilities of an amplifier. It is basically a ratio of output to input. The current gain for the three transistor configurations (CB, CE, and CC) are ALPHA(a), BETA (b), and GAMMA (g), respectively.

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

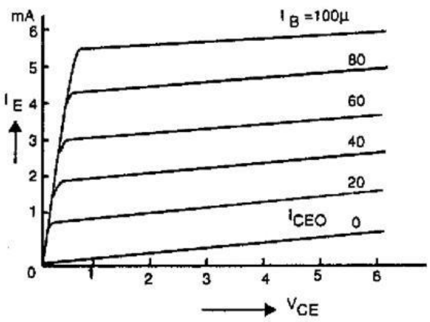
$$\gamma = \frac{\Delta I_E}{\Delta I_B}$$

i) Input Characteristics



- To determine the i/p characteristics Vce is kept at a suitable fixed value.
- The base collector voltage Vbc is increased in equal steps and the corresponding increase in Ib is noted.
- This is repeated for different fixed values of Vce.

ii) Output Characteristics



Current components in a Transistor

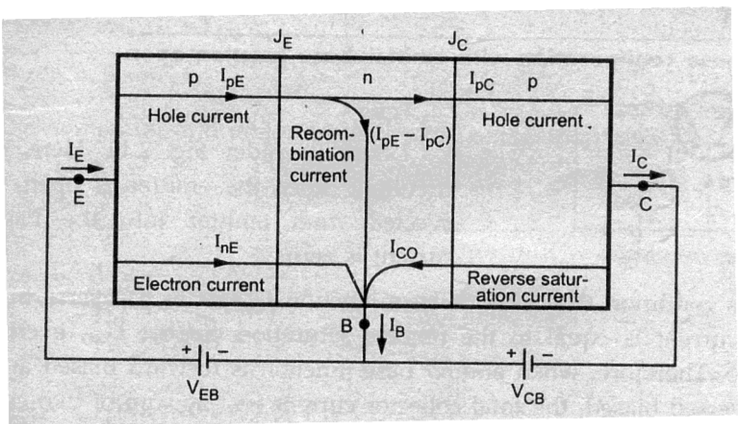
- As a result of biasing the active region current flows to drift and diffusion in various parts of transition.
- Due to forward bias across input junction, there across three phenomena.
  - a) The generation and Recombination of electrons and holes

    Let,

    n -> Electron concentration
    P -> Hole concentration
    Tn -> Life time of electron
    Tp -> Life time of Holes
    no -> Equilibrium density of electrons
    po -> Equilibrium density of Holes

Transistor Current Components

- In the figure we show the various components which flow across the forward-based emitter junction and the reverse-biased collector junction.
- The emitter current I_E consists of hole current I_{pE} (holes crossing from the emitter into base) and electron current I_{nE} (electron crossing from base into the emitter).
- The ratio of hole to electron currents, I_{pE} / I_{nE}, crossing the emitter junction is proportional to the ratio of the conductivity of the p material to that of the n material.
- In the commercial transistor the doping of the emitter is made much larger than the doping of the base.
- This future ensures (in a p-n-p transistor) that the emitter current consists almost entirely of the holes.
- Such a situation is desired since the current which results from electrons crossing the emitter junction from base to emitter does not contribute carriers which can reach the collector.
- Not all the holes crossing the emitter junction J_E reach the collector junction J_c because some of them combine with the electrons in the n – type base.
- If I_{pc} is the hole current at J_c, there must be a bulk recombination current I_{pE} - I_{pC} leaving the base (actually, electrons enter the base region through the base lead to supply those charges which have been lost by recombination with the holes injected into the base across $J_{E)}$.



- If the emitter were open-circuited so that I_E = 0, then I_{pC} would be zero.
- Under these circumstances, the base and collector would act as a

reverse-biased diode, and the collector current I_c would equal the reverse saturation current I_{CO}. If $I_E \neq 0$, then

- From figure, we note that

$$I_c = I_{co} - I_{pC}$$

- For a p-n-p transistor, I_{co} consists of holes moving across J_c from left to right (base to collector) and electrons crossing J_c in the opposite direction.
- Since the assumed reference direction for I_{co} in figure is from right to left, then for a p-n-p transistor, I_{co} is negative. For an n-p-n transistor, I_{co} is positive.

Emitter Efficiency:- (γ)

- The emitter, or injection, efficiency γ is defined as

$$\gamma \equiv \frac{\text{Current of injected carriers at } J_E}{\text{Total emitter current}}$$

Transport Factor:- (β^*)

- The transport factor β^* is defined as

$$\beta^* \equiv \frac{\text{injected carrier current reaching } J_c}{\text{injected carrier current at } J_E}$$

In the case of a p-n-p transistor we have

$$\beta^* = I_{pC} / I_{pE}$$

Large – signal current Gain:- (α)

- We define the ratio of the negative of the collector-current increment to the emitter-current change from zero (cutoff) to I_E as the large-signal currant gain of a common-base transistor, or

$$\alpha = - I_c – I_{co} / I_E$$

- since I_c and I_E have opposite signs, then α, as defined, is always positive Typical numerical values of α lie in the range of 0.90 to 0.995.

$\alpha = I_{pC} / I_E$

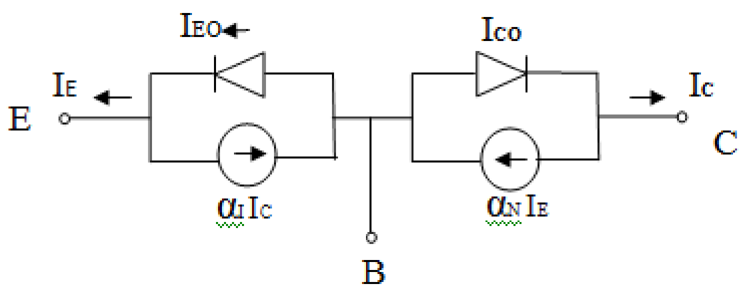
$= I_{pC} / I_{pE} \,.\, I_{pE} / I_E$

$\alpha = \beta^* \gamma$

$I_C = - \alpha I_E + I_{co}$

$I_c = - \alpha I_E + I_{co} (1- e^{Vc} / {}^{Vr})$

Description of Ebers-moll model



- The current equations derived above is interpreted in terms of a model shown in the figure.
- This model of transistor is known as Eber Moll model of transistor. From the diagram applying Kirchhoff's current law at the collector node, we get

$$I_C= -\alpha_N*I_E + I_{CO} *(1 – e^{V}{}_{CB}/V_t)$$

- Where α_N is the current gain of common base transistor mentioned above in normal mode of operation,V_{BC} is the base to collector voltage, I_{co} is the reverse saturation current of base collector junction.
- Similarly at emitter and base node by applying Kirchhoff's current law

$$I_E= -\alpha_I*I_C+I_{EO}(1 – e^{V}{}_{BE}/V_t),\ I_E+I_B+I_C = 0$$

- Where α_I is the inverted current gain of common base transistor with roles of collector and emitter interchanged, V_{BE} is the base to Emitter voltage, I_{co} is the reverse saturation current of base Emitter junction. αI and αI are related through the reverse saturation currents of the diode as

$$\alpha_I *I_{CO} = \alpha_N *I_{EO}$$

- The above equations are derived based on the assumption of low level minority carrier injection (the hole concentration injected into the base is very much less compared to the intrinsic electron concentration in base), in such a case emitter or collector current is mainly dominated by diffusion currents, drift current is negligible compared to drift currents.
- The Base to emitter voltage and base to collector voltage in terms of currents can be derived as follows

$$I_E= -\alpha_I*I_C+I_{EO}(1 – e^{V}{}_{BE}/V_t) ,\ \ I_C= -\alpha_N*I_E + I_{CO} *(1 – e^{V}{}_{CB}/V_t)$$

$$I_E+\alpha_I*I_C=I_{EO}(1 – e^{V}{}_{BE}/V_t) ,\ \ I_C+\alpha_N*I_E = I_{CO} *(1 – e^{V}{}_{CB}/V_t)$$

$$(I_E+\alpha_I*I_C)/I_{EO} = (1 – e^{V}{}_{BE}/V_t) ,\ \ (I_C+\alpha_N*I_E)/I_{CO} = (1 – e^{V}{}_{CB}/V_t)$$

$$e^{V}{}_{BE}/V_t = 1 – ((I_E+\alpha_I*I_C)/I_{EO}) ,\ \ e^{V}{}_{CB}/V_t = 1 -((I_C+\alpha_N*I_E)/I_{CO})$$

- Applying anti log on both sides we get

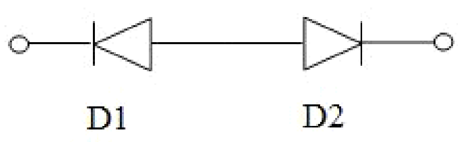
$$V_{BE}= V_t *\ln(1 – ((I_E+\alpha_I*I_C)/I_{EO})) ,\ \ V_{CB} = V_t *\ln(1 -((I_C+\alpha_N*I_E)/I_{CO}))$$

- For example in cutoff region I_E=0 amps and $I_C = I_{CO}$ then the base to emitter voltage is

$$V_{BE} = V_t*\ln(1-(\alpha_I*I_{CO})/I_{EO}))$$

$$V_{BE,\ cut\ off} = V_t*\ln(1-\alpha_N)$$

- Consider two diodes connected back to back in the configuration shown below



- It is obvious that if one junction is forward biased then other junction will be reverse biased
- consider for example diode D1 is forward biased and diode D2 is reverse biased much like a NPN transistor in active region according to the junction voltages only current order of reverse saturation current flows through the series junctions.
- This can be explained as follows: the reverse biased diode D2 at most will

allow only currents order of reverse saturation currents.

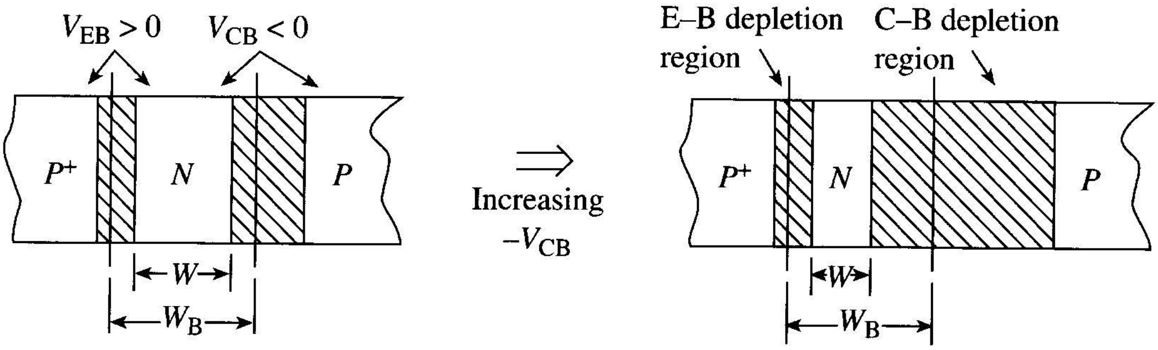
- Since D1 and D2 are in series same current should flow through both of them then only currents order of reverse saturation currents flow through their junctions.
- It is obvious that this is not the case with the transistor in active region (because of the internal design of transistor).
- The forward current entering the base is sweeped across into collector by the electric field generated by the reverse bias voltage applied across the base collector junction.

Base width modulation:-

As the applied base-collector voltage (VBC) varies, the base-collector depletion region varies in size. This variation causes the gain of the device to change, since the gain is related to the width of the effective base region. This effect is often called the "Early Effect"

An NPN bipolar transistor can be considered as two diodes connected anode to anode. In normal operation, the emitter-base junction is forward biased and the base-collector junction is reverse biased. In an npn-type transistor for example, electrons from the emitter wander (or "diffuse") into the base

- Base width has been assumed to be constant
- When bias voltages change, depletion widths change and the effective base width will be a function of the bias voltages
- Most of the effect comes from the C-B junction since the bias on the collector is usually larger than that on the E-B junction
- Base width gets smaller as applied voltages get larger



Early Effect: Common Base Input Characteristic

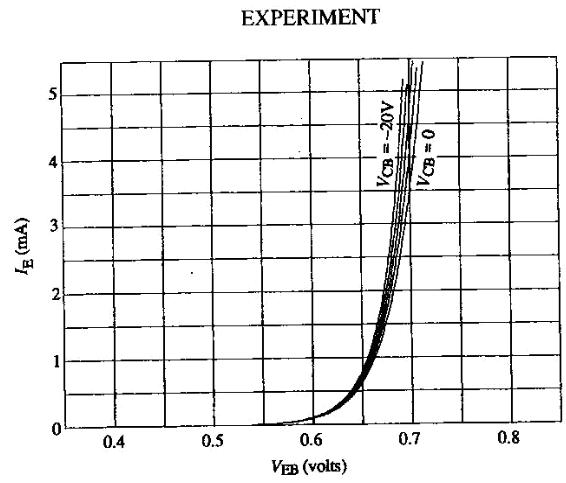
$$I_E = I_{F0}(e^{qV_{EB}/kT} - 1) - \alpha_R I_{R0}(e^{qV_{CB}/kT} - 1)$$ Ebers-Moll

Assuming $-V_{CB}$ > few kT/q and W/L_B << 1

$$I_{F0} \equiv qA\left(\frac{D_E}{L_E}n_{E0} + \frac{D_B}{L_B}p_{B0}\frac{\cosh\left(\frac{W}{L_B}\right)}{\sinh\left(\frac{W}{L_B}\right)}\right) \cong qA\frac{D_B}{W}p_{B0}$$

$$I_E \cong I_{F0}e^{qV_{EB}/kT} \cong qA\frac{D_B}{W}p_{B0}e^{qV_{EB}/kT}$$

- Exponential prefactor will increase as V_{CB} increases (W decreases)



(b)

Early Effect: Common Emitter Output Characteristic

$$I_C = \beta_{dc} I_B + I_{CE0} \qquad \beta_{dc} = \frac{1}{\frac{D_E}{D_B}\frac{W}{L_E}\frac{N_B}{N_E} + \frac{1}{2}\left(\frac{W}{L_B}\right)^2}$$

$$W_{eff} = W - W_{EB}\Big|_{Base} - W_{CB}\Big|_{Base} \cong W - W_{CB}\Big|_{Base}$$

$$W_{CB} = \left[\frac{2K_S\varepsilon_0}{q}\frac{(N_A+N_D)}{N_D N_A}(V_{biCB} - V)\right]^{1/2}$$

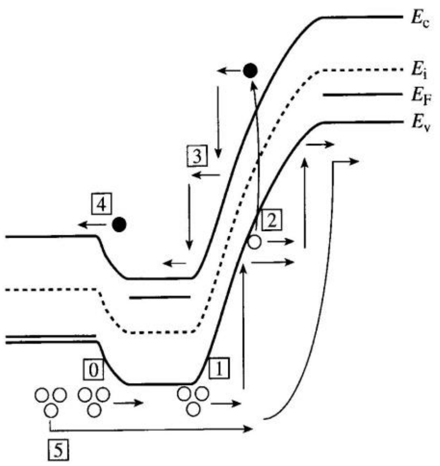
$$W_{CB}\Big|_{Base} = x_n = W_{CB}\Big|_{Base}\left(\frac{N_C}{N_C+N_B}\right)$$

- If $N_C << N_B$ most of the depletion is in the collector and modulation of base width is minimized – reduced Early Effect

Avalanche Multiplication Breakdown

- **Common Base**: Similar to single p-n junction V_{CB0} ? V_{BD}(B-C)
- **Common Emitter**: more complicated
  1. holes injected by FB emitter to base
  2. holes generate e-p pairs in C-B depletion
  3. e^- drift back into base
  4. e^- injected to emitter

5. more holes into base…..



Transistor breakdown

Transistor breakdown mechanism:

Avalanche breakdown: avalanche multiplication mechanism takes place at **CBJ or EBJ**

Base punch-through effect: the base width reduces to zero at high CBJ reverse bias

In CB configuration, BV_{CBO} is defined at $i_E = 0$.

The breakdown voltage is smaller than BV_{CBO} for $i_E > 0$.

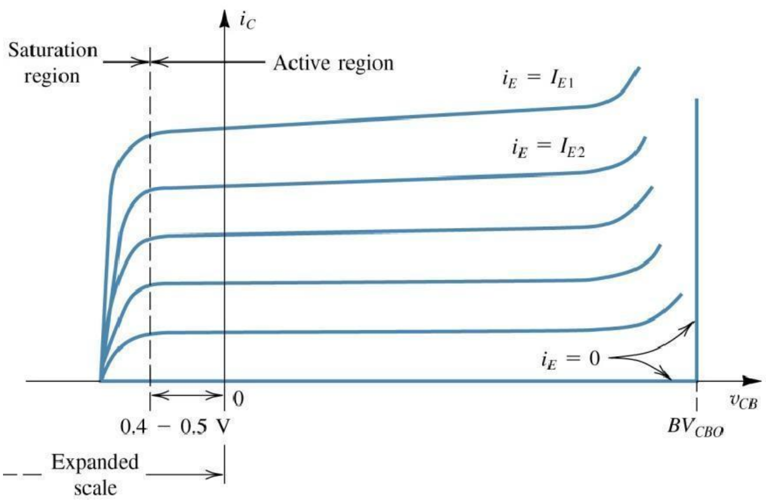
In CE configuration, BV_{CEO} is defined at $i_B = 0$.

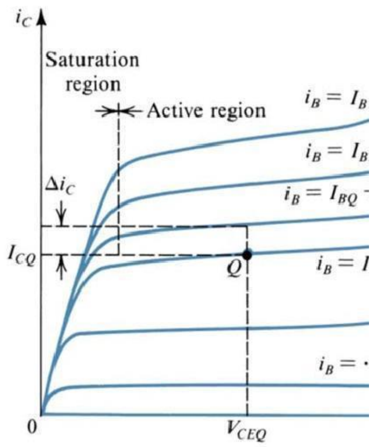
The breakdown voltage is smaller than BV_{CEO} for $i_B > 0$.

Typically, BV_{CEO} is about half of BV_{CBO} .

Breakdown of the BCJ is not destructive as long as the power dissipation is kept within safe limits

Breakdown of the EBJ is destructive because it will cause permanent degradation of Beta





Transistor Biasing

The basic function of transistor is amplification. The process of raising the strength of weak signal without any change in its general shape is referred as faithful amplification. For faithful amplification it is essential that:-

1. Emitter-Base junction is forward biased
2. Collector- Base junction is reversed biased
3. Proper zero signal collector current

The proper flow of zero signal collector current and the maintenance of proper collector emitter voltage during the passage of signal is called transistor biasing.

WHY BIASING?

If the transistor is not biased properly, it would work inefficiently and produce distortion in output signal.

HOW A TRANSISTOR CAN BE BIASED?

A transistor is biased either with the help of battery or associating a circuit with the transistor. The later method is more efficient and is frequently used. The circuit used for transistor biasing is called the biasing circuit.

BIAS STABILITY

- Through proper biasing, a desired quiescent operating point of the transistor amplifier in the active region (linear region) of the characteristics is obtained. It is desired that once selected the operating point should remain stable. The maintenance of operating point stable is called Stabilisation.
- The selection of a proper quiescent point generally depends on the following factors:

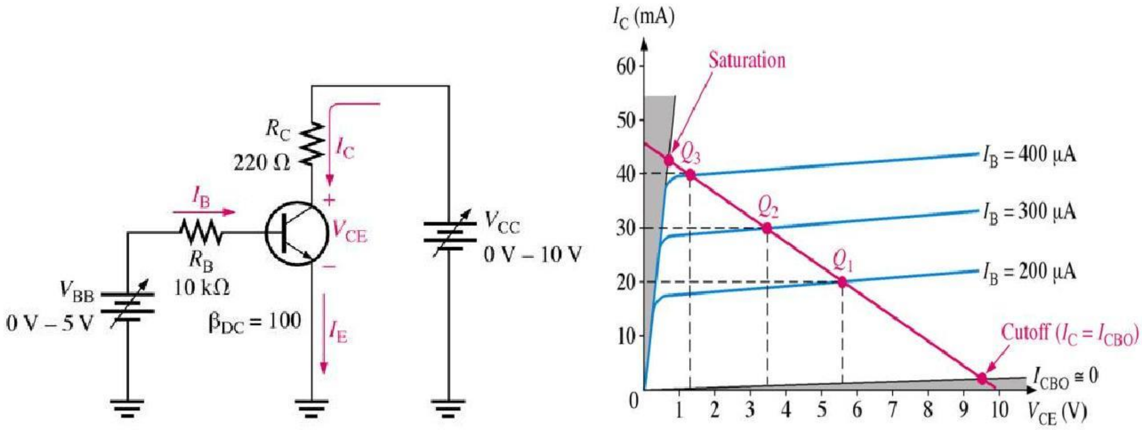
  (a) The amplitude of the signal to be handled by the amplifier and distortion level in signal

  (b) The load to which the amplifier is to work for a corresponding supply voltage

  (c) The operating point of a transistor amplifier shifts mainly with changes in temperature, since the transistor parameters — β, I_{CO} *and* V_{BE} *(where the symbols carry their usual meaning)—are functions of* temperature.

DC Operating Point

- For a transistor circuit to amplify it must be properly biased with dc voltages. The dc operating point between saturation and cutoff is called the **Q-point.** The goal is to set the Q-point such that that it does not go into saturation or cutoff when an a ac signal is applied.



(a) DC biased circuit

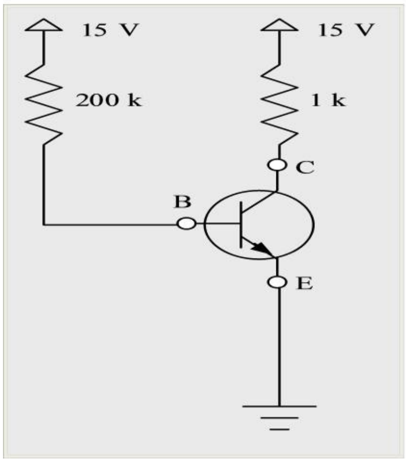
Requirements of biasing network

- Ensuring proper zero signal collector current.
- Ensuring VcE not falling below 0.5V for Ge transistor and 1V for Silicon transistor at any instant.
- Ensuring Stabilization of operating point. (zero signal IC and VcE)

<u>Various Biasing Circuits</u>

- **Fixed Bias Circuit**
- **Fixed Bias with Emitter Resistor**
- **Collector to Base Bias Circuit**
- **Potential Divider Bias Circuit**

<u>The Fixed Bias Circuit</u>



The Thermal Stability Factor : S_{Ico}

$$S_{Ico} = \frac{\partial I_c}{\partial I_{co}}$$

General Equation of S_{Ico} Comes out to be

$$S_{Ico} = \frac{1 + \beta}{1 - \beta\, (\partial I_b / \partial I_C)}$$

Applying KVL through Base Circuit we can write, $I_b R_b + V_{be} = V_{cc}$

Diff w. r. t. I_C, we get $(\partial I_b / \partial I_c) = 0$

$S_{Ico} = (1+\beta)$ is very large

Indicating high un-stability

Merits:

- It is simple to shift the operating point anywhere in the active region by merely changing the base resistor (RB).
- A very small number of components are required.

Demerits:

- The collector current does not remain constant with variation in temperature or power supply voltage. Therefore the operating point is unstable.
- When the transistor is replaced with another one, considerable change in the value of β can be expected. Due to this change the operating point will shift.
- For small-signal transistors (e.g., not power transistors) with relatively high values of β (i.e., between 100 and 200), this configuration will be prone to thermal runaway. In particular, the stability factor, which is a measure of the change in collector current with changes in reverse saturation current, is approximately β+1. To ensure absolute stability of the amplifier, a stability factor of less than 25 is preferred, and so small-signal transistors have large stability factors.

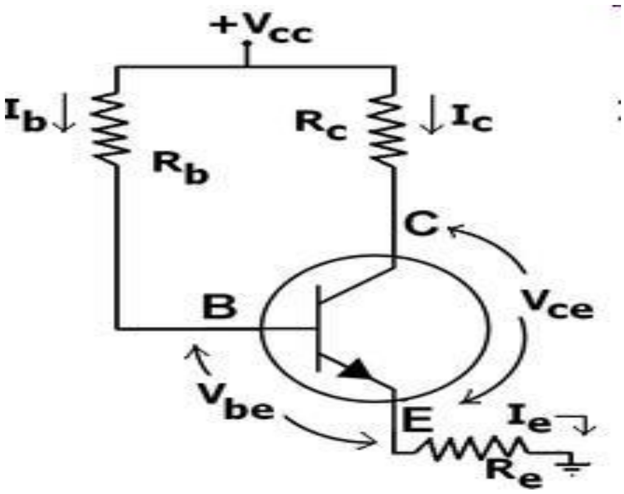
<u>Usage</u>:

- Due to the above inherent drawbacks, fixed bias is rarely used in linear circuits (i.e., those circuits which use the transistor as a current source). Instead, it is often used in circuits where transistor is used as a switch.

  However, one application of fixed bias is to achieve crude automatic gain control in the transistor by feeding the base resistor from a DC signal derived from the AC output of a later stage

Fixed bias with emitter resistor

The fixed bias circuit is modified by attaching an external resistor to the emitter. This resistor introduces negative feedback that stabilizes the Q-point.



Merits:

- The circuit has the tendency to stabilize operating point against changes in temperature and β-value.

Demerits:

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping RE very large, or making RB very low.

? If RE is of large value, high VCC is necessary. This increases cost as well as precautions necessary while handling.

? If RB is low, a separate low voltage supply should be used in the base circuit. Using two supplies of different voltages is impractical.

- In addition to the above, RE causes ac feedback which reduces the voltage gain of the amplifier.

Usage:

The feedback also increases the input impedance of the amplifier when seen from the base, which can be advantageous. Due to the above disadvantages, this type of biasing circuit is used only with careful consideration of the trade-offs involved.

The Collector to Base Bias Circuit

This configuration employs negative feedback to prevent thermal runaway and stabilize the operating point. In this form of biasing, the base resistor RF is connected to the collector instead of connecting it to the DC source Vcc. So any thermal runaway will induce a voltage drop across the Rc resistor that will throttle the transistor's base current.

Merits:

- Circuit stabilizes the operating point against variations in temperature

and β (i.e. replacement of transistor)

Demerits:

- As β -value is fixed (and generally unknown) for a given transistor, this relation can be satisfied either by keeping Rc fairly large or making Rf very low.
- If Rc is large a high Vcc is necessary, whichb increases cost as well as precautions necessary while handling
- If Rf is low, the reverse bias of the collector–base region is small, which limits the range of collector voltage swing that leaves the transistor in active mode.
- The resistor Rf causes an AC feedback, reducing the voltage gain of the amplifier. This undesirable effect is a trade-off for greater Q-point stability.

Usage: The feedback also decreases the input impedance of the amplifier as seen from the base, which can be advantageous. Due to the gain reduction from feedback, this biasing form is used only when the trade-off for stability is warranted.

The Potential Divider Bias Circuit

This is the most commonly used arrangement for biasing as it provide good bias stability. In this arrangement the emitter resistance ‗RE' provides stabilization. The resistance ‗RE' cause a voltage drop in a direction so as to reverse bias the emitter junction. Since the emitter-base junction is to be forward biased, the base voltage is obtained from R1-R2 network. The net forward bias across the emitter base junction is equal to VB- dc voltage drop across ‗RE'. The base voltage is set by Vcc and R1 and R2. The dc bias circuit is independent of transistor current gain. In case of amplifier, to avoid the loss of ac signal, a capacitor of large capacitance is connected across RE. The capacitor offers a very small reactance to ac signal and so it passes through the condensor.

The Potential Divider Bias Circuit

To find the stability of this circuit we have to convert this circuit into its Thevenin's Equivalent circuit

Merits:

- Operating point is almost independent of β variation.
- Operating point stabilized against shift in temperature.

Demerits:

- As β-value is fixed for a given transistor, this relation can be satisfied either by keeping RE fairly large, or making R1||R2 very low.
- If RE is of large value, high VCC is necessary. This increases cost as well as precautions necessary while handling.
- If R1 || R2 is low, either R1 is low, or R2 is low, or both are low. A low R1 raises VB closer to VC, reducing the available swing in collector voltage, and limiting how large RC can be made without driving the transistor out of active mode. A low R2 lowers Vbe, reducing the allowed collector current. Lowering both resistor values draws more current from the power supply and lowers the input resistance of the amplifier as seen from the base.
- AC as well as DC feedback is caused by RE, which reduces the AC voltage gain of the amplifier. A method to avoid AC feedback while retaining DC feedback is discussed below.

Usage:

The circuit's stability and merits as above make it widely used for linear circuits.

Summary

- The Q-point is the best point for operation of a transistor for a given collector current.
- The purpose of biasing is to establish a stable operating point (Q-point).

- The linear region of a transistor is the region of operation within saturation and cutoff.
- Out of all the biasing circuits, potential divider bias circuit provides highest stability to operating point.

Bias compensation :

Need for Bias compensation

- The operating collector current Ic in a transistor amplifier can be stabilized w r t the variations in Ico, VBE and β by using any of the biasing circuits.
- In certain cases due to negative feedback loss in signal gain is intolerable which affect the operating point
- Using compensation techniques drift of the operating point can be reduced
- Stabilization techniques refer to the use of resistive biasing circuits which permit IB to vary so as to keep IC relatively constant
- Compensation techniques use temperature sensitive devices to compensate for the variation in currents
- Often, a mixture of both the stabilization and compensation techniques are used

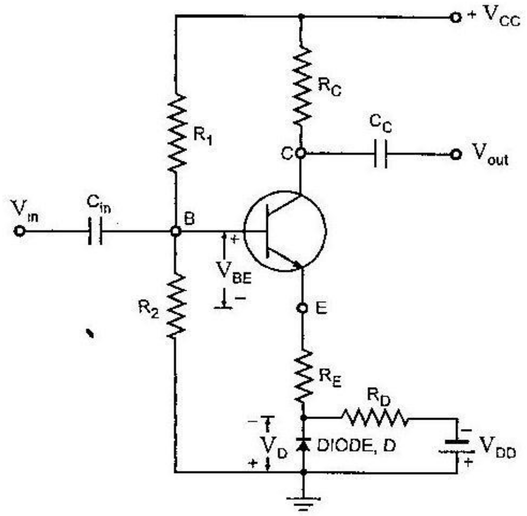
Devices used for compensation

- Diodes
- Thermistors
- Sensistors

Compensation provided by Diodes

- Compensation for variations in Base – Emitter voltage VBE (Silicon transistors)
- Compensation for variations in reverse saturation current IC0 (Germanium Transistor)

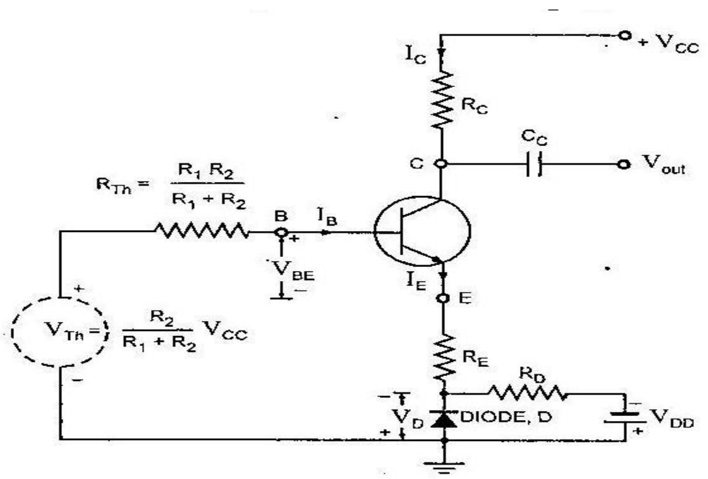
DIODE COMPENSATION FOR VARIATIONS IN BASE – EMITTER VOLTAGE



Working of the circuit

- The circuit utilizes the self Bias stabilization and diode compensation using silicon transistor.
- The diode is kept forward biased by the source VDD and resistor R D
- The diode employed is of the same material and type of the transistor to have the same temperature coefficient (-2.5mv/°c).

Circuit analysis



Applying kirchhoff's voltage law to the base portion

VTH = IB RTH + VBE + IE RE – VD

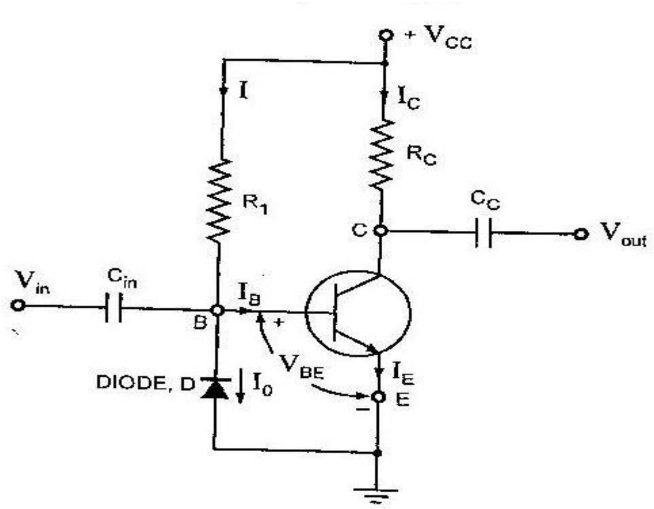
IE = IB + IC

VTH = IB RTH + VBE + (IB + IC) RE–VD

= IB (RTH + RE) + ICRE + VBE –VD

- I C = β IB + (1+ β)ICO
- VTH ={(IC – (1+ β)ICO)/ β }(RTH + RE) + ICRE +VBE –VD
- I C = β [VTH – (VBE – VD)]+ (1+ β) ICO (RTH +RE)/(RTH + (1+ β)RE)
- Variations in VBE and V D are same due to temperature variation.
- (VBE-V D) remains unchanged.
- Collector current IC becomes insensitive to variations in VBE .

DIODE COMPENSATION FOR VARIATION IN IC0



Working of the Circuit

- The figure shows the circuit using diode compensation for a Germanium transistor.
- In Germanium transistors changes in reverse saturation current IC0 with temperature variations cause change in collector stability.
- The Diode D is used in the circuit of the same material and type as the transistor
- The reverse saturation current of the transistor IC0 and of the Diode I0, will increase with the increase in temperature.
- From the circuit diagram
  I= VCC- VBE/R1 ≅ VCC/ R1

  = constant VBE is very small in comparison with the VCC.

- Since Diode is reverse biased by the VBE the current through diode is the reverse saturation current I 0 . Base current

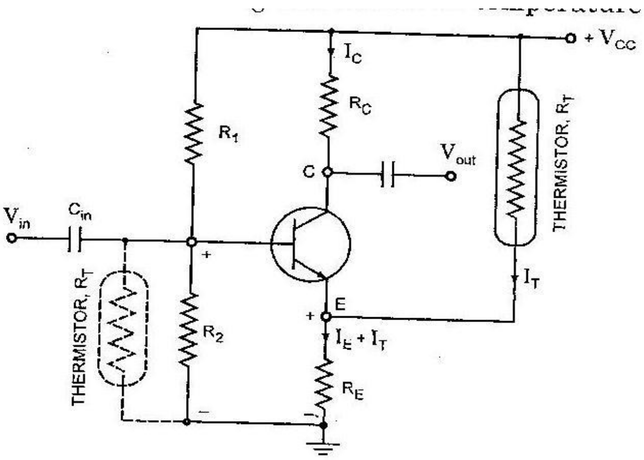
  IB = I - I 0

  IC = βIB + (1+ β)IC0

  = βI - βI0 +(1+ β) IC0

Thermistor compensation

- Thermistor is a device which is having negative temperature coefficient.

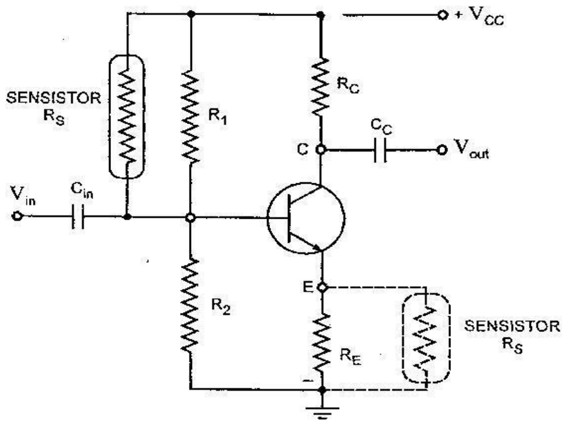
- 

Working of the circuit

- Circuit shows thermistor compensation in a self – bias CE amplifier.
- Thermistor R T has negative temperature coefficient.
- Negative temperature coefficient means resistance decreases exponentially with increase in temperature T
- Thermistor can be placed in any one of the two positions as shown in Fig
- Thermister RT is used to minimize the increase in collector current due to variations in ICO , VBE or β with temperature
- If the temperature increases
  - Thermistor resistance decreases.
  - Current flowing through RT (IT) increases.
  - Since the voltage drop across RE increases in the direction, it reverse biases the transistor Base –Emitter junction which reduces IB and keeps IC constant.
  - Thus RT compensates the increase in IC
  - Thus the temperature sensitivity of RT provides compensation to the increase in collector current IC due to rise in temperature T

- The same result is obtained if the transistor RT is placed in the base circuit across R2 instead of in collector circuit

Sensistor Compensation



Working of the Circuit

- Instead of thermistor compensation, compensation can be done by using sensistor
- Sensistor is a temperature sensitive device.
- Sensistor has positive temperature coefficient.
- The sensistor may be placed either in parallel with R1 Or in parallel with RE
- The sensistor can also be placed in place of RE rather than in parallel with RE

With the increase in temperature

- The resistance of R S increases.
- So, the resistance of parallel combination (R S || R1) increases.
- Hence voltage drop across R 2 decreases
- Decrease in VR2 decreases the net forward emitter Bias (VBE)
- Hence Collector current I C decreases
- Decrease in I C compensates the increase in collector current I C due to increase in IC0 ,β or VBE because of temperature rise

Summary

- In order to avoid loss in signal gain due to negative feedback compensation is required.

- Effects on VBE ,β of a transistor by temperature are to be compensated for better stability of the operation point of the amplifier
- This bias compensation uses a diode for the variations in VBE and IC0.
- The diode and transistors used should be of same type and material
- We have discussed the circuits using thermistors & sensistors.
- The circuits stabilize IC against variations in ICO,β & VBE due to rise in temperature

Heat sink

- A heat sink is an electronic device that incorporates either afan or a peltier device to keep a hot component such as aprocessor cool. There are two heat sink types: active and passive.
- Active heat sinks utilize power and are usually a fan type or some other peltier cooling device. If you are looking to purchase an active heat sink, it is recommended that you purchase fans with ball-bearing motors that often last much longer than sleeve bearings. Sometimes these types of heat sinks are referred to as a HSF, which is short for heat sink and fan.
- Passive heat sinks are 100% reliable, as they have no mechanical components. Passive heat sinks are made of an aluminum-finned radiator that dissipates heat through convection. For passive heat sinks to work to their full capacity, it is recommended that there is a steady air flow moving across the fins. The above picture is an example of a heat sink that is both active and passive.
- Heatspreaders are another name for heat sinks and commonly used to describe the covers on computer memory that helps dissipate the heat produced by the memory.

How Heat Sinks Work

- Though the term **heat sink** probably isn't one most people think of when they hear the word computer, it should be. Without heat sinks, modern computers couldn't run at the speeds they do. Just as you cool down with a cold bottle of Gatorade after a high impact workout, heat sinks cool down your computer's processor after it runs multiple programs at once. And without a quality heat sink, your computer processor is at risk of overheating, which could destroy your entire system, costing you hundreds, even thousands of dollars.

- But what exactly is a heat sink and how does it work? Simply put, a **heat sink** is an object that disperses heat from another object. They're most commonly used in computers, but are also found in cell phones, DVD players and even refrigerators. In computers, a heat sink is an attachment for a chip that prevents the chip from overheating and, in modern computers, it's as important as any other component.

- If you aren't very tech-savvy, think of the heat sink like a car radiator. The same way a radiator draws heat away from your car's engine, a heat sink draws heat away from your computer's central processing unit (CPU). The heat sink has a **thermal conductor** that carries heat away from the CPU into fins that provide a large surface area for the heat to dissipate throughout the rest of the computer, thus cooling both the heat sink and processor. Both a heat sink and a radiator require airflow and, therefore, both have fans built in.

- Before the 1990s, heat sinks were usually only necessary in large computers where the heat from the processor was a problem. But with the introduction of faster processors, heat sinks became essential in almost every computer because they tended to overheat without the aid of a cooling mechanism.

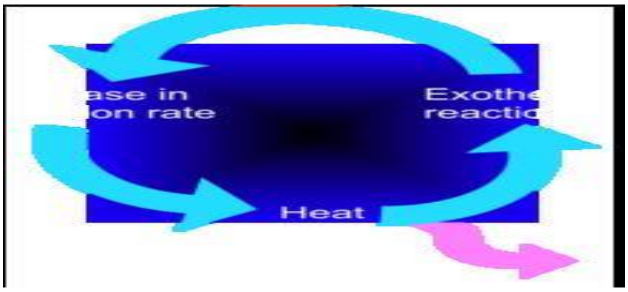
Thermal runaway

Thermal runaway refers to a situation where an increase in temperature changes the conditions in a way that causes a further increase in temperature, often leading to a destructive result. It is a kind of uncontrolled positive feedback.

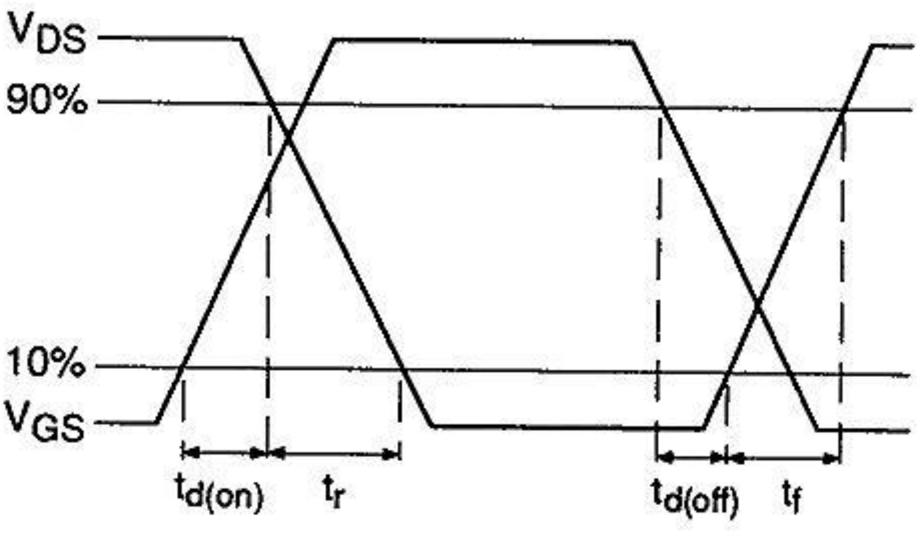
In other words, "thermal runaway" describes a process which is accelerated by increased temperature, in turn releasing energy that further increases temperature. In chemistry (and chemical engineering), this risk is associated with strongly exothermic reactions that are accelerated by temperature rise. In electrical engineering, thermal runaway is typically associated with increased current flow and power dissipation, although exothermic chemical reactions can be of concern here too. Thermal runaway can occur in civil engineering, notably when the heat released by large amounts of curing concrete is not controlled. In astrophysics, runaway nuclear fusion reactions in stars can lead to nova and several types of supernova explosions, and also occur as a less dramatic event in the normal evolution of solar mass stars, the "helium flash".

There are also concerns regarding global warming that a global average increase of 3-4 degrees Celsius above the pre-industrial baseline could lead to a further unchecked increase in surface temperatures due to positive feedback. he maximum average power in which a transistor can dissipate depends upon the construction of transistor and lie in the range of few milliwatts and 200W. The maximum power is limited by the temperature that the collector Base junction can withstand. The maximum power dissipation is usually specified for the transistor enclosure is 25 degree celsius. The junction temperature may increase either because of rise in ambient temperature or because of self heating. The problem of self heating arises due to dissipation of power at the collector junction.

The leakage current Icbo is extremely temperature dependent and increases with the rise in temperature of collector-base junction. With the increase in collector current Ic, collector power dissipation increases which raises the junction temperature that leads to further increase in collector current Ic. The process is cumulative and may lead to the eventual destruction of transistor. **This phenomenon is known as THERMAL RUNAWAY** of transistor. In practice the Thermal Runaway can be prevented by a well designed circuit called as **STABILIZATION Circuitry.**



Switching characteristics of a Power Transistor



In a power electronic circuit the power transistor is usually employed as a switch i.e. it operates in either ―cut off‖ (switch OFF) or saturation (switch ON) regions. However, the operating

characteristics of a power transistor differs significantly from an ideal controlled switch in the following respects.

- It can conduct only finite amount of current in one direction when —ON‖
- It can block only a finite voltage in one direction.
- It has a voltage drop during —ON‖ condition
- It carries a small leakage current during OFF condition
- Switching operation is not instantaneous
- It requires non zero control power for switching

Of these the exact nature and implication of the first two has been discussed in some depth in the previous section. The third and fourth non idealities give rise to power loss termed the conduction power loss. In this section the nature and implications of the last two non idealities will be discussed in detail.

Turn On characteristics of a Power Transistor

From the description of the basic operating principle of a power transistor presented in the previous sections it is clear that minority carriers must be moved across different regions of a power transistor in order to make it switch between cut off and saturation regions of operation. The time delay in the switching operation of a power transistor is due to the time taken by the minority carriers to reach appropriate density levels in different regions. The exact level of minority carrier densities (and depletion region widths) required for proper switching is determined by the collector current and biasing collector voltage during switching, both of which are determined by external circuits. The rate at which these densities are attained is determined by the base current waveform. Therefore, the switching characteristics of a power transistor is always specified in relation to the external load circuit and the base current waveform.

Turn Off Characteristics of a Power Transistor

During Turn OFF a power transistor makes transition from saturation to cut off region of operation. Just as in the case of Turn ON, substantial redistribution of minority charge carriers are involved in the Turn OFF process. Idealized waveforms of several important variables in the clamped inductive switching circuit

The —Turn OFF‖ process starts with the base drive voltage going negative to a value -VBB. The base-emitter voltage however does not change from its forward bias value of VBE(sat) immediately, due to the excess, minority carriers stored in the base region. A negative base current starts removing this excess carrier at a rate determined by the negative base drive voltage and the base drive resistance. After a time —ts‖ called the storage time of the transistor, the remaining stored charge in the base becomes insufficient to support the transistor in the hard saturation region. At this point the transistor enters quasi saturation region and the collector voltage starts rising with a small slope. After a further time interval —trv1‖ the transistor completes traversing through the quasi saturation region and enters the active region. The stored charge in the base region at this point is insufficient to support the full negative base current. VBE starts falling forward –VBB and the negative base current starts reducing. In the active region, VCE increases rapidly towards VCC and at the end of the time interval —trv2‖ exceeds it to turn on D. VCE remains clamped at

VCC, thereafter by the conducting diode D. At the end of trv2 the stored base charge can no longer support the full load current through the collector and the collector current starts falling. At the end of the current fall time tfi the collector current becomes zero and the load current freewheels through the diode D. Turn OFF process of the transistor ends at this point. The total Turn OFF time is given by Ts (OFF) = ts + trv1 + trv2 + tfi

As in the case of —Turn ON‖ considerable power loss takes place during Turn OFF due to simultaneous existence of ic and VCE in the intervals trv1, trv2 and tfi. The last trace of Fig 3.7 (a) shows the instantaneous power loss profile during these intervals. The total energy last per turn off operation is given by the area under this curve. For safe turn off the average power dissipation during trv1 + trv2 + tfi should be less than the power dissipation limit set by the FBSOA corresponding to a pulse width greater than trv1 + trv2 + tfi.

Turn OFF time intervals of a power transistor are strongly influenced by the operating conditions and the base drive design. Manufacturers usually specify these values as functions of collector current for given positive and negative base current and case temperatures. Variations of these time intervals as function of the ratio of positive to negative base currents for different collector currents are also specified.

In this section and the precious one inductive load switching have been considered. However, if the load is resistive. The freewheeling diode D will not be used. In that case the collector voltage (VCE) and collector current (ic) will fall and rise respectively together during Turn ON and rise and fall respectively together during Turn OFF. Other characteristics of the switching process will remain same. The switching Power loss in this case will also be substantially lower.

Questions for practice:

What is bipolar junction transistor? how are its terminals named?

Explain the operation of npn and pnp transistors.

What are the different configurations of BJT?

Explain the input and output characteristics of a transistor in CB configuration.

Derive the relationship between α and β.

How will you determine h-parameters from the characteristics of CE configuration.

What is the relation $I_{B,}I_E$ and I_c in CB configuration?

What is meant by Q-point?

Draw the Ebers-moll model for a PNP transistor and give the equations for emitter current and collector current.

What is need for biasing a transistor?

What is thermal runaway? how it can be avoided?

What three factors contribute to thermal instability?

Define stability factor. why would it seem more reasonable to call this an instability factor?

Draw a fixed bias circuit and derive an expression for the stability factor.

Derive an expression for stability factor of a collector-to-base bias circuit.

Mention the disadvantages of collector-to-base bias. can they be overcome?

Draw a circuit diagram of CE transistor amplifier using emitter biasing. describe qualitatively the stability action of circuit.

Why does potential divider method of bias become universal?

Determine the stability factor for CB amplifier circuit.

How will you provide temperature compensation for the variations of V_{BE} and stabilization of the operating point?