The ideal diode

![Diode circuit symbol](image)

Diode circuit symbol

$i–v$ characteristic

forward bias

reverse bias

Real Diode

$i–v$ characteristic given by

\[ i = I_s \left( e^{v/V_{th}} - 1 \right) \]

where

\[ V_{th} = \frac{kT}{q} = 25 \text{ mV at room temperature} \]

Constant Voltage Drop Model for Diode

![Diode characteristic](image)

Diode characteristic

![Equivalent-circuit](image)

Equivalent-circuit

A typical value of $V_{D0}$ is 0.7 V

Bipolar Junction Transistor (BJT)

![Circuit Symbols](image)

Circuit Symbols

Voltage polarities and current flow in the active mode

(a) npn transistor, (b) pnp transistor.
Summary of BJT Current-Voltage Relationships in the Active Mode

\[ i_C = I_e \left( \frac{v_{RE}}{v_{th}} \right) \text{ (nnp)} \]

\[ i_C = I_e \left( \frac{v_{RE}}{v_{th}} \right) \text{ (pnp)} \]

\[ V_{th} = \frac{kT}{q} = 25 \text{ mV at room temperature} \]

\[ i_E = i_C + i_B \]

\[ i_B = \frac{i_C}{\beta} = \frac{i_E}{\beta + 1} = (1 - \alpha) i_E \]

\[ i_C = \alpha i_E = \beta i_B \]

\[ i_E = \frac{i_C}{\alpha} = (\beta + 1) i_B \]

\[ \alpha = \beta + 1, \quad \beta = \frac{\alpha}{1 - \alpha}, \quad 0 < \alpha < 1 \]

Conditions and Models for the Operation of the BJT in Various Modes

**NPN**

\[ I_B = 0 \quad + \quad V_{RC} < 0.4 \text{ V} \quad - \quad I_C = 0 \]

\[ V_{BE} < 0.5 \text{ V} \quad - \]

\[ I_B > 0 \quad + \quad V_{RC} < 0.4 \text{ V} \quad - \quad I_C = \beta I_B \]

\[ V_{BE} = 0.7 \text{ V} \quad - \]

\[ I_B > 0 \quad + \quad V_{RC} = 0.5 \text{ V} \quad - \quad I_C = \beta I_B \]

\[ V_{BE} = 0.7 \text{ V} \quad - \]

**PNP**

\[ I_B = 0 \quad + \quad V_{LB} < 0.5 \text{ V} \quad - \quad I_C = 0 \]

\[ V_{CE} < 0.3 \text{ V} \quad - \]

\[ I_B > 0 \quad + \quad V_{LB} < 0.5 \text{ V} \quad - \quad I_C = \beta I_B \]

\[ V_{CE} = 0.7 \text{ V} \quad - \]

\[ I_B > 0 \quad + \quad V_{LB} = 0.5 \text{ V} \quad - \quad I_C = \beta I_B \]

\[ V_{CE} = 0.2 \text{ V} \quad - \]

**Cutoff**

EBJ: Reverse Biased
CBJ: Reverse Biased

**Active**

EBJ: Forward Biased
CBJ: Reverse Biased

**Saturation**

EBJ: Forward Biased
CBJ: Forward Biased
Small-signal Parameters and Equivalent Circuit Models

\[ g_m = \frac{I_C}{V_{th}} \]

\[ r_\pi = \frac{\beta}{g_m} \Rightarrow r_\pi > > \frac{1}{g_m} \quad V_{th} = \frac{kT}{q} = 25 \text{ mV at room temperature} \]

\[ r_e = \frac{\alpha}{g_m} \approx \frac{1}{g_m} \]

Two versions of the simplified hybrid-π model for the small-signal operation of the BJT. The equivalent circuit in (a) represents the BJT as a voltage-controlled current source, and that in (b) represents the BJT as a current-controlled current source.

Amplifier Parameters and their Measurement

\[ R_i \]

\[ R_i = \frac{V_i}{i_i} \]

\[ G_m \text{ and } A_i \]

\[ G_m = \frac{i_o}{v_i} \]

\[ A_i = \frac{i_o}{i_i} = \frac{v_o}{v_i} = G_m R_i \]

\[ R_o \]

\[ R_o = \frac{v_o}{i_x} \]

\[ A_v \]

\[ A_v = \frac{v_o}{v_i} = -G_m R_o \]
### BJT Amplifier Configurations

<table>
<thead>
<tr>
<th>Amplifier Type</th>
<th>Transistor Type</th>
<th>$R_i$</th>
<th>$R_o$</th>
<th>$G_m$</th>
<th>$A_v = -G_m R_o$</th>
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<tbody>
<tr>
<td>NPN</td>
<td></td>
<td>$r_e$</td>
<td>$R_C$</td>
<td>$g_m$</td>
<td>$-g_m R_C$</td>
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<td>Common Emitter</td>
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<tr>
<td>Common Base</td>
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<td>$r_e \approx \frac{1}{g_m}$</td>
<td>$R_C$</td>
<td>$-g_m$</td>
<td>$g_m R_C$</td>
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<td>Common Collector</td>
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<tr>
<td>(Emitter Follower)</td>
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<td>$r_e + (\beta + 1) R_L$</td>
<td>$R_L | r_e | = \frac{1}{g_m}$</td>
<td>$-g_m$</td>
<td>$\frac{R_L}{g_m + R_L}$</td>
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</table>
MOSFET (MOS Field Effect Transistor)

Cross-section of an NMOS transistor.

The drain current $i_D$ versus the drain-to-source voltage $V_{DS}$ for an NMOS transistor operated with $V_{GS} > V_T$.

Equations for NMOSFET:

\[
\begin{align*}
    i_D &= \begin{cases} 
    0 & \text{cutoff} \\
    k \frac{W}{L} \left( V_{GS} - V_T \right) & \text{linear, nonsaturation} \\
    \frac{k}{2} \frac{W}{L} \left( V_{GS} - V_T \right)^2 & \text{saturation}
    \end{cases} \\
\end{align*}
\]

Voltage polarities and current flow in the active mode
(a) NMOS transistor, (b) PMOS transistor.

Small-signal equivalent circuit for MOSFET.
# MOSFET Amplifier Configurations

<table>
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<tr>
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<th>R&lt;sub&gt;i&lt;/sub&gt;</th>
<th>R&lt;sub&gt;o&lt;/sub&gt;</th>
<th>G&lt;sub&gt;m&lt;/sub&gt;</th>
<th>A&lt;sub&gt;v&lt;/sub&gt; = -G&lt;sub&gt;m&lt;/sub&gt; R&lt;sub&gt;o&lt;/sub&gt;</th>
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<tr>
<td>Common Drain</td>
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