Bipolar Junction Transistors (BJT)

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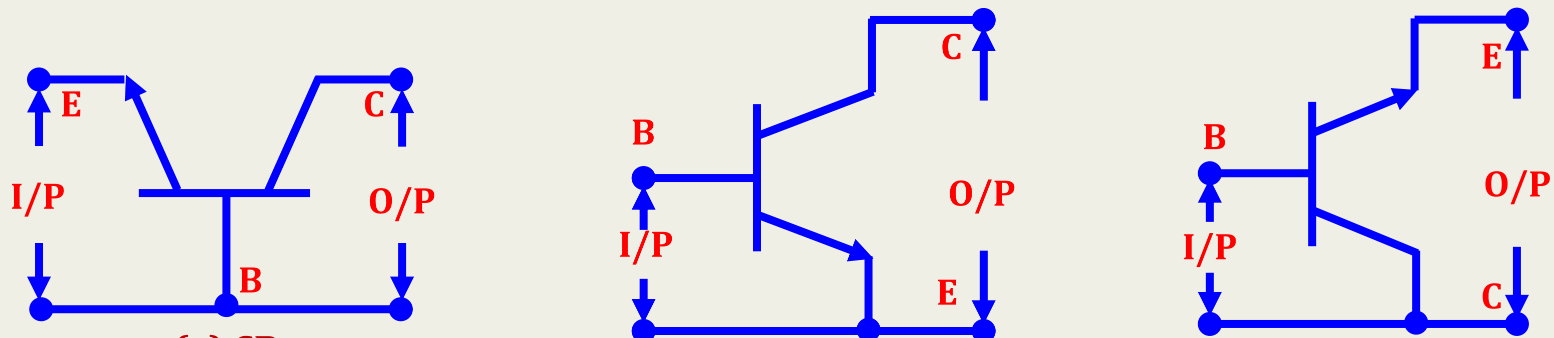
BJT Circuits

- Most electronic devices take the signal between two input terminals and deliver from it an output signal between two output terminals.
- The BJT has only three terminals, so one of these is usually shared (i.e. made common) between input and output circuits.
- Thus, a transistor can be connected in a circuit in ways:

  (i) common base (CB), (ii) common emitter (CE), and

  (iii) common collector (CC) mode or configurations.



(a) CB (b) CE (C) CC

BJT Circuits (contd..)

- **Each circuit connection has specific advantages and disadvantages.**
- **Regardless of circuit connection, the emitter-base junction is always forward-biased, while the collector-base junction is reverse-biased.**
- **The CE configuration is the one most commonly encountered since it provides both good current and voltage gain for ac signals.**
- **In the CE configuration the input is between the base and the emitter and the output is between the collector and the emitter.**
- **All three configurations will be covered in the module lectures.**

Common Base Configuration

- **1. Common-base current amplification factor (α):**
- **The quantity α represents the fraction of the emitter current contributed by the carriers injected into the base and reach the collector. It is defined by the ratio of output collector current I_C to input emitter current I_E and is known as dc or static α. It is denoted by α_{dc}.**
- **Thus, $\alpha_{dc} = \frac{I_C}{I_E}$.**

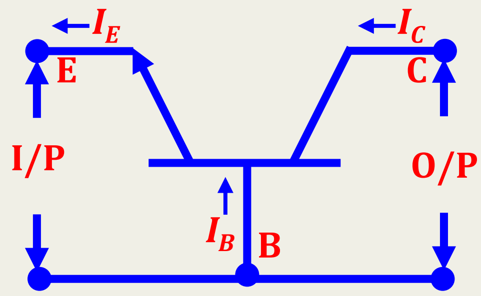


Fig. CB

- **The small-signal short-circuit current transfer ratio (or gain) in CB mode is defined by the ratio of change in collector current to the change in emitter current at constant collector-base voltage V_{CB} and is known as ac or dynamic α.**
- **Thus, $\alpha_{ac} = \left.\frac{\Delta I_C}{\Delta I_E}\right|_{V_{CB=\text{const.}}}$.**

Common Base Configuration (contd..)

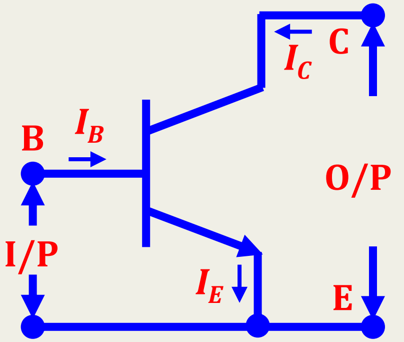
- In general, is not α is not a constant for a given transistor, but varies with the emitter current I_E, collector-base voltage V_{CB} , and the temperature.
- It is clear that α is less than unity. This value can be increased (but not more than unity) by decreasing the base current. This can be achieved by making the base thin and doping it lightly. Typical values of α range from 0.9 to 0.995.

2. Expression for Collector Current:

- Total collector current consists of:
- (i) part of emitter current which reaches the collector, i.e. αI_E , and
- (ii) leakage current I_{CBO}.
- Therefore, the total collector current is given by,
- $I_C = \alpha I_E + I_{CBO}$ … … (1)
- Since, $I_E = I_C + I_B$,
- therefore, $I_C = \alpha\,(I_C + I_B) + I_{CBO}$
- Thus, $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha}$ … … (2)
- From (1) and (2) it is clear that I_C can be controlled either by I_E or I_B .
- I_{CBO} is usually small and may be neglected in transistor circuit calculation.

Common Emitter Configuration

- **2. Common-emitter current amplification factor (β):**
- **The quantity β represents the maximum current gain of a transistor in CE mode. It is defined by the ratio of output collector current I_C to input base current I_B and is known as dc or static β. It is denoted by β_{dc}. Thus, $\beta_{dc} = \frac{I_C}{I_B}$.**



(b) CE

- **The small-signal short-circuit current transfer ratio (or gain) in CE mode is defined by the ratio of change in collector current to the change in base current at constant collector-emitter voltage V_{CE} and is known as ac or dynamic β.**
- **Thus, $\beta_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE=\text{const.}}}$.**
- **In general, less than 5% of emitter current flows as the base current. Therefore, the value of β is greater than 20. Usually, its value ranges from 20 to 200.**

Common Emitter Configuration (contd..)

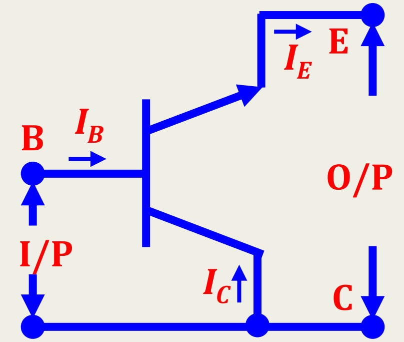
- **3. Relationship between α and β:**
- $$\alpha = \frac{\Delta I_C}{\Delta I_E} \quad \text{and} \quad \beta = \frac{\Delta I_C}{\Delta I_B}$$
- **Since, $I_E = I_C + I_B$, therefore,**
- **therefore, $\Delta I_E = \Delta I_C + \Delta I_B$**
- **or,** $\frac{\Delta I_E}{\Delta I_C} = \frac{\Delta I_B}{\Delta I_C} + 1$
- **or,** $\frac{1}{\alpha} = \frac{1}{\beta} + 1$
- **Hence,** $\beta = \frac{\alpha}{1-\alpha}$.
- **It is clear that as α approaches unity, β approaches infinity. In other words, the current gain in CE mode is very high. For this reason, CE mode circuit arrangement is used in almost all (~ 90 to 95%) transistor applications.**

Common Emitter Configuration (contd..)

- **4. Expression for Collector Current:**
- **Total collector current is given by,**
- $I_C = \alpha I_E + I_{CBO}$ … … (1)
- **Since,** $I_E = I_C + I_B$,
- **therefore,** $I_C = \alpha\,(I_C + I_B) + I_{CBO}$
- **or,** $(1 - \alpha)I_C = \alpha I_B + I_{CBO}$
- **or,** $I_C = \frac{\alpha}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha}$
- **or,** $I_C = \beta I_B + (1 + \beta)I_{CBO}$ … … (2) [as, $\beta = \alpha/(1 - \alpha)$, then $(1 + \beta) = 1/(1 - \alpha)$]
- **From (2), it is seen that if $I_B = 0$, then the collector current is abbreviated as I_{CEO}, which represent the collector current when the base is open.**
- **Thus,** $I_{CEO} = \frac{1}{1-\alpha} I_{CBO} = (1 + \beta)I_{CBO}$ … … (3)
- **(3) indicates that the value of I_{CEO} is much larger than $I_{CBO.}$**
- **Thus, the collector current:** $I_C = \beta I_B + I_{CEO}$ **, and**
- **the emitter current:** $I_E = (1 + \beta)I_B + I_{CEO}$

Common Collector Configuration

- 5. Common-collector current amplification factor (γ):
- The quantity γ represents the maximum current gain of a transistor in CC mode. It is defined by the ratio of output emitter current I_E to input base current I_B and is known as dc or static γ. It is denoted by γ_{dc}.
- Thus, $\gamma_{dc} = \frac{I_E}{I_B}$.



(c) CC

- The small-signal short-circuit current transfer ratio (or gain) in CC mode is defined by the ratio of change in emitter current to the change in base current at constant collector-emitter voltage V_{CE} and is known as ac or dynamic γ.
- Thus, $\gamma_{ac} = \left.\frac{\Delta I_E}{\Delta I_B}\right|_{V_{CE=\text{const.}}}$.
- CC circuit provides about the same current gain as the CE circuit as $\Delta I_E \cong \Delta I_C$.

Common Collector Configuration

- **6. Relationship between α, β and γ:**
- $\alpha = \frac{\Delta I_C}{\Delta I_E}$; $\beta = \frac{\Delta I_C}{\Delta I_B}$; **and** $\gamma = \frac{\Delta I_E}{\Delta I_B}$
- **Since,** $I_E = I_C + I_B$ **,**
- **therefore,** $\Delta I_E = \Delta I_C + \Delta I_B$
- **or,** $1 = \frac{\Delta I_C}{\Delta I_E} + \frac{\Delta I_B}{\Delta I_E}$
- **or,** $1 = \alpha + \frac{1}{\gamma}$
- **Thus,** $\gamma = \frac{1}{1-\alpha} = 1 + \beta$.

Common Collector Configuration (contd..)

- **7. Expression for Collector Current:**
- **Total collector current is given by,**
- $I_C = \alpha I_E + I_{CBO}$ ... ... (1)
- Since, $I_E = I_C + I_B$,
- therefore, $I_E = \alpha I_E + I_{CBO} + I_B$
- or, $(1 - \alpha)I_E = I_B + I_{CBO}$
- or, $I_E = \frac{1}{1-\alpha} I_B + \frac{I_{CBO}}{1-\alpha}$ ... ... (2)
- Thus, $I_E = \gamma I_B + I_{CEO}$ ... ... (3)
- Thus, $\gamma_{ac} = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE=\text{const.}}}$.
- **CC circuit has very high input resistance (~750 Ω) and very low output resistance (~25 Ω).**
- **Due to this reason, voltage gain of CC circuit is always less than 1.**
- **Therefore, CC circuit arrangement is seldom used for amplification.**
- **However, CC circuit is used for impedance matching, i.e. for driving a low impedance load and from a high impedance source.**

Transistor Characteristics

- **1. Common Base (CB) Characteristics:**
- **The circuit arrangement for determining CB characteristics of a *npn* transistor is shown in Fig. (a).**

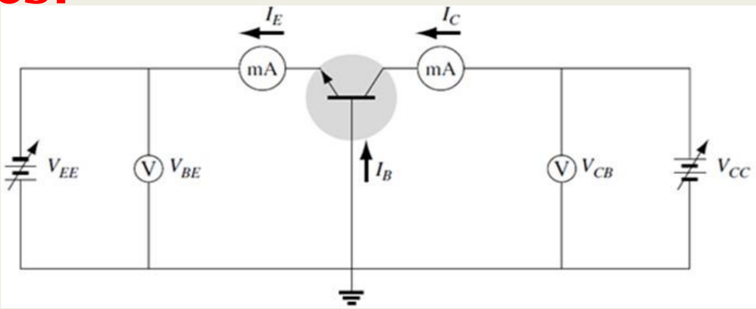


Fig. (a): Experimental set-up to draw input and output characteristics.

- **(a) Input Characteristics:**
- **In CB mode, input current is emitter current I_E, input voltage is emitter-base voltage V_{EB}, and output voltage is collector-base voltage V_{CB}.**
- **Thus, the input characteristics in CB mode is the plot of I_E versus V_{EB} for different constant value of V_{CB}.**
- **A set of such input characteristic is depicted in Fig. (b).**

CB Transistor Characteristics

- For a given V_{CB}, the plot is just like a forward-biased *pn*-junction diode.
- However, with an increase of V_{CB}, I_E increases for a fixed V_{EB}.
- When $|V_{CB}|$ increases, width of the depletion region at the CB-junction increases, thereby reducing the effective base width.
- Thus, the chances of recombination of carriers in the base region is reduced.
- Hence, more carriers from the base will cross the EB-junction and reach the emitter region to contribute to the emitter current I_E.
- The change of the effective base width by the collector voltage is termed as the ***base width modulation***, also known as the ***Early effect***.

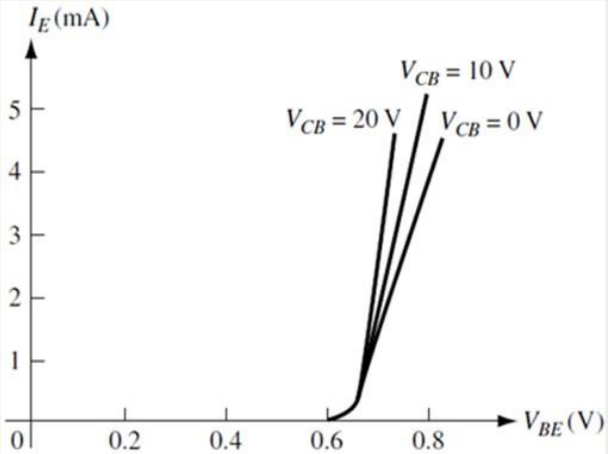


Fig. (b): Input characteristics.

- It is seen that below certain voltage V_γ, known as ***cutin***, or ***offset***, or ***threshold voltage*** of the transistor, emitter current is very small.
- Usually, $V_\gamma \approx 0.6$ for Si and $V_\gamma \approx 0.1$ for Ge transistor.

- **Dynamic Input Resistance:**
- **The dynamic input resistance can be calculated from the slope of the input characteristic curve as:**
- $r_i = \left.\frac{\Delta V_{EB}}{\Delta I_E}\right|_{V_{CB=\text{const.}}}$.
- **The dynamic input resistance r_i is very low (20 to 100 Ω).**
- **Since the curve is non linear, value of r_i varies with the point of measurement.**
- **With the increase in V_{BE} the curve tends to become more vertical, resulting in decrease in dynamic input resistance r_i .**

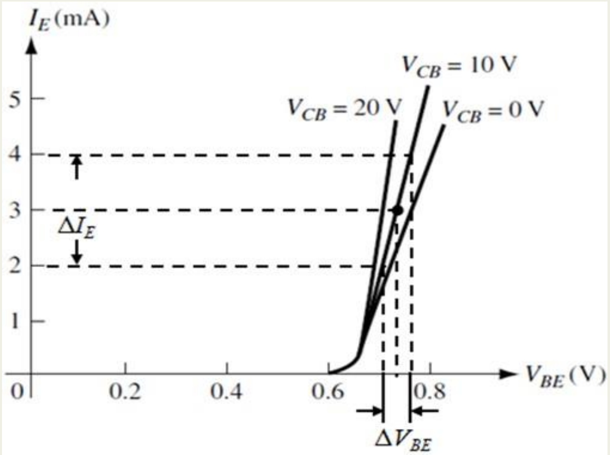


Fig. (b): Input characteristics.

CB Transistor Characteristics (contd..)

- **(b) Output Characteristics:**
- **In CB mode, output current is collector current I_C, output voltage is collector-base voltage V_{CB}, and input current is emitter current I_E.**
- **Thus, the output characteristics in CB mode is the plot of I_C versus V_{CB} for different constant value of I_E.**

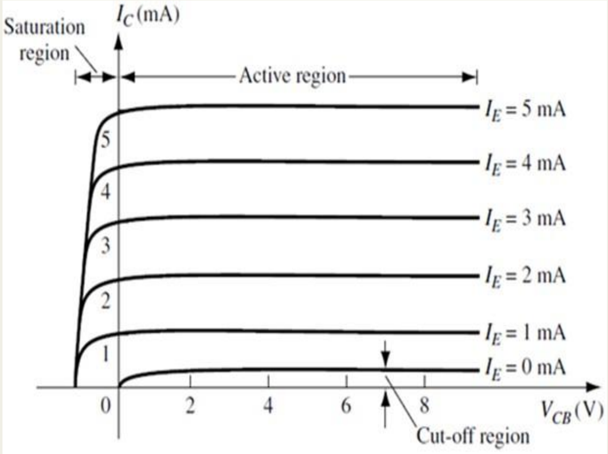


Fig. (c): Output characteristics.

- **A typical set of such output characteristic is depicted in Fig. (c).**
- **In *npn* transistor I_E and V_{EB} are negative, and I_C, I_B, and V_{CB} are positive.**
- **The signs are reversed for an *pnp* transistor.**

CB Transistor Characteristics (contd..)

- A close look at the output characteristics reveals the following points:
- (i) Each curve starts at $I_C = 0$ and rises rapidly for a small (positive) increase in V_{CB} .
- (ii) When V_{CB} is negative, CB-junction is actually forward-biased, hence an electron current flows from the collector to the base,

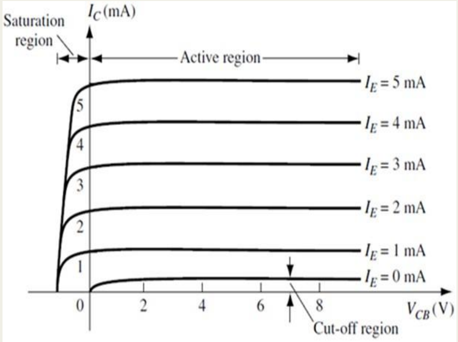


Fig. (c): Output characteristics.

- i.e. in opposite direction to the original electron current flow from emitter-to-base-to-collector.
- When forward bias is sufficiently large, flow of electrons from collector to base predominates, resulting in to be negative (i.e. positive value of decreasing), as shown in Fig. (c).
- The portion of the plot where V_{CB} is positive is called ***saturation region***.
- By definition, a transistor is operating in saturation region when both the E-B and C-B junctions are forward-biased, and the collector current $I_C \cong I_E$,

CB Transistor Characteristics (contd..)

- (iii) It is seen that when V_{CB} is positive the curve is more or less flat.
- This is due to the fact that CB junction is reverse-biased and since EB junction is forward-biased, most of the carriers emitted from the emitter reach the collector as the recombination in the base region is small.
- Hence, for a fixed I_E , I_C remains constant and independent of V_{CB} . Thus, the collector current $I_C \cong I_E$.
- The portion of the plot where V_{CB} is positive is called *active region*.
- By definition, a transistor is operating in active region when both the E-B junction is forward-biased and C-B junction is reverse-biased.

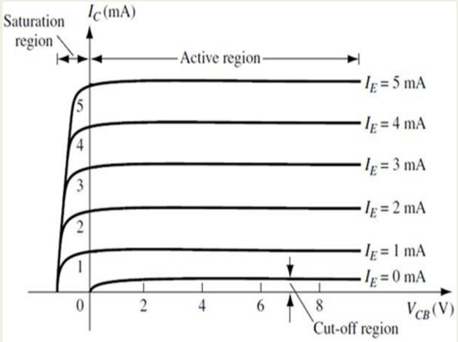


Fig. (c): Output characteristics.

- (iv) In active region, almost flat curves indicate that for a given I_E, I_C increases slightly with an increase in V_{CB} .
- The transistor output characteristics (in CB mode) is similar to that of the current source. It means that the transistor should have high output resistance r_o .

CB Transistor Characteristics (contd..)

- (v) It is also seen that I_C is not zero when $I_E = 0$. It has a very small value.
- This is reverse leakage current I_{CBO} (or I_{CO}).
- The conditions that exist when $I_E = 0$ for CB configuration is shown in Fig. (d).
- When $I_E = 0$ (emitter open), no injection of from emitter to base takes place.
- The only collector current is the reverse Saturation (leakage) current I_{CBO} .
- The region of the output characteristic below $I_E = 0$ line is called the *cutoff region*.
- It is called so because $I_C \approx 0$ (negligibly small) there (cutoff).
- A transistor is defined to be cutoff when both the E-B and C-B junctions are reverse-biased.
- At room temperature, I_{CBO} is ~ 2 to 5 μA for Ge and 0.1 to 1 μA for Si.

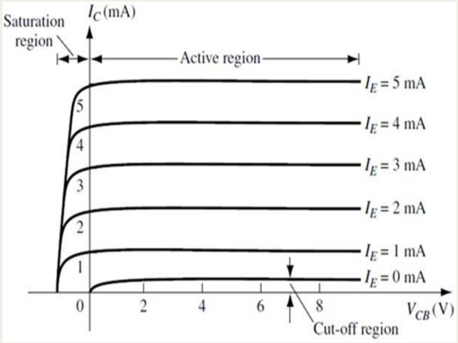


Fig. (c): Output characteristics.

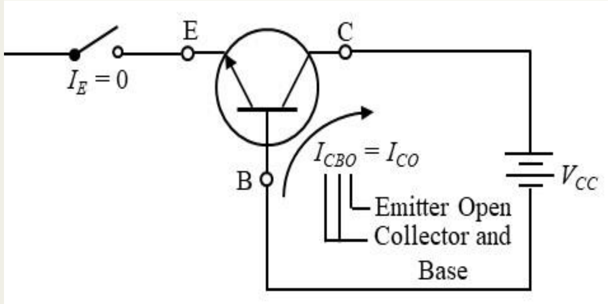


Fig. (d): Reverse leakage current in CB configuration.

CB Transistor Characteristics (contd..)

- **Dynamic output resistance:**
- **It can be calculated from the slope of the output characteristic curve as:**
- $r_o = \left.\dfrac{\Delta V_{CB}}{\Delta I_C}\right|_{I_{E=\text{const.}}}$.
- **It is very high (~ 1 MΩ).**
- **CB current amplification factor (α):**
- **The dc or static α is given by:**
- $\alpha_{dc} = \dfrac{I_C}{I_E}$.
- **The ac or dynamic α is given by:**
- $\alpha_{ac} = \left.\dfrac{\Delta I_C}{\Delta I_E}\right|_{V_{CB=\text{const.}}}$.

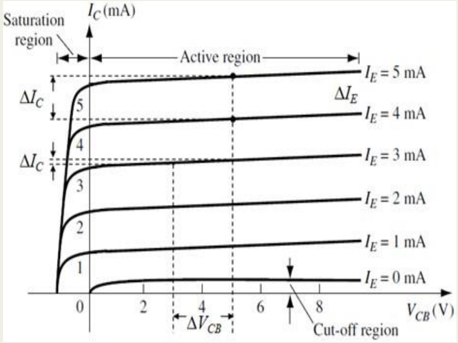


Fig. (e): Output characteristics.

- **2. Common Emitter (CE) Characteristics:**
- **The circuit arrangement for determining CE characteristics of a *npn* transistor is shown in Fig. (a).**

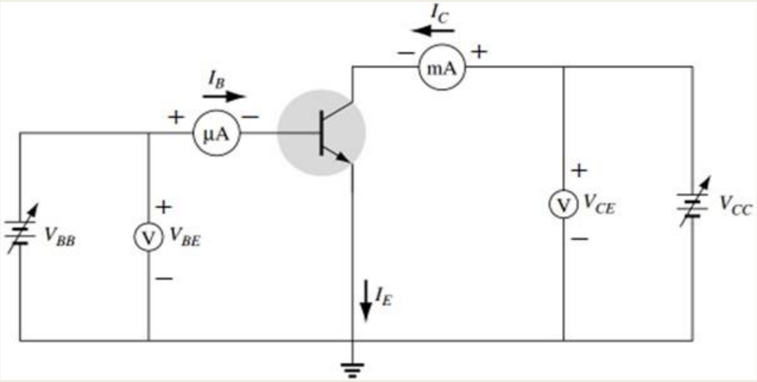


Fig. (a): Experimental set-up to draw input and output characteristics.

- **(a) Input Characteristics:**
- **In CB mode, input current is base current I_B, input voltage is Base-emitter voltage V_{BE}, and output voltage is collector-emitter voltage V_{CE}.**
- **Thus, the input characteristics in CE mode is the plot of I_B versus V_{BE} for different constant value of V_{CE}.**
- **A set of such input characteristic is depicted in Fig. (b).**

CE Transistor Characteristics (contd..)

- For a given V_{CE} , the plot is just like a forward-biased *pn*-junction diode.
- However, with an increase of $|V_{CE}|$ for a fixed V_{BE} , width of the depletion region at the CB junction increases, thereby reducing the effective base width. However, with an increase of V_{CB} , I_E increases for a fixed V_{EB} .
- Thus, there are fewer recombination of injected carriers in the base resulting in a corresponding reduction in base current I_B .

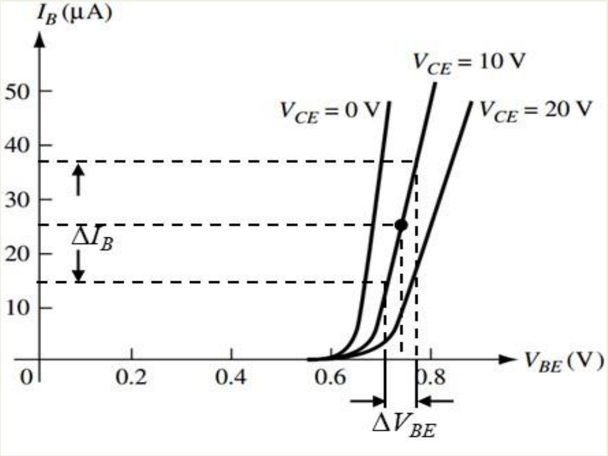


Fig. (b): Input characteristics.

- Dynamic Input Resistance: The dynamic input resistance can be calculated from the slope of the input characteristic curve as:
- $r_i = \left.\dfrac{\Delta V_{BE}}{\Delta I_B}\right|_{V_{CE=\text{const.}}}$.
- The dynamic input resistance r_i is moderate (100 to 1000 Ω).
- Since the curve is non linear, value of r_i varies with the point of measurement.
- With the increase in V_{BE} the curve tends to become more vertical, resulting in decrease in r_i .

CE Transistor Characteristics (contd..)

- **(b) Output Characteristics:**
- **In CE mode, output current is collector current I_C, output voltage is collector-emitter voltage V_{CE}, and input current is emitter current I_b.**
- **Thus, the output characteristics in CE mode is the plot of I_C versus V_{CE} for different constant value of I_B.**
- **A typical set of such output characteristic is depicted in Fig. (c).**

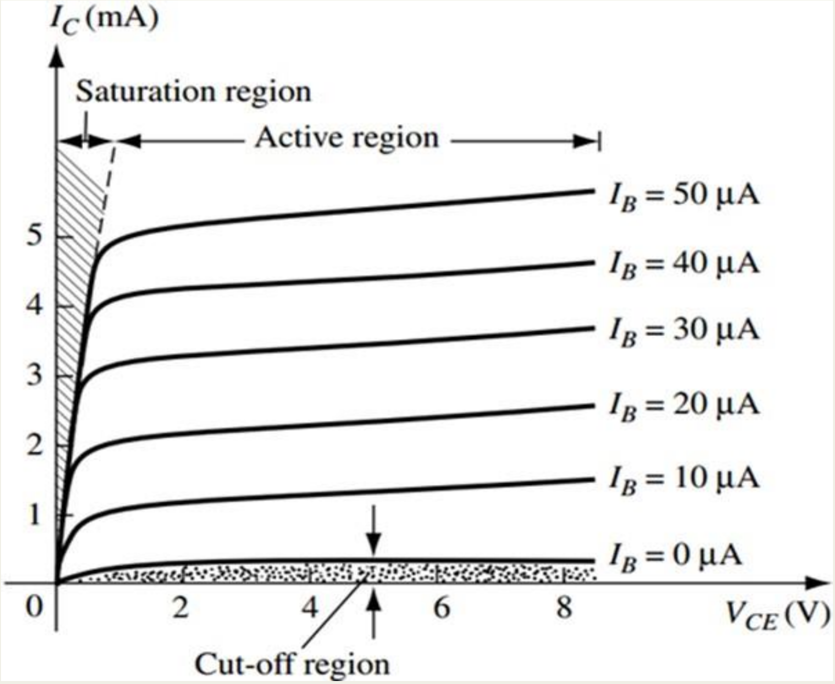


Fig. (c): Output characteristics CE *npn* transistor.

CE Transistor Characteristics (contd..)

- A close look at the output characteristics reveals the following points:
- (i) Each curve starts at $I_E = 0$ and rises rapidly for a small (positive) increase in $|V_{CE}|$.
- (ii) When $|V_{CE}|$ is small, only a few tenth of a volt, then V_{CB} (= $V_{CE} - V_{BE}$) is negative,
- i.e., the collector-base junction actually becomes forward-biased.

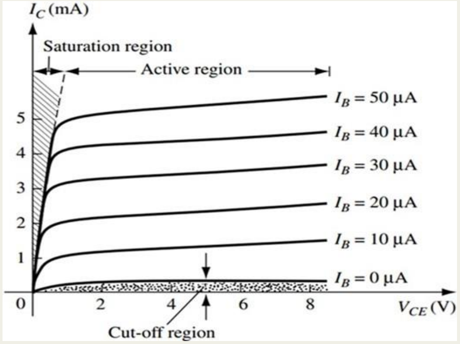


Fig. (c): Output characteristics.

- Therefore, in this condition, both the junctions of the transistor in CE mode are forward-biased.
- The portion of the plot where V_{CB} is positive so that the collector-base junction becomes forward-biased is called ***saturation region***.
- This is called saturation region, because output collector current I_C no longer depends on the input base current I_B .
- In this region, there is a large change in collector current I_C with a small change in collector-emitter voltage V_{CE}.

CE Transistor Characteristics (contd..)

- (iii) It is seen that for a fixed I_B , I_C increases slowly as V_{CE} increases due to the base width modulation or Early effect.
- Also the curves are not horizontal lines, and the slopes of these curves is somewhat greater than that of the CB output characteristic curves.
- The portion of the plot where more positive V_{CE} makes V_{CB} also positive so that the C-B junction becomes reverse-biased is called *active region*.

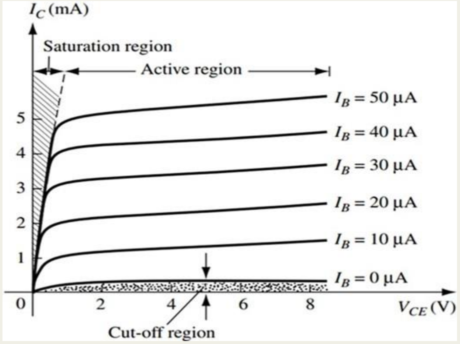


Fig. (c): Output characteristics.

- By definition, a transistor is operating in active region when both the E-B junction is forward-biased and C-B junction is reverse-biased.
- (iv) In the active region, for a fixed V_{CE} , a small change in I_B (of order of μA) produces a large change in I_C (of order of mA).

CE Transistor Characteristics (contd..)

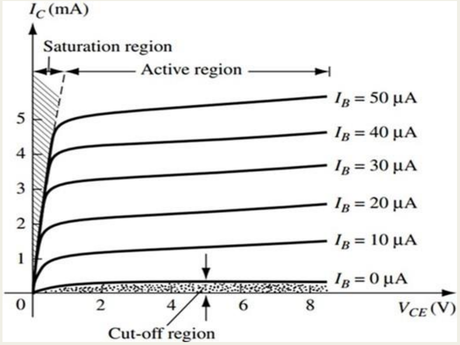


Fig. (c): Output characteristics.

- **(v) It is also seen that I_C is not zero when $I_B = 0$. It has a very small value.**
- **The conditions that exist when $I_B = 0$ for CE configuration is shown in Fig. (d).**
- **As V_{CE} makes the C-B junction reverse-biased, thus when $I_B = 0$ (i.e., base open), only minority carriers flow from collector to emitter.**
- **Thus, the only collector current is the reverse saturation (leakage) current I_{CEO} .**
- **The region of the output characteristic below the $I_B = 0$ line is called the *cutoff region*.**
- **It is called so because $I_C \approx 0$ (negligibly small) there (cutoff).**
- **A transistor is defined to be cutoff when both the E-B and C-B junctions are reverse-biased.**

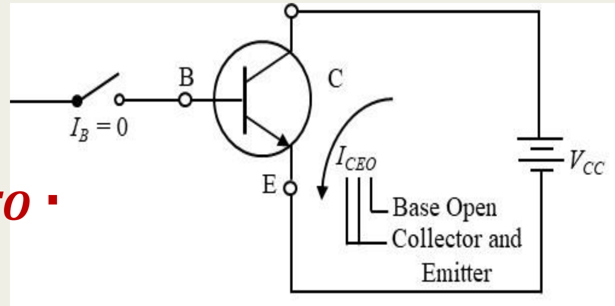


Fig. (d): Reverse leakage current in CE configuration.

CE Transistor Characteristics (contd..)

- **CE current amplification factor (β):**
- $\beta_{dc} = \frac{I_C}{I_B}$; **and**
- $\beta_{ac} = \frac{\Delta I_C}{\Delta I_B}\Big|_{V_{CE=\text{const.}}}$.
- **Important Note: At 25°C,**
- **For a typical Si *n-p-n* transistor:**
- $V_{BE,\,sat}$ **= 0.8 V,** $V_{CE,\,sat}$ **= 0.2 V, and** $V_{BE,\,\text{active}}$ **= 0.7 V.**
- **For Ge *n-p-n* transistor:**
- $V_{BE,\,sat}$ **= 0.3 V,** $V_{CE,\,sat}$ **= 0.1 V, and** $V_{BE,\,\text{active}}$ **= 0.2 V.**
- **For *p-n-p* transistor, the sign of the voltages are just reversed.**

CC Transistor Characteristics

- **3. Common Collector (CC) Characteristics:**
- **The circuit arrangement for determining CC characteristics of an *npn* transistor is shown in Fig. (a).**
- **(a) Input Characteristics:**
- **The input characteristics in CC mode is the plot of input current I_B versus input voltage V_{BC} for different constant values of output voltage V_{CE} .**
- **A set of such input characteristic is depicted in Fig. (b).**

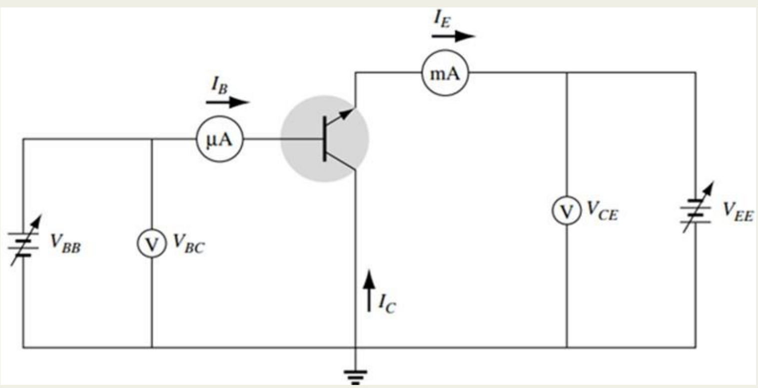


Fig. (a): Experimental set-up to draw input and output characteristics of *npn* CC transistor.

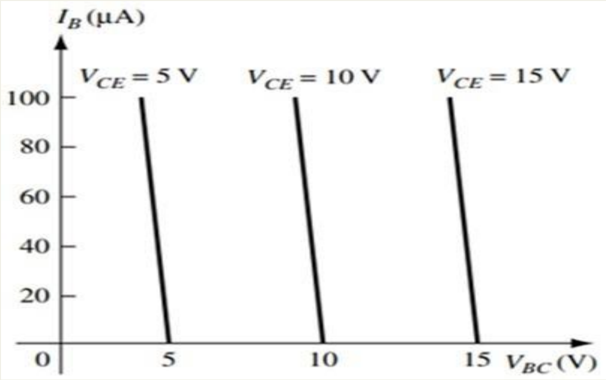


Fig. (b): Input characteristics of *npn* CC transistor.

CC Transistor Characteristics (contd..)

- It is seen that input current I_B decreases to zero as input voltage V_{BC} increases slightly for a fixed value of output voltage V_{CE} .
- For transistor, $V_{BE} = V_{CE} - V_{BC}$.
- Thus, when V_{BC} is increased keeping voltage V_{CE} constant, V_{BE} decreases and therefore I_B decreases.
- Hence, if the value of V_{BC} is allowed to increase to a point where it is near to the value of V_{CE} , the value of V_{BE} approaches zero, and no base current I_B will flow.

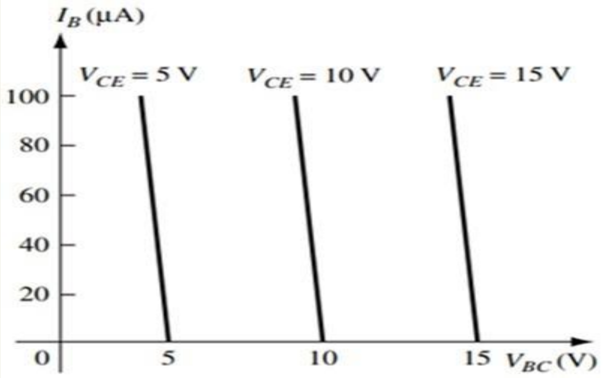


Fig. (b): Input characteristics of *npn* CC transistor.

CC Transistor Characteristics (contd..)

- **(b) Output Characteristics:**
- **The output characteristics in CC mode is the plot of output current I_E versus output voltage V_{CE} for different constant values input current of I_B.**
- **Since current I_C is approximately equal to I_E, the CC output characteristics are identical to those of CE output characteristics.**
- **A set of such output characteristic is depicted in Fig. (c).**
- **CC current amplification factor (γ):**
- $\gamma_{dc} = \frac{I_E}{I_B}$; **and**
- $\gamma_{ac} = \left.\frac{\Delta I_E}{\Delta I_B}\right|_{V_{CE=\text{const.}}}$.

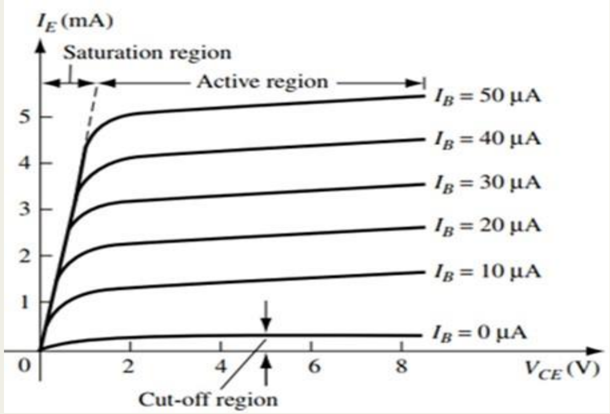


Fig. (c): Output characteristics of *npn* CC transistor.

THANK YOU!