Analog & Digital Electronics
Course No: PH-218

BJT
Lec-6: I-V characteristics and Ebers-Moll Model

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I-V Characteristics of BJT under common base configuration

- Input characteristics are like a normal forward biased diode.
- As the CB junction is reverse biased, the current $I_C$ is independent of collector voltage and depends only upon the emitter current $I_E$. The collector current is almost constant and work as a current source.
- When $I_E=0$, $I_C=I_{CB0}$ is the leakage current caused by the minority carriers crossing the pn-junction.

$$I_C = \alpha I_E + I_{CB0}$$
I-V Characteristics of BJT common emitter configuration

- Input characteristics are like a normal forward biased diode.
- As the CE junction is reverse biased, the current $I_C$ is independent of collector voltage and depends only upon the base current $I_B$.
- In real diode, the collector current slightly increases with increase in collector emitter voltage (Early effect).
- At low value of $V_{CE}$, the CBJ becomes forward-biased and the transistor enters the saturation region.
Early Effect (Base width modulation)

Observed by James Early

\[ I_C = I_s \left( \frac{e^{V_{BE}}}{kT} \right) \left[ 1 + \frac{V_{CE}}{V_A} \right] \]

\( V_A \) is called the Early voltage and ranges from about 50 V to 100 V.

Early effect can be modeled as

\[ I_C = I'_c + \frac{V_{CE}}{r_o} \]

where \( I'_c = I_s \exp\left( \frac{eV_{BE}}{kT} \right) \)

\[ r_o \equiv \left[ \frac{\partial I_C}{\partial V_{CE}} \right]_{V_{BE}=\text{constant}}^{-1} \quad r_o = \frac{V_A}{I'_c} \]

- When \( V_{CB} \) increases:
  - depletion region of CBJ widens
  - so the effective base width decreases (base-width modulation)
Base punch through

- If reverse bias voltage of C-B junction is kept on increasing, a situation arises where E-B and C-B space charge regions touch each other, and the width of the quasi-neutral base region becomes zero, Known as base punch through.

Any increase in $V_{CB}$ beyond the punch-through point lowers the E-B potential barrier and allows a large injection of carriers from the emitter directly into the collector.

- If punch-through occurs, the maximum voltage ($V_{CB0}$ or $V_{CE0}$) that can be applied to a BJT is limited.
DC Load Line Analysis

Application of KVL in output (CE) circuit:
\[ V_{CE} = V_{CC} - I_C R_C \]; is called Load line equation.
When \( I_C = 0 \), \( V_{CE} = V_{CC} \); When \( V_{CE} = 0 \), \( I_C = V_{CC}/R_C \)

➢ The operating point \( Q (V_{CEQ}, I_{CEQ}) \) is determined by finding the intersection point of load line and BJT output characteristics for a particular value of base current.
Ebers-Moll Model (Large-Signal Model)

- The Ebers-Moll (EM) model is a large-signal model for BJT. It relates the transistor d.c terminal currents to voltages.

- EM model is low frequency (static) model based on the fact that BJT is composed of two pn junctions – EB and CB junction.

- Therefore terminal currents of BJT can be expressed as a superposition of the currents due to the two pn junctions.

\[
\begin{align*}
D_E & : E-B \text{ junction diode} \\
D_C & : C-B \text{ junction diode}
\end{align*}
\]

\[
\begin{align*}
I_{DE} &= I_{SE} (e^{\frac{V_{BE}}{V_T}} - 1) \\
I_{DC} &= I_{SC} (e^{\frac{V_{BC}}{V_T}} - 1)
\end{align*}
\]

\[
\begin{align*}
I_{DE} &= \frac{I_C}{\alpha} = \frac{I_S}{\alpha} (e^{\frac{V_{BE}}{V_T}} - 1) = I_{SE} (e^{\frac{V_{BE}}{V_T}} - 1)
\end{align*}
\]
Ebers-Moll Model (Large-Signal Model)

Reverse Active Mode

Forward Active Mode

\[ I_E = I_{DE} - \alpha_R I_{DC} \]
\[ I_C = -I_{DC} + \alpha_F I_{DC} \]
\[ I_B = (1-\alpha_F)I_{DE} + (1-\alpha_R)I_{DC} \]

\[ I_E = \frac{I_S}{\alpha_F} \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) - I_S \left( e^{\frac{V_{BC}}{V_T}} - 1 \right) \]
\[ I_C = I_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{V_{BC}}{V_T}} - 1 \right) \]
Ebers-Moll Model (Large-Signal Model)

**BJT Forward Active Mode**

BE forward-biased, BC reverse-biased:

\[
D_C \quad i_{DC} \quad \alpha_F i_{DE} \\
D_E \quad i_{DE} \quad \alpha_R i_{DC}
\]

\[
(i_{SC} = I_S / \alpha_R) \quad (i_{SE} = I_S / \alpha_F)
\]

**BJT Reverse Active Mode**

BE reverse-biased, BC forward-biased:

\[
D_C \quad i_{DC} \quad \alpha_F i_{DE} \\
D_E \quad i_{DE} \quad \alpha_R i_{DC}
\]

\[
(i_{SC} = I_S / \alpha_R) \quad (i_{SE} = I_S / \alpha_F)
\]
Ebers-Moll Model (Large-Signal Model)

BJT Cut-off Mode

BE reverse-biased, 
BC reverse-biased:

Diodes simplified as constant voltage drops.
Their parallel current sources can be omitted.

BJT Saturation Mode

BE forward-biased, 
BC forward-biased:
BJT with input ac signal

\[ i_C = I_C + I_c \]

\[ i_B = I_B + I_b \]

\[ i_E = I_E + I_e \]

\[ i_C = I_C + I_c \]

\[ I_B, I_C, I_E - D.C. \text{ currents} \]

\[ I_b, I_c, I_e - A.C. \text{ currents} \]

\[ I_B, I_C, I_E - D.C. + A.C. \text{ currents} \]

Similarly,

\[ V_{BE}, V_{CE} - D.C. \text{ Voltages} \]

\[ v_{be}, v_{ce} - A.C. \text{ Voltages} \]

\[ v_{BE}, v_{CE} - D.C. + A.C. \text{ Voltages} \]
Biasing schemes for BJT

- Biasing refers to the application of D.C. voltages to setup the operating point in such a way that output signal is undistorted throughout the whole operation.

- Also once selected properly, the Q point should not shift because of change of $I_C$ due to

  (i) $\beta$ variation
  (ii) Temperature variation

**Different biasing schemes**

(i) Fixed bias (base resistor biasing)
(ii) Collector base bias
(iii) Emitter bias
(iv) Voltage divider bias
\[ I_E = I_{DE} - \alpha_R I_{DC} \]
\[ I_C = -I_{DC} + \alpha_F I_{DC} \]
\[ I_B = (1 - \alpha_F) I_{DE} + (1 - \alpha_R) I_{DC} \]

\[ I_E = \frac{I_S}{\alpha_F} \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) - I_S \left( e^{\frac{V_{BE}}{V_T}} - 1 \right) \]
\[ I_C = I_S \left( e^{\frac{V_{BC}}{V_T}} - 1 \right) - \frac{I_S}{\alpha_R} \left( e^{\frac{V_{BC}}{V_T}} - 1 \right) \]