In this lecture you will learn:

- The operation of bipolar junction transistors
- Forward and reverse active operations, saturation, cutoff
- Ebers-Moll model

PNP Bipolar Junction Transistors (BJTs)

NPN Bipolar Junction Transistor

- Emitter: N-doped \(N_{dE}\)
- Base: P-doped \(N_{aB}\)
- Collector: N-doped \(N_{dC}\)
PNP Bipolar Junction Transistor

PNP BJT: Basic Operation

Suppose:

The base-emitter junction is forward biased
\[ V_{BE} < 0 \]

The base-collector junction is zero biased
\[ V_{CB} = 0 \]

This biasing scheme will put the device in the “forward active” operation (to be discussed fully later)
Consider the action in the base first ($V_{BE} < 0$ and $V_{CB} = 0$)

- The holes diffuse from the emitter, cross the depletion region, and enter the base
- In the base, the holes are the minority carriers
- In the base, the holes diffuse towards the collector
- As soon as the holes reach the base-collector depletion region they are immediately swept away into the collector by the strong electric fields in the depletion region

Consider the base first:

In the base, the hole population can be written as:

$$ p(x) = p_{no} + p'(x) $$

Boundary conditions:

- $p'(x_n) = \frac{n_i^2}{N_{db}} \left( -\frac{q V_{BE}}{kT} - 1 \right)$
- $p'(x_n + W_B) = \frac{n_i^2}{N_{db}} \left( e^{\frac{q V_{BC}}{kT}} - 1 \right) = 0$
PNP BJT: Electron-Hole Populations

Consider the emitter now:

In the emitter, the electron population can be written as:

\[ n(x) = n_{po} + n'(x) \]

Equilibrium electron density  Excess electron density

In the emitter, the excess electron population satisfies the differential equation:

\[ \frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{L_n^2} = 0 \]

Boundary conditions

\[ n'(-x_p - W_E) = 0 \]

\[ n'(-x_p - W_B) = 0 \]
PNP BJT: Electron-Hole Populations

- Ignore carrier recombination (i.e. assume $L_n = \infty$)

\[ \frac{\partial^2 n'(x)}{\partial x^2} = 0 \]

Boundary conditions:

\[ n'(-x_p) = \frac{n_p^2}{N_{aE}} \left( \frac{-q V_{BE}}{kT} - 1 \right) \]

\[ n'(-x_p - W_E) = 0 \]

Solution is:

\[ n'(x) = n'(-x_p) \left( 1 + \frac{x + x_p}{W_E} \right) = \frac{n_p^2}{N_{aE}} \left( \frac{-q V_{BE}}{kT} - 1 \right) \left( 1 + \frac{x + x_p}{W_E} \right) \]

PNP BJT: Electron and Hole Current Densities

In the base:

- The hole current is:

\[ J_p(x) = -q D_p \frac{\partial p(x)}{\partial x} = -qn_i^2 \frac{D_p}{N_{dB} W_B} \left( \frac{-q V_{BE}}{kT} - 1 \right) \]

In the emitter:

- The electron current is:

\[ J_n(x) = q D_n \frac{\partial n(x)}{\partial x} = -qn_i^2 \frac{D_n}{N_{aE} W_E} \left( \frac{-q V_{BE}}{kT} - 1 \right) \]
Emitter current:

- The current flowing out of the emitter is the sum of the total electron and total hole currents in the emitter:

\[
I_E = -qn^2A \left( \frac{D_n}{N_{ae}W_E} + \frac{D_p}{N_{db}W_B} \right) e^{\frac{-qV_{BE}}{KT}} - 1
\]

Collector Current:

- The current going into the collector is due to the holes that got swept from the Base through the Base-Collector depletion region by the electric-fields:

\[
I_C = -qn^2A \frac{D_p}{N_{db}W_B} e^{\frac{-qV_{BE}}{KT}} - 1
\]

Base Current:

- The current going into the Base is due to the electrons that got injected from the base into the emitter:

\[
I_B = -qn^2A \frac{D_n}{N_{ae}W_E} e^{\frac{-qV_{BE}}{KT}} - 1
\]
PNP BJT: Terminal Currents

\[ I_E = -qn^2 A \left( \frac{D_n}{N_{ae}W_E} + \frac{D_p}{N_{dB}W_B} \right) \left( e^{-\frac{-qV_{BE}}{KT}} - 1 \right) \]

\[ I_C = -qn^2 A \left( \frac{D_p}{N_{dB}W_B} \right) \left( e^{-\frac{-qV_{BE}}{KT}} - 1 \right) \]

\[ I_B = -qn^2 A \left( \frac{D_n}{N_{ae}W_E} \right) \left( e^{-\frac{-qV_{BE}}{KT}} - 1 \right) \]

\[ I_E = I_B + I_C \]

PNP BJT: Circuit Level Parameters

**Current gain \( \beta_F \):**

Current gain of the BJT in the forward active operation is defined as the ratio of the collector and base currents:

\[ \beta_F = \frac{I_C}{I_B} = \frac{D_p}{N_{dB}W_B} \cdot \frac{N_{ae}W_E}{D_n} \Rightarrow I_C = \beta_F I_B \]

Typical values of \( \beta_F \) are between 20-200 and:

\[ N_{ae} >> N_{db} > N_{ac} \]

**\( \alpha_F \):**

In the forward active operation \( \alpha_F \) is defined as the ratio of the collector and emitter currents:

\[ \alpha_F = \frac{I_C}{I_E} = \frac{D_p}{D_n} \cdot \frac{N_{db}W_B}{N_{ae}W_E + \frac{D_p}{D_n} N_{ae}W_E} \Rightarrow I_C = \alpha_F I_E \]

Transistor relation:

\( \alpha_F \) and \( \beta_F \) are related:

\[ \beta_F = \frac{\alpha_F}{1 - \alpha_F} \]
PNP BJT: Ebers-Moll Model for Forward Active Operation

Suppose:

\[ V_{BE} < 0 \]
\[ V_{CB} = 0 \]

The circuit level simplified model with an ideal diode and a current-controlled current source models the PNP transistor in the forward active operation.

\[ I_F = qn^2A \left( \frac{D_p}{N_{SE}W_E} + \frac{D_p}{N_{DB}W_B} \right) \left( \frac{-e^{qV_{BE}/kT}}{e^{qV_{BE}/kT}} - 1 \right) \]
\[ = I_{ES} \left( \frac{-e^{qV_{BE}/kT}}{e^{qV_{BE}/kT}} - 1 \right) \]

PNP BJT: Forward and Reverse Active Operations

Forward active operation

\[ \beta_F = \frac{I_C}{I_B} \]
\[ \alpha_F = \frac{I_C}{I_E} \]
\[ \beta_F = \frac{\alpha_F}{1 - \alpha_F} \]

Reverse active operation

\[ \beta_R = \frac{I_C}{I_B} \]
\[ \alpha_R = \frac{I_E}{I_C} \]
\[ \beta_R = \frac{\alpha_R}{1 - \alpha_R} \]

In a well designed transistor: \( \beta_F \gg \beta_R \)
The circuit level simplified model with an ideal diode and a current-controlled current source models the PNP transistor in the reverse active operation.

PNP BJT: Ebers-Moll Model and Terminal Currents

Terminal currents:

\[ I_R = I_{CS} \left( \frac{qV_{CB}}{e^{KT} - 1} \right) = I_{CS} \left( \frac{-qV_{BE}}{e^{KT} - 1} \right) \]

And

\[ I_B = (1 - \alpha_F)I_F + (1 - \alpha_R)I_R \]

\[ I_C = \alpha_F I_F - I_R \]

\[ I_E = I_F - \alpha_R I_R \]
PNI BJT: Different Regimes of Operation

**Forward Active**
- $V_{BE} > 0$
- $V_{CB} \geq 0$
- $I_B < 0$ & $I_C = \beta_F I_B$
- $V_{CE} < V_{BE}$
- $I_F < 0$
- $I_E > 0$
- $I_R > 0$

**Saturation**
- $V_{CB} < 0$
- $V_{BE} > 0$
- $I_B < 0$
- $V_{CE} > V_{BE}$
- $I_F > 0$
- $I_E < 0$
- $I_R < 0$

**Reverse Active**
- $V_{CB} < 0$
- $V_{BE} \leq 0$
- $I_B > 0$
- $V_{CE} < V_{BE}$
- $I_F > 0$
- $I_E > 0$
- $I_R < 0$

In forward active operation:
- $I_B < 0$, $V_{BE} < 0$, $V_{CB} \leq 0$

Since: $V_{CE} = V_{CB} + V_{BE}$

$\Rightarrow$ In forward active operation: $V_{CE} \leq V_{BE}$

$I_C = -qn^2 A \left( \frac{D_p}{N_{db} W_B} \left( e^{-\frac{qV_{BE}}{kT}} - 1 \right) \right) = \beta_F I_B$

$\Rightarrow$ Independent of $V_{CE}$

**Forward active**:
- Base-emitter junction forward biased
- Base-collector junction reversed biased
- $I_B < 0$, $V_{BE} < 0$, $V_{CB} \leq 0$

**Saturation**:
- Base-emitter junction forward biased
- Base-collector junction forward biased
- $I_B < 0$, $V_{BE} < 0$, $V_{CB} > 0$
Carrier Densities in Different Regimes of Operation

**Forward active:**
\[ V_{BE} < 0 \quad V_{CB} \leq 0 \]
- \( n'(x) \) electrons
- \( p'(x) \) holes
- \( N_{aE} \) holes
- \( N_{dB} \) holes
- \( N_{aC} \) holes

**Saturation:**
\[ V_{BE} < 0 \quad V_{CB} > 0 \]
- \( n'(x) \) electrons
- \( p'(x) \) electrons
- \( n'(x) \) holes

The forward biased base-collector junction reduces the magnitude of the collector current!

PNP BJT: Regimes of Operation - II

**Forward active:**
- Base-emitter junction forward biased
- Base-collector junction reversed biased
- \( I_B < 0 \quad V_{BE} < 0 \quad V_{CB} \leq 0 \)

**Saturation:**
- Base-emitter junction forward biased
- Base-collector junction forward biased
- \( I_B < 0 \quad V_{BE} < 0 \quad V_{CB} > 0 \)

**Cutoff:**
- Base current zero
- \( I_B = 0 \)

**Reverse active:**
- Base-emitter junction reverse biased
- Base-collector junction forward biased
- \( I_B < 0 \quad V_{BE} \geq 0 \quad V_{CB} > 0 \)
PNP BJT: A Simple Amplifier Circuit

Current gain (in forward active regime):
\[
\frac{I_C}{I_B} = \beta_F
\]

Load line equation:
\[
V_{CE} = -I_C R - V_{DD} \\
\Rightarrow I_C = -\frac{V_{DD} + V_{CE}}{R}
\]

Curves for increasing $|I_B|$

- Forward active: $I_B < 0$ & $I_C = \beta_F I_B$  
- Saturation: $I_B < 0$ & $V_{CE} > V_{BE}$

Lesson: Don’t let the base-collector junction become forward biased

A Silicon PNP BJT

Metal base contact  |  Metal emitter contact  |  Metal collector contact

Insulator ($\text{SiO}_2$)  |  N+ (contact) |  P+ (emitter)  |  Insulator ($\text{SiO}_2$)  
N (base)  |  P (collector)  |  Insulator ($\text{SiO}_2$)  
P+ (contact layer)  |  P (substrate)