Chapter 17

Transistors and Applications
Objectives

- Describe the basic structure and operation of bipolar junction transistors (BJT)
- Explain the operation of a BJT class A amplifier
- Analyze class B amplifiers
- Analyze a transistor switching circuit
- Describe the basic structure and operation of JFETs and MOSFETs
- Analyze two types of FET amplifier configurations
Bipolar Junction Transistors (BJTs)

- The **bipolar junction transistor** (BJT) is constructed with three doped semiconductor regions separated by two pn junctions.
- Regions are called **emitter**, **base** and **collector**.
Bipolar Junction Transistors (BJTs)

- The term **bipolar** refers to the use of both holes and electrons as charge carriers in the transistor structure.
- In order for the transistor to **operate** properly, the two junctions must have the correct **dc bias voltages**
  - the base-emitter (BE) junction is forward biased
  - the base-collector (BC) junction is reverse biased
DC Operation of Bipolar Junction Transistors (BJTs)

Transistor Currents:
\[ I_E = I_C + I_B \]

alpha (\( \alpha_{DC} \)):
\[ \alpha_{DC} = \frac{I_C}{I_E} \]

beta (\( \beta_{DC} \)):
\[ \beta_{DC} = \frac{I_C}{I_B} \]

\( \beta_{DC} \) typically has a value between 20 and 200
DC Operation of Bipolar Junction Transistors (BJTs)

DC voltages for the biased transistor:

Collector voltage:
\[ V_C = V_{CC} - I_C R_C \]

Base voltage:
\[ V_B = V_E + V_{BE} \]

– for silicon transistors, \( V_{BE} = 0.7 \text{ V} \)
DC Operation of Bipolar Junction Transistors (BJTs)

Example: Determine $I_B$, $I_C$, and $V_C$ in below circuit

$I_B = (1-0.7)/(22 \times 10^3) = 13.6 \, \mu A$

$I_C = \beta_{DC} I_B = (50)(13.6 \times 10^{-6})$

$= 680 \, \mu A$

$V_C = 10 - (680 \times 10^{-6})(1.0 \times 10^3)$

$= 9.32 \, V$
DC Operation of Bipolar Junction Transistors (BJTs)

The two dc bias sources can be replaced by a single dc source.

Input resistance at the base:

\[ R_{\text{IN}} \approx \beta_{\text{DC}} R_E \]

Base voltage:

\[ V_B \approx \left( \frac{R_2}{R_1 + R_2} \right) V_{\text{CC}} \]

Emitter voltage:

\[ V_E = V_B - 0.7V \]
DC Operation of Bipolar Junction Transistors (BJTs)

Example: Determine $V_B$, $V_E$, $V_C$, $V_{CE}$, $I_B$, $I_E$, and $I_C$

\[
V_B \cong \frac{10k\Omega}{32k\Omega}(30V) = 9.38 \text{ V}
\]

\[
V_E = 9.38\text{V} - 0.7\text{V} = 8.68 \text{ V}
\]

\[
I_E = \frac{V_E}{R_E} = \frac{8.68\text{V}}{1k\Omega} = 8.68 \text{ mA}
\]

\[
I_C = I_E - I_B \cong I_E = 8.68 \text{ mA}
\]

\[
I_B = \frac{I_C}{\beta_{DC}} = \frac{8.68\text{mA}}{100} = 86.8 \text{ µA}
\]

\[
V_C = V_{CC} - I_C R_C = 30\text{V} - (8.68\text{mA})(1k\Omega)
\]

\[
= 21.3 \text{ V}
\]

\[
V_{CE} = V_C - V_E = 21.3\text{V} - 8.68\text{V} = 12.6 \text{ V}
\]
BJT Class A Amplifiers

- Generally, **class A amplifiers** are used in low-power applications
- **Collector characteristic curves:**

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![Collector characteristic curves](image_url)

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**Saturation region**

**Active region**

**Breakdown region**

**Cutoff region**

**I_C versus V_CE curve for one value of I_B**

**Family of I_C versus V_CE curves for several values of I_B**

(I_B1 < I_B2 < I_B3, etc.)
BJT Class A Amplifiers

In a class A amplifier, the transistor conducts for the full cycle of the input signal (360°).

The transistor is operated in the active (or linear) region, between saturation and cutoff:
- saturation is when both junctions are forward biased
- the transistor is in cutoff when $I_B = 0$

The load line is drawn on the collector curves between saturation and cutoff.
BJT Class A Amplifiers

- The base current, $I_B$, is established by the base bias.
- The point at which the base current curve intersects the dc load line is the **quiescent** or **Q-point** for the circuit.
BJT Class A Amplifiers

- A common-emitter (CE) amplifier
  - voltage gain, current gain, and power gain are all greater than 1
BJT Class A Amplifiers

A common-collector (CC) amplifier
- voltage gain is approximately 1, but current gain is greater than 1
The third configuration is the **common-base** (CB)
- the base is the grounded (common) terminal
- the input signal is applied to the emitter
- output signal is taken off the collector
- output is in-phase with the input
- voltage gain is greater than 1
- current gain is always less than 1
BJT Class B Amplifiers

When an amplifier is biased such that it operates in the linear region for 180° of the input cycle and is in cutoff for 180°, it is a **class B amplifier**

- Class B amplifier is more efficient than a class A, you can get more output power for a given amount of input power.
BJT Class B Amplifiers

In order to get a linear reproduction of the input waveform, the class B amplifier is configured in a **push-pull** arrangement.
BJT Class B Amplifiers

Illustration of **crossover distortion** in a class B push-pull amplifier:
BJT Class B Amplifiers

The transistors in a class B amplifier must be biased above cutoff to eliminate crossover distortion
The BJT as a Switch

- When used as an electronic switch, a transistor normally is operated alternately in **cutoff** and **saturation**
  - A transistor is in **cutoff** when the base-emitter junction is not forward-biased. $V_{CE}$ is approximately equal to $V_{CC}$
  - When the base-emitter junction is forward-biased and there is enough base current to produce a maximum collector current, the transistor is **saturated**
Field-Effect Transistors (FETs)

The junction field-effect transistor (JFET) is operated with a reverse biased junction to control current in a channel

- the device is identified by the material in the channel, either \textit{n-channel} or \textit{p-channel}
Field-Effect Transistors (FETs)

The channel of JFET is formed between the gate regions – controlling the reverse biasing voltage on the gate-to-source junction controls the channel size and the drain current, $I_D$
Field-Effect Transistors (FETs)

The **metal-oxide semiconductor field-effect transistor (MOSFET)** differs from the JFET in that it has no pn junction; instead, the gate is insulated from the channel by a silicon dioxide (SiO$_2$) layer.
Field-Effect Transistors (FETs)

MOSFETs may be depletion mode (D-MOSFET) or enhancement mode (E-MOSFET)

(D-mode) (Normally ON)
Field-Effect Transistors (FETs)

MOSFETs may be depletion mode (D-MOSFET) or enhancement mode (E-MOSFET)
Field-Effect Transistors (FETs)

**D-MOSFET**
- Channel may be enhanced or restricted by gate voltage

**E-MOSFET**
- Channel is created by gate voltage
FET Amplifiers

- Voltage gain of a FET is determined by the *transconductance* ($g_m$) with units of Siemens (S)
  \[ g_m = \frac{I_d}{V_g} \]
- All FET’s provide extremely high input resistance

(CS Amplifier)  (CD Amplifier)
Cross-sectional View of IC
IC Fabrication Process

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<table>
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| **1** | 晶圓準備  
包括長晶、圓柱化、切片和研磨。 | **4** | 組裝和封裝  
沿切刻線切割晶圓，以分隔每個晶粒。 |
| **2** | 晶圓製造  
包括清洗、加層、圖案化、蝕刻、摻雜。 |   | 晶粒黏著、金屬打線及晶粒封裝。 |
| **3** | 測試/分類  
包括探針、測試、分類晶圓上的每個晶粒。 | **5** | 最後測試  
確定IC通過電性和環境測試。 |

**:單晶矽**  
**:砂棒切片**  
**:切刻線**  
**:單一晶粒**  
**:組織**  
**:封裝**  
**:缺陷晶粒**
Summary

- A bipolar junction transistor (BJT) consists of three regions: emitter, base, and collector.
- The two types of bipolar transistor are the npn and the pnp.
- The term bipolar refers to two types of current: electron current and hole current.
- A field-effect transistor (FET) has three regions: source, drain, and gate.
Summary

A junction field-effect transistor (JFET) is operated with a reverse-biased gate-to-source pn junction.

JFET current between the drain and source is through a channel whose width is controlled by the amount of reverse bias on the gate-source junction.

The two types of JFETs are n-channel and p-channel.

Metal-oxide semiconductor field-effect transistors (MOSFETs) differ from JFETs in that the gate of a MOSFET is insulated from the channel.
Summary

- The D-MOSFET has a physical channel between the drain and the source.
- The E-MOSFET has no physical channel.
- Two main types of BJT amplifier configurations are the common-emitter (CE) and common collector (CC). A third type is the common base (CB).
- Two main types of FET amplifier configurations are common-source (CS) and common-drain (CD).
Summary

- The class A amplifier conducts for the entire 360° of the input cycle and is normally used for low-power applications.
- The class B amplifier conducts for 180° of the input cycle and is normally used for high-power applications.

Diagram:
- npn (bipolar)
- pnp (bipolar)
- n channel (JFET)
- p channel
- n channel (D-MOSFET)
- p channel
- n channel (E-MOSFET)
- p channel