Bipolar Transistors

Description

This document describes the electrical characteristics of bipolar transistors.
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1. Transistor characteristics

Equivalent parameters of a transistor include the device parameters closely related to its internal operation and the circuit parameters that are represented as a matrix by treating the transistor as a four-terminal network.

Equivalent circuits are also divided into small-signal and large-signal equivalent circuits, depending on the amplitude of signals to be handled. Since there are numerous equivalent circuits, circuit designers should carefully consider the scopes and limitations of their applications. Table 1.1 categorizes equivalent circuits. Chapter 1 focuses on commonly used small-signal equivalent circuits.

### Table 1.1 List of transistor equivalent circuits

<table>
<thead>
<tr>
<th>Transistor equivalent circuits</th>
<th>Device parameters</th>
<th>Circuit parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small-signal equivalent circuits</td>
<td>Early's T-type equivalent circuit (Common-base circuit)</td>
<td>Matrices showing the relationship between the input and output by voltage and current</td>
</tr>
<tr>
<td>(General linear circuits such as amplifiers, oscillators, modulators, and demodulators)</td>
<td>Giacchetto's π-type equivalent circuit (Common-collector and common-emitter circuits)</td>
<td>a-b matrixes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>g-h matrices (low frequency)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>y-z matrices (high frequency)</td>
</tr>
<tr>
<td>Large-signal equivalent circuits - device parameters</td>
<td>Matrices showing the relationship between the input and output by power</td>
<td>Ebers-Moll current control model</td>
</tr>
<tr>
<td>(Nonlinear circuits such as pulse, digital, and switching circuits)</td>
<td>s matrices (ultra-high frequency)</td>
<td>Beaufoy-Sparkes charge control model</td>
</tr>
<tr>
<td></td>
<td>(transmittance coefficient and reflection coefficient indications)</td>
<td>Linvil density control model</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other nonlinear models</td>
</tr>
</tbody>
</table>
1.1. Device parameters

(1) Early’s T-type equivalent circuit

Figure 1.1 shows Early’s T-type equivalent circuit.

![Figure 1.1 Early’s T-type equivalent circuit](image)

(a) $r_e$: Emitter resistance

$r_e$ is the forward-bias resistance across the base-emitter junction, which is calculated as:

$$ r_e = \frac{k T}{q I_E} \text{ (Ω)} \quad (1-1) $$

$k$: Boltzmann constant (1.38×10^{-23} J/K)

$T$: Absolute temperature (K)

$q$: Elementary charge (1.602×10^{-19} C)

$I_E$: Emitter current (A)

At room temperature (300 K), Equation 1-1 is restated as follows when the emitter current is given in mA:

$$ r_e \approx \frac{26}{I_E \text{ (mA)}} \text{ (Ω)} \quad (3-2) $$
(b) \( C_e \): Emitter capacitance (\( C_{Te} + C_{De} \))

The emitter capacitance is the sum of the depletion capacitance \( C_{Te} \) and the diffusion capacitance \( C_{De} \) in the base-emitter junction. The depletion layer capacitance in the base-emitter junction can be ignored since it is far smaller than the diffusion capacitance. The depletion layer capacitance \( C_{Te} \) and the diffusion capacitance \( C_{De} \) can be calculated using Equation 1-3 and Equation 1-4 respectively:

\[
C_{Te} = A_e \sqrt{\frac{1}{2} \varepsilon \frac{q}{\phi_0 - V_{b'e}}} \quad (F) \quad (1-3)
\]

\( A_e \): Emitter junction area \((m^2)\)
\( \varepsilon \): Dielectric constant
\( nN \): Majority carrier density \((m^{-3})\) on the side with higher specific resistance
(\( NPN \) in this case)
\( \phi_0 \): Contact potential difference (potential barrier in thermodynamic equilibrium) \((V)\)
\( V_{b'e} \): Voltage applied across the base-emitter junction \((V)\)

\[
C_{De} = \frac{q I_E W^2}{2 k T D} \quad (F) \quad (1-4)
\]

\( W \): Base width \((m)\)
\( D \): Diffusion coefficient of minority carriers in the base layer \((m^2/s)\)

(c) \( \mu \): Voltage feedback ratio (Early constant)

This constant due to the Early effect is a base-width modulation parameter.

\[
\mu = \frac{k T d_C}{3 q W (\phi_0 - V_{b'e})} \quad (F) \quad (1-5)
\]

\( d_C \): Width of the collector depletion layer \((m)\)

(d) \( r_c \): Collector resistance

This is a base-width modulation parameter, which is represented as:

\[
 r_c = \frac{1}{I_E \left( \frac{\partial \alpha}{\partial V_{b'C}} \right)} \quad (\Omega) \quad (1-6)
\]

\( r_c \) is typically 1 to 2 M\( \Omega \).
(e) \( C_c \): Collector capacitance

As is the case with the emitter capacitance, the collector capacitance is the sum of the depletion layer capacitance \( C_{TC} \) and the diffusion capacitance \( C_{DC} \) in the collector-base junction.

The diffusion capacitance in the collector-base junction can be ignored since it is far smaller than the depletion layer capacitance. The depletion layer capacitance can be calculated as:

\[
C_{TC} = A_C \left( \frac{\epsilon^2 q a}{\phi_0 - V_{b'c}} \right)^{3/2} \quad (F)
\]

\( A_C \): Collector junction area (m\(^3\))

\( a \): Dopant concentration gradient (m\(^{-4}\))

\( V_{b'c} \): Voltage applied across the base-collector junction (V)

\( C_{TC} \) is typically 1 to 10 pF.

(f) \( \alpha \): DC current gain

This is the only parameter of Early’s T-type equivalent circuit that exhibits frequency dependence and can be calculated as:

\[
\alpha = \frac{\alpha_0}{1 + j \omega C_e r_c}
\]

\[
f_{\alpha} = \frac{1}{2 \pi C_e r_c}
\]

Hence:

\[
\alpha = \frac{\alpha_0}{1 + j \frac{f}{f_{\alpha}}}
\]

\( \alpha_0 \): Value of \( \alpha \) at low frequency

\( f_{\alpha} \): \( \alpha \) cut-off frequency (frequency at which \( \alpha \) drops by 3 dB)
Figure 1.2 shows the frequency locus of $\alpha$. The measurement of $\alpha$ reveals that the difference between theoretical and measured values increases as the frequency approaches $f_\alpha$. This is because Early’s T-type equivalent circuit is based on primary approximation of physical phenomena.

To correct this error, Thomas-Moll included the excess phase parameter $m$ in the equation:

$$\alpha = \frac{\alpha_0}{1 + j \frac{f}{f_\alpha}} e^{-j m f} \quad \text{......................................................... (1-9)}$$

This equation matches well with measured values at frequencies lower than $f_\alpha$.

**Figure 1.2 Frequency locus of $\alpha$**

(g) $r_{bb'}$: Base spreading resistance

This is the resistance from the center of the base layer to the external base terminal that contributes to the operation of a transistor and is determined by the shape and dimensions of the transistor and the specific resistance of the base layer. The comb-shaped base spreading resistance can be calculated as follows.

$$r_{bb'} \approx \frac{1}{12} \frac{\rho_B}{W} \frac{L}{Z} \quad \text{......................................................... (1-10)}$$

$\rho_B$ Specific resistance of the base layer (Ω·m)
In a common-emitter configuration, the DC current gain ($\beta$) of a transistor is represented as follows using $\pi$-type equivalent circuit:

$$\beta = \frac{\alpha_0}{1 - \alpha_0} \left( \frac{1}{1 + j \omega C_{b'e} r_{b'e}} \right) = \frac{\beta_0}{1 + j \omega C_{b'e} r_{b'e}}$$

As is the case with $f_\alpha$, let’s define the $\beta$ cut-off frequency $f_\beta$ as the frequency at which the absolute value of $\beta$ equals $\beta_0/\sqrt{2}$. Then, $f_\beta$ is calculated as:

$$f_\beta = \frac{1}{2 \pi C_{b'e} r_{b'e}}$$

$$\beta = \frac{1}{1 + j \frac{f}{f_\beta}}$$

(1-11)

(2) $\pi$-type equivalent circuit

Figure 1.3 shows the $\pi$-type equivalent circuit, which is essentially the same as the T-type equivalent circuit described above. The $\pi$-type equivalent circuit differs from the T-type equivalent circuit only in that, in principle, the parameters of the former have no frequency response.

Since the physical meaning of each parameter is easy to understand, the $\pi$-type equivalent circuit is widely used. To use it for circuit calculation, it is convenient to simplify the basic configuration shown in Figure 1.3, considering the frequency range.

Table 1.2 shows the relationships of the parameters of the T-type and the $\pi$-type equivalent circuits.
### Table 1.2 Relationships between the parameters of the T-type and the π-type equivalent circuits

<table>
<thead>
<tr>
<th>T-type equivalent circuit</th>
<th>π-type equivalent circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_e$</td>
<td>$C_{b'e}$</td>
</tr>
<tr>
<td>$r_e$</td>
<td>$r_{b'e}$</td>
</tr>
<tr>
<td>$\frac{1}{1 - a_0}$</td>
<td></td>
</tr>
<tr>
<td>$C_c$</td>
<td>$C_{b'c}$</td>
</tr>
<tr>
<td>$\frac{1}{r_e} \frac{\mu (1 - a_0)}{r_e}$</td>
<td>$\frac{1}{r_{b'c}}$</td>
</tr>
<tr>
<td>$\frac{r_e}{\mu}$</td>
<td>$r_{ce}$</td>
</tr>
<tr>
<td>$\frac{a_0}{r_e}$</td>
<td>$g_m$</td>
</tr>
<tr>
<td>$r_{bb'}$</td>
<td>$r_{bb'}$</td>
</tr>
</tbody>
</table>
1.2. Circuit parameters

(1) Matrices showing the relationships between the input and the output by voltage and current

This method regards a transistor as a four-terminal circuit network to describe it only with the electrical characteristics of its terminals irrespective of the physical characteristics of the transistor.

There are six types of matrices (a, b, g, h, y and z) that represent the relationships among the input and output voltages and currents. Of the six types, the h and y matrices are used relatively frequently.

Figure 1.4 and Figure 1.5 show the definitions of the h and y matrices. The suffixes e and b following the letters i, r, f, and o distinguish between the common-emitter and common-base configurations.

\[
\begin{bmatrix}
V_1 \\
I_2
\end{bmatrix} =
\begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
V_2
\end{bmatrix} =
\begin{bmatrix}
h_i & h_r \\
h_r & h_o
\end{bmatrix}
\begin{bmatrix}
I_1 \\
V_2
\end{bmatrix}
\]

**Figure 1.4 Circuit network using the h matrix**

\[
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix} =
\begin{bmatrix}
y_{11} & y_{12} \\
y_{21} & y_{22}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} =
\begin{bmatrix}
y_i & y_r \\
y_r & y_o
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]

**Figure 1.5 Circuit network using the y matrix**

The parameters in the matrices have the following meanings:

- \(h_i\): Input impedance
- \(y_i\): Input admittance
- \(h_r\): Reverse voltage feedback ratio
- \(y_r\): Reverse transfer admittance
- \(h_f\): Forward current gain
- \(y_f\): Forward transfer admittance
- \(h_o\): Output admittance
- \(y_o\): Output admittance

The h matrices are often used for low-frequency regions whereas the y matrices are commonly used for high-frequency regions.
(2) Matrix showing the relationships between the input and the output by power

The S matrices (scattering matrices) are commonly used to represent the phenomena in microwave circuits such as the reflection and transmission of waves.

As the frequency limits of semiconductor devices increase, the S matrices are sometimes used to describe their circuit parameters.

Figure 1.6 shows the definitions of the S matrix.

\[
\begin{bmatrix}
  b_1 \\
  b_2 \\
\end{bmatrix} = \begin{bmatrix}
  S_{11} & S_{12} \\
  S_{21} & S_{22} \\
\end{bmatrix} \begin{bmatrix}
  a_1 \\
  a_2 \\
\end{bmatrix} = \begin{bmatrix}
  S_i & S_r \\
  S_f & S_o \\
\end{bmatrix} \begin{bmatrix}
  a_1 \\
  a_2 \\
\end{bmatrix}
\]

**Figure 1.6 Circuit network using the S matrix**

Each parameter has the following meaning:

- \( S_{11} \) : Input reflection coefficient
- \( S_{12} \) : Reverse transmission coefficient
- \( S_{21} \) : Forward transmission coefficient
- \( S_{22} \) : Output reflection coefficient

As is the case with the h and y matrices, the suffixes e and b denote the common-emitter and common-base configurations respectively.
### Table 1.3 Interrelation of parameters

<table>
<thead>
<tr>
<th>([h])</th>
<th>([y])</th>
<th>([s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(h_i)</td>
<td>(h_r)</td>
<td>(\frac{1}{y_i} - \frac{y_r}{y_i})</td>
</tr>
<tr>
<td>(h_f)</td>
<td>(h_o)</td>
<td>(\frac{y_f}{y_i} - \frac{y_i y_o - y_f y_i}{y_i})</td>
</tr>
<tr>
<td>(\frac{1}{h_i} - \frac{h_r}{h_i})</td>
<td>(\frac{h_f}{h_i} - \frac{h_o - h_r h_f}{h_i})</td>
<td>(\frac{(1 + y_i)(1 + y_o) + y_f y_i}{(1 + y_i)(1 + y_o) - y_r y_f} - 2y_f)</td>
</tr>
<tr>
<td>(\frac{(h_i - 1)(h_o + 1) - h_r h_f}{(h_i + 1)(h_o + 1) - h_r h_f})</td>
<td>(\frac{2h_r}{(h_i + 1)(h_o + 1) - h_r h_f})</td>
<td>(\frac{(1 + h_i)(1 - h_o) + h_r h_f}{(h_i + 1)(h_o + 1) - h_r h_f})</td>
</tr>
</tbody>
</table>
### Table 1.4 Conversion formulas for h parameters

<table>
<thead>
<tr>
<th>Known h parameters</th>
<th>Common-emitter</th>
<th>Common-collector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Converted h parameters</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Common-base</td>
<td>Common-emitter</td>
</tr>
<tr>
<td>h_{le}  (=) (h_{ib}+\Delta h_{ib}), h_{oe}  (=) (h_{ob}+\Delta h_{ob})</td>
<td>(\frac{h_{ib}}{1+h_{fb}}), (\frac{\Delta h_{ib}}{1+h_{fb}})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-\frac{h_{fb}}{1+h_{fb}}), (\frac{h_{ob}}{1+h_{fb}})</td>
<td>(-\frac{1}{1+h_{fb}}), (\frac{h_{ob}}{1+h_{fb}})</td>
</tr>
<tr>
<td>h_{ie} = h_{le} - h_{re}, h_{oe} = h_{oe} - h_{re}</td>
<td>(\frac{h_{ie}}{1+h_{fe}}), (\frac{\Delta h_{ie}}{1+h_{fe}})</td>
<td>(h_{le}), (1-h_{re})</td>
</tr>
<tr>
<td></td>
<td>(-\frac{h_{fe}}{1+h_{fe}}), (\frac{h_{oe}}{1+h_{fe}})</td>
<td>(-\left(1 + h_{fe}\right)), (h_{oe})</td>
</tr>
<tr>
<td>h_{ic} = h_{ic} - h_{rc}</td>
<td>(\frac{-h_{ic}}{h_{fc}}), (\frac{-\Delta h_{ic}}{h_{fc}}) , (1)</td>
<td>(h_{ic}), (1-h_{rc})</td>
</tr>
<tr>
<td></td>
<td>(-\left(1 + h_{fe}\right)), (\frac{-h_{oc}}{h_{fc}})</td>
<td>(-\left(1 + h_{fc}\right)), (h_{oc})</td>
</tr>
</tbody>
</table>

\(\Delta h_{ie} = h_{le} h_{oe} - h_{re} h_{fe}\), \(\Delta h_{ib} = h_{ib} h_{ob} - h_{rb} h_{fb}\), \(\Delta h_{ic} = h_{ic} h_{oc} - h_{rc} h_{fc}\)
Table 1.5 Conversion formulas for y parameters

<table>
<thead>
<tr>
<th>Known y parameters</th>
<th>Converted y parameters</th>
<th>Common-base</th>
<th>Common-emitter</th>
<th>Common-collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common-emitter</td>
<td>∑y_b</td>
<td>- (y_{rb} + y_{ob})</td>
<td>∑y_b</td>
<td>- (y_{ib} + y_{fb})</td>
</tr>
<tr>
<td></td>
<td>-(y_{fb} + y_{ob})</td>
<td>y_{ob}</td>
<td>-(y_{ib} + y_{rb})</td>
<td>y_{ib}</td>
</tr>
<tr>
<td></td>
<td>∑y_e</td>
<td>-(y_{re} + y_{oe})</td>
<td>y_{ie}</td>
<td>-(y_{ie} + y_{re})</td>
</tr>
<tr>
<td></td>
<td>-(y_{fe} + y_{oe})</td>
<td>y_{oe}</td>
<td>-(y_{ie} + y_{fe})</td>
<td>∑y_e</td>
</tr>
<tr>
<td>Common-collector</td>
<td>y_{oc}</td>
<td>-(y_{fc} + y_{oc})</td>
<td>y_{ic}</td>
<td>-(y_{ic} + y_{rc})</td>
</tr>
<tr>
<td></td>
<td>-(y_{rc} + y_{oc})</td>
<td>∑y_{c}</td>
<td>-(y_{ic} + y_{fc})</td>
<td>∑y_{c}</td>
</tr>
</tbody>
</table>

∑y_e = y_{ie} + y_{re} + y_{fe} + y_{oe}
∑y_b = y_{ib} + y_{rb} + y_{fb} + y_{ob}
∑y_c = y_{ic} + y_{rc} + y_{fc} + y_{oc}

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Table 1.6 h parameters converted using T-type equivalent circuit

<table>
<thead>
<tr>
<th></th>
<th>Common-base</th>
<th>Common-emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_{ib} )</td>
<td>( \frac{r_e + r_{bb}'}{1 + j \frac{f}{f_{T\alpha}}} \left(1 - \alpha_0\right) + j \frac{f}{f_{T\alpha}} )</td>
<td>( h_{ie} )</td>
</tr>
<tr>
<td>( h_{ib} )</td>
<td></td>
<td>( r_{bb}'+ \frac{r_e}{(1 - \alpha_0) + j \frac{f}{f_{T\alpha}}} )</td>
</tr>
<tr>
<td>( h_{rb} )</td>
<td>( j 2 \pi f C_c r_{bb}' )</td>
<td>( h_{re} )</td>
</tr>
<tr>
<td>( h_{rb} )</td>
<td>( \frac{- \alpha_0}{1 + j \frac{f}{f_{T\alpha}}} )</td>
<td>( h_{re} )</td>
</tr>
<tr>
<td>( h_{rb} )</td>
<td>( \frac{- \alpha_0}{1 + j \frac{f}{f_{T\alpha}}} )</td>
<td>( \frac{\alpha_0}{(1 - \alpha_0) + j \frac{f}{f_{T\alpha}}} )</td>
</tr>
<tr>
<td>( h_{ob} )</td>
<td>( j 2 \pi f C_c )</td>
<td>( h_{oe} )</td>
</tr>
<tr>
<td>( h_{ob} )</td>
<td>( \frac{2 \pi f_\alpha C_c \left(1 + j \frac{f}{f_{T\alpha}}\right)}{(1 - \alpha_0) + j \frac{f}{f_{T\alpha}}} )</td>
<td>( 2 \pi f_\alpha C_c \frac{j \frac{f}{f_{T\alpha}}}{(1 - \alpha_0) + j \frac{f}{f_{T\alpha}}} )</td>
</tr>
</tbody>
</table>

Table 1.7 y parameters converted using T-type equivalent circuit

<table>
<thead>
<tr>
<th></th>
<th>Common-base</th>
<th>Common-emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_{ib} )</td>
<td>( \frac{1 + j \frac{f}{f_{T\alpha}}}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( y_{ie} )</td>
</tr>
<tr>
<td>( y_{ib} )</td>
<td>( \frac{1 + j \frac{f}{f_{T\alpha}}}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( \frac{(1 - \alpha_0) + j \frac{f}{f_{T\alpha}}}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
</tr>
<tr>
<td>( y_{rb} )</td>
<td>( - 2 \pi f_\alpha C_c \frac{j \frac{f}{f_{T\alpha}} \left(1 + j \frac{f}{f_{T\alpha}}\right)}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( y_{re} )</td>
</tr>
<tr>
<td>( y_{rb} )</td>
<td>( - 2 \pi f_\alpha C_c \frac{j \frac{f}{f_{T\alpha}} \left(1 + j \frac{f}{f_{T\alpha}}\right)}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( - 2 \pi f_\alpha C_c \frac{r_e}{r_{bb}'} + j \frac{f}{f_{T\alpha}} )</td>
</tr>
<tr>
<td>( y_{rb} )</td>
<td>( - \frac{\alpha_0}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( y_{re} )</td>
</tr>
<tr>
<td>( y_{rb} )</td>
<td>( - \frac{\alpha_0}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( \frac{\alpha_0}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
</tr>
<tr>
<td>( y_{ob} )</td>
<td>( 2 \pi f_\alpha C_c \frac{j \frac{f}{f_{T\alpha}} \left(1 + r_e \frac{r_e}{r_{bb}'} + j \frac{f}{f_{T\alpha}}\right)}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( y_{oe} )</td>
</tr>
<tr>
<td>( y_{ob} )</td>
<td>( 2 \pi f_\alpha C_c \frac{j \frac{f}{f_{T\alpha}} \left(1 + r_e \frac{r_e}{r_{bb}'} + j \frac{f}{f_{T\alpha}}\right)}{r_e + j r_{bb}' \frac{f}{f_{T\alpha}}} )</td>
<td>( Same as for y_{ob} )</td>
</tr>
</tbody>
</table>
Bipolar Transistors
Application Note

<table>
<thead>
<tr>
<th>(1) Common-base</th>
<th>(1) Common-base</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>(a)</td>
</tr>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
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<td>(b)</td>
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<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
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<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
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<td>(d)</td>
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<tr>
<td><img src="image7" alt="Diagram" /></td>
<td><img src="image8" alt="Diagram" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>(2) Common-emitter</th>
<th>(2) Common-emitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>(a)</td>
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<tr>
<td><img src="image9" alt="Diagram" /></td>
<td><img src="image10" alt="Diagram" /></td>
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<td>(b)</td>
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<td><img src="image11" alt="Diagram" /></td>
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<td>(c)</td>
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<tr>
<td><img src="image13" alt="Diagram" /></td>
<td><img src="image14" alt="Diagram" /></td>
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<td>(d)</td>
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</tr>
<tr>
<td><img src="image15" alt="Diagram" /></td>
<td><img src="image16" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Solid line: Theoretical curves
Dashed line: Measured curves

**Figure 1.7** Frequency locus of h parameters

**Figure 1.8** Frequency locus of y parameters
See Table 1.3 to Table 1.5 for the relationships among the circuit parameters and the conversion between the common-base and common-emitter parameters. Figure 1.7 and Figure 1.8 show the frequency loci of the h and y parameters obtained from Table 1.6 and Table 1.7 respectively. The parameters described above vary with the operating point and temperature. Circuit designers should understand their effects on the parameters.

1.3. Low-frequency, low-noise amplifiers

(1) Designing low-noise amplifiers

It is necessary to select and use transistors carefully when designing low-noise amplifiers. Voltage, current, and signal source impedance should be considered to ensure that the transistors are used within the ranges that exhibit the best performance of the transistors. To help circuit designers obtain the best performance from low-noise transistors, this section describes the concept of noise characteristics, the optimal conditions of transistors, and the relationships between the noise figures of transistors and the S/N ratios of amplifiers.

(2) Noise characteristics of transistors

The noise figure (NF) of a transistor is given by:

\[
NF = 10 \log \left( \frac{E_{si}}{E_{ni}} / \frac{E_{so}}{E_{no}} \right)^2
= 20 \log \left( \frac{E_{si}}{\sqrt{4kT R_g B}} / \frac{E_{so}}{E_{no}} \right)
\] ............................ (1-12)

\[E_{si}: \text{Input signal voltage}\]
\[E_{ni}: \text{Input noise voltage}\]
\[E_{so}: \text{Output signal voltage}\]
\[E_{no}: \text{Output noise voltage}\]
\[k: \text{Boltzmann constant (1.38×10^{-23} J/°K)}\]
\[T: \text{Absolute temperature (K)}\]
\[R_g: \text{Signal source resistance}\]
\[B: \text{Noise bandwidth (Hz)}\]

or \[E_{ni} = \sqrt{4kT R_g B}\]
Figure 1.9 shows the NF-vs-frequency curve, which is divided into three regions: 1) 1/f region, 2) white noise region, and 3) $f^2$ noise region.

![Noise figure, NF (dB)](image)

**Figure 1.9 Relationship between NF and frequency**

<table>
<thead>
<tr>
<th>Item</th>
<th>1/f noise region</th>
<th>White noise region</th>
<th>$f^2$ noise region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Noise decreases at -3 dB/oct in proportion to frequency f.</td>
<td>Noise remains constant over a range of frequency.</td>
<td>Noise increases at 6 dB/oct in proportion to frequency f.</td>
</tr>
<tr>
<td>Cause</td>
<td>Surface fluctuation</td>
<td>Thermal noise caused by the base spreading resistance $r_{bb'}$.</td>
<td>Fluctuation caused by current separation</td>
</tr>
<tr>
<td>Audio applications</td>
<td>Noise generated</td>
<td>Noise generated</td>
<td>Not noise generated</td>
</tr>
</tbody>
</table>
A transistor can be modeled with a voltage noise source \( e_N \) and a current noise source \( i_N \) as shown below.

\[
e_N = \sqrt{4kT R_N B}
\]

\[
i_N = \sqrt{2qI_b B}
\]

\( R_N \) : Equivalent noise resistance \((\Omega)\)

\( q \) : Elementary charge \( 1.602 \times 10^{-19} \text{ C} \)

**Figure 1.10 Noise source of transistor**

Considering the ideal transistor without any noise source, the noise figure \((\text{NF})\) is given by:

\[
\text{NF} = 10 \log \left( \frac{4kTR_g + e_N^2 + i_N^2 + R_g^2 + 2\gamma e_N i_N}{4kTR_g} \right) \quad (1-13)
\]

\( B \) : 1Hz

\( \gamma \) : Correlation function of \( e_N \) and \( i_N \)

Equation 1-13 shows that \( \text{NF} \) is a function of \( e_N \) and \( i_N \).

It is evident from Equation 1-13 that the noise figure \( \text{NF} \) is dependent on the collector current \( I_C \) and the signal source impedance \( R_g \). Let the total noise voltage be \( e_{NT} \). Then,

\[
\bar{e}_{NT}^2 = 4kTR_g + e_N^2 + i_N^2 + R_g^2 + 2\gamma e_N i_N \quad (1-14)
\]

Figure 1.11 shows the relationship between the total noise voltage and the signal source impedance \( R_g \).

**Figure 1.11 Total noise voltage – Signal source resistance**
Referring to the curve of Device C in Figure 1.11, the noise figure can be seen as a difference (B) between its noise voltage and the thermal noise at $R_g = 100 \, \Omega$.

$$NF = 20 \left( \log \beta - \log \alpha \right) \rightarrow B \text{ in Figure 1.11}$$

As can be seen from Equation 1-14, voltage noise is more dominant in the small $R_g$ region. However, current noise is dominant in the region where $R_g$ increases. $R_g$, $e_{NT}$, and noise figure can be shown by plotting contours of the constant noise figure as shown in Figure 1.12 and Figure 1.13.

**Figure 1.12 NF – $R_g$, $I_C$ (1)**

These noise figure contours can be used to determine the optimal usage condition of an amplifier.

Use the signal source impedance of the amplifier to obtain the collector current $I_C$ at which the noise figure is minimum from the noise figure contours at $f = 1 \, \text{kHz}$ and $f = 10 \, \text{Hz}$.

When designing a low-noise amplifier, it is necessary to consider the conditions of the circuits preceding and following the amplifier. The next subsection describes an amplifier’s noise, considering the foregoing.
(3) Amplifier noise

The signal-to-noise (S/N) ratio is an important factor in designing an amplifier.

\[
S / N = 20 \log \left( \frac{\text{Rate output}}{\text{Output noise voltage}} \right) \quad \text{(dB)} \quad \cdots \quad (1-15)
\]

From Equation 1-12, Equation 1-15 can be restated as follows to include NF.

\[
S / N = 20 \log \left( \frac{E_{so}}{E_{no}} \right)
\]

\[
= 10 \log \left( \frac{E_{so}^2}{E_{no}^2} \right)
\]

\[
= 10 \log \left( \frac{E_{si}^2}{E_{no}^2} \cdot 10^{\frac{NF}{10}} \right)
\]

\[
= 10 \log \left( \frac{E_{si}^2}{4kT R_g B} \right) - NF \quad \text{(dB)} \quad \cdots \quad (1-16)
\]

Amplifier’s S/N ratio (dB) = Input S/N ratio (dB) - Amplifier’s NF (dB)

Noise figure of multi-stage amplifiers

The noise figure of a multi-stage amplifier like the one shown in Figure 1.14 can be calculated as follows:

\[
NF_T = NF_1 + \frac{NF_2 - NF_1}{G_1} + \frac{NF_3 - NF_2}{G_1 G_2} \quad \cdots \quad (1-17)
\]

\[
\begin{align*}
&\text{NF}_1: \text{Noise figure of the first amplifier} \\
&\text{NF}_2: \text{Noise figure of the second amplifier} \\
&\text{NF}_3: \text{Noise figure of the third amplifier} \\
&G_1: \text{Power gain of the first amplifier} \\
&G_2: \text{Power gain of the second amplifier} \\
&G_3: \text{Power gain of the third amplifier}
\end{align*}
\]

Figure 1.14 Noise figure of a multi-stage amplifier
The equivalent noise resistance ($R_N$) of this amplifier is:

$$R_N = R_{N1} + \frac{R_{N2}}{A_1} + \frac{R_{N3}}{(A_1 A_2)^2}$$  \hspace{1cm} (1-18)

**Figure 1.15 Equivalent noise resistance of a multi-stage amplifier**

Equation 1-17 and Equation 1-18 indicate that, if the power gain of the first amplifier ($A_1$) is sufficiently large, the total noise figure $NF_T$ is:

$$NF_T \approx NF_1$$  \hspace{1cm} (1-19)

The total noise figure of the multi-stage amplifier is close to that of the first amplifier.

**Calculating the total noise figure $NF_T$ of a multi-stage amplifier from the nominal NF parameters of transistors**

The NF values in the transistor datasheets are the measurements taken at spot frequencies (such as 1 kHz, 100 Hz, and 10 Hz). These values cannot be used without adjustment to design a wide-bandwidth amplifier with low-frequency boost. Since the $f^2$ noise region lies in the high-frequency region, only the 1/f and white noise regions are related to low-frequency amplification.

Assuming:

$$\left\{\begin{array}{l}
\bar{e}_g^2 : \text{Mean square voltage of the thermal noise generated by signal source resistance } R_g \\
\bar{e}_w^2 : \text{Mean square voltage of white noise} \\
e^{-2}_{1/f} : \text{Mean square voltage of 1/f noise}
\end{array}\right.$$

the following equation is derived from the definition of the noise figure:

$$NF (\text{white noise region}) = \frac{\bar{e}_g^2 + \bar{e}_w^2}{\bar{e}_g^2} = NF_{(1kHz)}$$  \hspace{1cm} (1-21)

$NF(1kHz)$ : NF at the 1-kHz spot frequency
\( \bar{e}_w^2 \) is calculated as follows from Equation 1-21:

\[
\bar{e}_w^2 = (NF_{(1 \text{kHz})} - 1) \bar{e}_g^2 \tag{1-22}
\]

Let the noise figure at 10 Hz be \( NF_{(10 \text{Hz})} \). Then,

\[
NF_{(10 \text{Hz})} = \frac{\bar{e}_g^2 + \bar{e}_w^2 + \bar{e}_{1/f(10 \text{Hz})}^2}{\bar{e}_g^2} \tag{1-23}
\]

From Equation (1-22),

\[
\bar{e}^2_{1/f(10 \text{Hz})} = (NF_{(10 \text{Hz})} - NF_{(1 \text{kHz})}) \bar{e}_g^2 \tag{1-24}
\]

Since the 1/f noise decreases at -3 dB/oct in proportion to frequency, \( \bar{e}^2_{1/f} \) at a normal frequency can be calculated as follows:

\[
\bar{e}^2_{1/f} = (NF_{(10 \text{Hz})} - NF_{(1 \text{kHz})}) \bar{e}_g^2 \frac{10}{f} \tag{1-25}
\]

References

1) WILLIAM A. RHEINFELDER : DESIGN OF LOW NOISE TRANSISTOR INPUT CIRCUITS, LONDON ILIFFE BOOKS LTD. (1964)

2) J. WATSON : SEMICONDUCTOR CIRCUIT DESIGN, ADAM HILGE LTD. (1970)
1.4. Switching characteristics

When a pulse current is applied to the input terminal “IN” of the circuit shown in Figure 1.16, the current waveforms of the base and collector become as shown in Figure 1.17. The switching times of the transistor are defined as the delay times \( t_d \), \( t_r \), \( t_{stg} \), and \( t_f \) of the output waveform relative to the input waveform.

![Switching time test circuit](image1)

![Switching waveforms and the definitions of switching times](image2)

\( t_d \) is a delay time, \( t_r \) is a rise time, \( t_{stg} \) is a storage time, and \( t_f \) is a fall time. These expressions are obtained as follows:

\[
t_r = \tau_R \cdot h_{FE} \ln \left( \frac{h_{FE} \cdot I_{B1}}{h_{FE} \cdot I_{B1} - 0.9 \cdot I_C} \right) \tag{1-25}
\]

\[
t_{stg} = \tau_S \ln \left( \frac{h_{FE} \cdot (I_{B1} - I_{B2})}{I_C - h_{FE} \cdot I_{B2}} \right) \tag{1-26}
\]

\[
t_f = \tau_F \cdot h_{FE} \ln \left( \frac{I_C - h_{FE} \cdot I_{B2}}{0.1 \cdot I_C - h_{FE} \cdot I_{B2}} \right) \tag{1-27}
\]

where,

\[
\tau_R = \tau_F = \frac{1}{2 \pi f_T} + 1.7 \cdot R_L \cdot C_{TC} \tag{1-28}
\]

\[
\tau_S = \frac{0.6}{2 \pi f_b} + \frac{\tau_{NC}}{2} \tag{1-29}
\]
Equation 1-25 shows that \( t_r \) can be reduced by raising \( h_{FE} \) to increase the drive capability of the base drive circuit and by increasing \( f_T \).

Equation 1-27 denotes that \( t_r \) increases when \( h_{FE} \) is increased and decreases when the switching current ratio \( (I_C/I_{B2}) \) is reduced.

Equation 1-26 indicates that the lifetimes of minority carriers in the base and collector layer in relation to the minority carrier recombination process are important factors of \( t_{stg} \). \( h_{FE} \) and \( t_{stg} \) are in proportion to each other. Therefore, advanced technology is required to reduce all of \( t_r \), \( t_r \), and \( t_{stg} \).

Equation 1-25 to Equation 1-27 are functions of \( h_{FE} \). Although it is desirable to reduce \( h_{FE} \) in order to reduce the switching times, \( h_{FE} \) should be high enough to reduce the base drive power. Figure 1.18 shows the dependency of \( h_{FE} \) on the collector current. \( h_{FE} \) has a peak as shown by curve A. The peak of the \( h_{FE} \) curve is often located on the low-current side relative to the operating point shown by the dashed line, with \( h_{FE} \) at the operating point being lower than the peak \( h_{FE} \) value. Regarding the measurement of the switching times at the operating point, the switching times (particularly \( t_{stg} \)) depend on the peak \( h_{FE} \) more strongly than on the \( h_{FE} \) at the operating point. The peak \( h_{FE} \) value can be reduced by making the \( h_{FE} \) curve shallower and moving its peak toward the large-current side as shown by curve B. By doing this, the trade-off between the \( h_{FE} \) and switching times, which was a problem in the above case, is ameliorated. A multi-emitter structure increases the effective area of the emitter and therefore helps flatten the \( h_{FE} \) curve.

Equations 1-28 and 1-29, which are outer logarithmic terms of Equations 1-25 to 1-27, include \( f_T \) and \( f_B \), i.e., parameters that represent frequency responses of a transistor. To increase the breakdown voltage and the safe operating area, it is unavoidable to increase the width and depth of the base at the expense of frequency responses.

Since the transition frequency \( f_T (f_T < f_B) \) is a few megahertz, the first term of Equations 1-28 and 1-29 is considered to be \( 10^{-6} \) to \( 10^{-7} \) seconds. The multi-emitter power transistor improves a frequency response an order of magnitude lower than this.

The second term of Equation 1-28, a time constant determined by the collector capacitance and the load resistance, is normally as small as \( 10^{-7} \) to \( 10^{-8} \) seconds. The second term of Equation 1-29 is of the order of \( 10^{-6} \) seconds. The first and second terms...
were almost equal in conventional transistors. However, the switching characteristics of a transistor can be improved by improving the multi-emitter structure because this helps make the first term negligibly small compared with the second term.

In addition, $\tau_{nc}$ in the second term can be controlled by diffusing heavy metals called “lifetime killers” into the collector layer. The lifetime can be made more controllable by making the first term negligible.

As described above, the switching times of a transistor can be reduced by improving the large-current characteristics of $h_{FE}$ (i.e., the $h_{FE}$ linearity) and the high-frequency response.
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