Chapter #6: Bipolar Junction Transistors
Introduction

• IN THIS CHAPTER YOU WILL LEARN
  • The physical structure of the bipolar transistor and how it works.
  • How the voltage between two terminals of the transistor controls the current that flows through the third terminal, and the equations that describe these current-voltage relationships.
  • How to analyze and design circuits that contain bipolar transistors, resistors, and dc sources.
  • How the transistor can be used to make an amplifier.
  • How to obtain linear amplification from the fundamentally nonlinear BJT.
  • The three basic ways for connecting a BJT to be able to construct amplifiers with different properties.
  • Practical circuits for bipolar-transistor amplifiers that can be constructed by using discrete components.
Introduction

• This chapter examines another three-terminal device.
  • bipolar junction transistor
  • Presentation of this material mirrors chapter 5.

• Three-terminal device
  • Multitude of applications
    • Signal amplification/Digital logic/Memory circuit/Switch
  • Voltage between two terminals to control the current flowing in third terminal

• BJT was invented in 1948 at Bell Telephone Laboratories
  • Ushered in a new era of solid-state circuits
  • It was replaced by MOSFET as predominant transistor used in modern electronics.
4.1. Device Structure and Physical Operation

- Figure 4.1. shows simplified structure of BJT
- Consists of three semiconductor regions:
  - **emitter** region (n-type)
  - **base** region (p-type)
  - **collector** region (n-type)
- Type described above is referred to as *npn*
  - However, *pnp* types do exist
4.1.1. Simplified Structure and Modes of Operation

- Transistor consists of two \textit{pn}-junctions:
  - \textbf{emitter-base} junction (EBJ)
  - \textbf{collector-base} junction (CBJ)

- Operating \textbf{mode} depends on biasing
  - \textbf{active} mode – used for amplification
  - \textbf{cutoff} and \textbf{saturation} modes – used for switching

- Bipolar (electron and hole) participate in conduction
4.1.2. Operation of the \textit{n}pn-Transistor in the Active Mode

- Active mode is “most important”
- Two external voltage sources are required for biasing to achieve it
- Refer to Figure 4.3

\textbf{Figure 4.3:} Current flow in an \textit{n}pn transistor biased to operate in the active mode. (Reverse current components due to drift of thermally generated minority carriers are not shown.)
Current Flow

• Forward bias on emitter-base junction will cause current to flow

• This current has two components:
  • electrons injected from emitter into base
  • holes injected from base into emitter

• It will be shown that first (of the two above) is desirable
  • This is achieved with heavy doping of emitter, light doping of base
Current Flow

- **emitter current** \( (i_E) \) – is current which **flows across EBJ**
  - Flows “out” of emitter lead
- **minority carriers** – in \( p \)-type region
  - These electrons will be **injected from emitter** into base.
  - Opposite direction
- Because base is thin, concentration of excess minority carriers within it will **exhibit constant gradient**
\( n_p(0) = n_{p0} e^{v_{BE}/V_T} \)  

Figure 4.4 Profiles of minority-carrier concentrations in the base and in the emitter of an nnp transistor operating in the active mode: \( v_{BE} > 0 \) and \( v_{CB} \geq 0 \).
Current Flow

• Concentration of minority carrier $n_p$ at boundary EBJ is defined by (4.1)

• Concentration of minority carriers $n_p$ at boundary of CBJ is zero
  • Positive $v_{CB}$ causes these electrons to be swept across junction

\[
n_p(x) = \text{concentration of minority carriers at position } x \text{ (where 0 represents EBJ boundary)}
\]

\[
n_{p0} = \text{thermal-equilibrium value of minority carrier (electron) concentration in base region}
\]

\[
v_{BE} = \text{voltage applied across base-emitter junction}
\]

\[
V_T = \text{thermal voltage (constant)}
\]

\[
\text{(eq4.1) } n_p(0) = n_{p0} e^{v_{BE} / V_T}
\]
Current Flow

• Tapered minority-carrier concentration profile exists

• It causes electrons injected into base to diffuse through base toward collector

• As such, electron diffusion current \((I_n)\) exists.

\[
A_E = \text{cross-sectional area of the base-emitter junction}
\]
\[
q = \text{magnitude of the electron charge}
\]
\[
D_n = \text{electron diffusivity in base}
\]
\[
W = \text{width of base}
\]

\[
(eq 4.2) \quad I_n = A_E q D_n \frac{dn_p (x)}{dx}
\]

\[
(eq 4.2) \quad I_n = A_E q D_n \left( - \frac{dn_p (0)}{W} \right)
\]

This simplification may be made if gradient assumed to be straight line.
Current Flow

• Some “diffusing” electrons will combine with holes (majority carriers in base)

• Since base is very thin and lightly doped, recombination is minimal

• Recombination does, however, cause gradient to take slightly curved shape
  • The straight line is assumed
Recombination causes actual gradient to be curved, not straight.

\[ n_p(0) = n_{p0} e^{v_{BE} / V_T} \]  

Figure 4.4: Profiles of minority-carrier concentrations in the base and in the emitter of an npn transistor operating in the active mode: \( v_{BE} > 0 \) and \( v_{CB} \geq 0 \).
The Collector Current

- It is observed that most diffusing electrons will reach boundary of collector-base depletion region
- Because collector is more positive than base, these electrons are swept into collector
  - collector current \((i_C)\) is approximately equal to \(I_n\)
  - \(i_C = I_n\)

\[
(i_4.3) \quad i_C = I_s e^{v_{BE}/V_T}
\]

saturation current: \(I_s = \frac{A_E q D_n n_{p0}}{W}\)

\[
(i_4.4) \quad I_s = \frac{A_E q D_n n_i^2}{W N_A}
\]

\(ni= \text{intrinsic carrier density}\)
\(NA= \text{doping concentration of base}\)
The Collector Current

- Magnitude of $i_C$ is independent of $v_{CB}$
  - As long as collector is positive, with respect to base
- **saturation current** ($I_S$) – is inversely proportional to $W$ and directly proportional to area of EBJ
  - Typically between $10^{-12}$ and $10^{-18}$A
  - Also referred to as **scale current**
The Base Current

**base current** \((i_B)\) – composed of two components:

- \(i_{b1}\) – due to holes injected from base region into emitter
- \(i_{b2}\) – due to holes that have to be supplied by external circuit to replace those recombined
The Base Current

• **common-emitter current gain** \((\beta)\) – is influenced by **two** factors:
  • width of base region \((W)\)
  • relative doping of base emitter regions \((N_A/N_D)\)

• High Value of \(\beta\) (50~200, >1000)
  • thin base (small \(W\) in nanometers)
  • lightly doped base / heavily doped emitter (small \(N_A/N_D\))

\[
\beta = \text{transistor parameter}
\]

\[
\text{(eq4.5)}\quad i_B = \frac{i_C}{\beta}
\]

\[
\text{(eq4.6)}\quad i_B = \frac{I_S}{\beta} e^{v_{BE} / V_T}
\]
The Emitter Current

- **All current which enters transistor must leave**
  - \( i_E = i_C + i_B \)

- Equations (4.7) through (4.13) expand upon this idea

- **\( \alpha \): common-base current gain** (less than but very close to unity)

\[
\begin{align*}
\text{this expression is generated through combination of (4.5) and (4.7)} \\
\text{(eq4.8/4.9) } i_E &= \frac{\beta + 1}{\beta} i_C = \frac{\beta + 1}{\beta} \left( I_s e^{v_{BE}/V_T} \right) \\
\text{(eq4.10) } i_C &= \alpha i_E \\
\text{(eq4.11) } \alpha &= \frac{\beta}{\beta + 1} \quad \text{(eq4.13) } \beta = \frac{\alpha}{1 - \alpha} \\
\text{(eq4.12) } i_E &= \frac{I_s}{\alpha} e^{v_{BE}/V_T}
\end{align*}
\]
Recapitulation and Equivalent-Circuit Models

- Previous slides present first-order BJT model.
  - Assumes *npn* transistor in active mode
- Basic relationship is collector current \((i_C)\) is related exponentially to forward-bias voltage \((v_{BE})\)
  - It remains independent of \(v_{CB}\) as long as this junction remains reverse biased
    - \(v_{CB} > 0\)
    - \(i_B\) is much smaller than \(i_C\)
- Nonlinear voltage-controlled current source
**Figure 4.5**: Large-signal equivalent-circuit models of the *npn* BJT operating in the forward active mode.