

Bipolar Transistors Electrical Characteristics

Description

This document describes the electrical characteristics of bipolar transistors.

Table of Contents

Description.....	1
Table of Contents.....	2
1. Transistor characteristics.....	4
1.1. Device parameters	5
1.2. Circuit parameters.....	11
1.3. Low-frequency, low-noise amplifiers.....	18
1.4. Switching characteristics	25
RESTRICTIONS ON PRODUCT USE	28

List of Figures

Figure 1.1 Early's T-type equivalent circuit	5
Figure 1.2 Frequency locus of α	8
Figure 1.3 π -type equivalent circuit	9
Figure 1.4 Circuit network using the h matrix	11
Figure 1.5 Circuit network using the y matrix	11
Figure 1.6 Circuit network using the S matrix	12
Figure 1.7 Frequency locus of h parameters.....	17
Figure 1.8 Frequency locus of y parameters.....	17
Figure 1.9 Relationship between NF and frequency	19
Figure 1.10 Noise source of transistor	20
Figure 1.11 Total noise voltage – Signal source resistance	20
Figure 1.12 NF – R_g , I_c (1)	21
Figure 1.13 NF – R_g , I_c (2)	21
Figure 1.14 Noise figure of a multi-stage amplifier	22
Figure 1.15 Equivalent noise resistance of a multi-stage amplifier.....	23
Figure 1.16 Switching time test circuit.....	25
Figure 1.17 Switching waveforms and the definitions of switching times	25
Figure 1.18 I_c vs. h_{FE}	25

List of Tables

Table 1.1 List of transistor equivalent circuits	4
Table 1.2 Relationships between the parameters of the T-type and the π -type equivalent circuits	10
Table 1.3 Interrelation of parameters.....	13
Table 1.4 Conversion formulas for h parameters	14
Table 1.5 Conversion formulas for y parameters.....	15
Table 1.6 h parameters converted using T-type equivalent circuit	16
Table 1.7 y parameters converted using T-type equivalent circuit	16
Table 1.8 Types of noise.....	19

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

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

1.1. Device parameters

(1) Early's T-type equivalent circuit

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

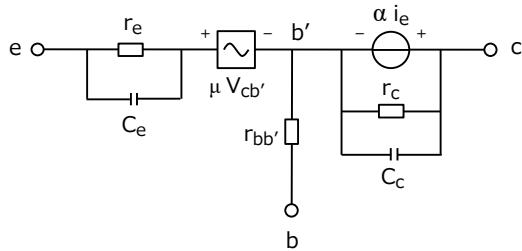


Figure 1.1 Early's T-type equivalent circuit

(a) r_e : Emitter resistance

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

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

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:

$$r_e \approx \frac{26}{I_E \text{ (mA)}} \text{ (} \Omega \text{)} \quad \dots \dots \dots \quad (3-2)$$

(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:

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

A_e : Emitter junction area (m^2)

ϵ : Dielectric constant

nN : Majority carrier density (m^{-3}) on the side with higher specific resistance (NPN in this case)

ϕ_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) μ : 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:

$$C_{TC} = A_C \sqrt[3]{\frac{\epsilon^2 q a}{12 \phi_0 - V_{b'c}}} \quad (F) \quad (1-7)$$

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) α : DC current gain

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

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

$$f_\alpha = \frac{1}{2 \pi C_e r_e}$$

Hence:

$$\alpha = \frac{\alpha_0}{1 + j \frac{f}{f_\alpha}} \quad (1-8)$$

α_0 : Value of α at low frequency

f_α : α cut-off frequency (frequency at which α drops by 3 dB)

Figure 1.2 shows the frequency locus of α . The measurement of α reveals that the difference between theoretical and measured values increases as the frequency approaches f_α . 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:

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

This equation matches well with measured values at frequencies lower than f_α .

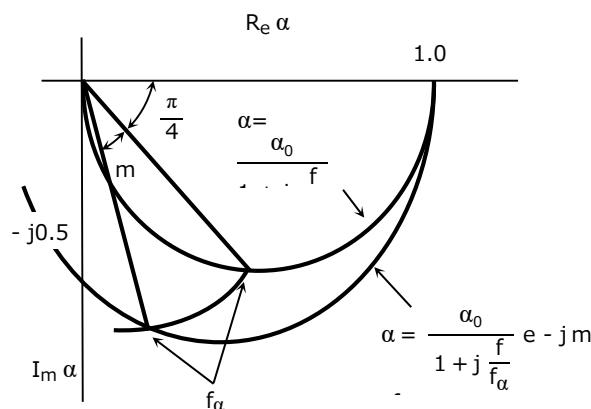
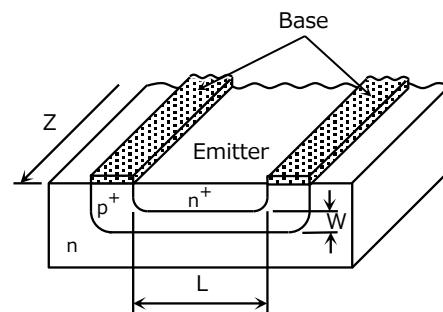


Figure 1.2 Frequency locus of α

(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.



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

ρ_B Specific resistance of the base layer ($\Omega \cdot \text{m}$)

In a common-emitter configuration, the DC current gain (β) of a transistor is represented as follows using π -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_a , let's define the β cut-off frequency f_β as the frequency at which the absolute value of β equals $\beta_0/\sqrt{2}$. Then, f_β is calculated as:

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

$$\beta = \frac{1}{1 + j \frac{f}{f_\beta}} \quad \dots \dots \dots \quad (1-11)$$

(2) π -type equivalent circuit

Figure 1.3 shows the π -type equivalent circuit, which is essentially the same as the T-type equivalent circuit described above. The π -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 π -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 π -type equivalent circuits.

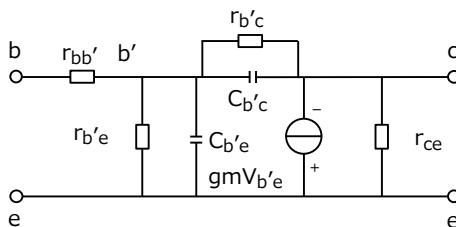


Figure 1.3 π -type equivalent circuit

**Table 1.2 Relationships between the parameters of the
T-type and the π -type equivalent circuits**

T-type equivalent circuit	π -type equivalent circuit
C_e	$C_{b'e}$
$\frac{r_e}{1 - \alpha_0}$	$r_{b'e}$
C_c	$C_{b'c}$
$\frac{1}{r_e} - \frac{\mu(1 - \alpha_0)}{r_e}$	$\frac{1}{r_{b'c}}$
$\frac{r_e}{\mu}$	r_{ce}
$\frac{\alpha_0}{r_e}$	g_m
$r_{bb'}$	$r_{bb'}$

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.

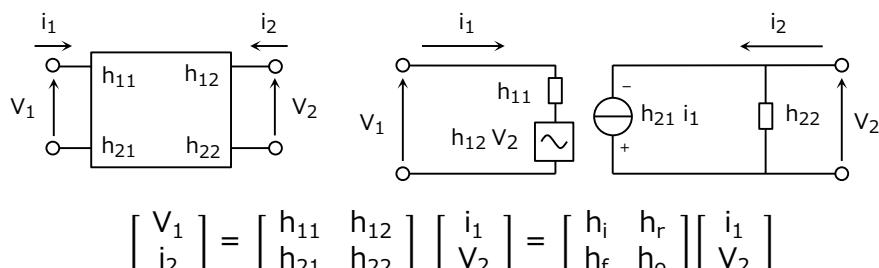


Figure 1.4 Circuit network using the h matrix

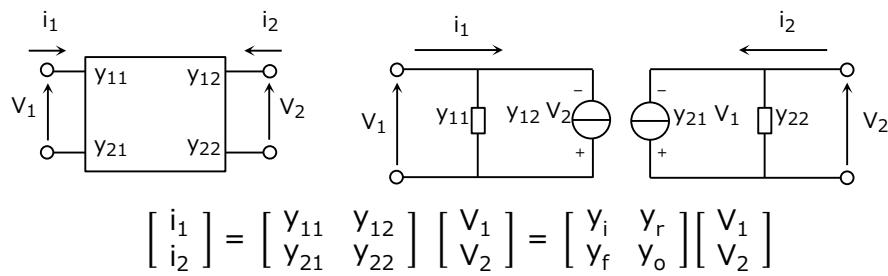


Figure 1.5 Circuit network using the y matrix

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

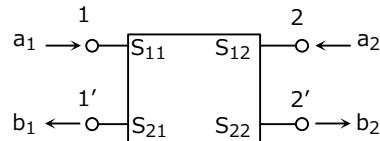
The h matrices are often used for low-frequency regions whereas the y matrices are commonly used for high-frequency regions.

(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

	[h]		[y]		[s]	
[h]	h_i	h_r	$\frac{1}{y_i}$	$-\frac{y_r}{y_i}$	$\frac{(1 + s_i)(1 + s_o) - s_r s_f}{(1 - s_i)(1 + s_o) + s_r s_f}$	$\frac{2s_r}{(1 - s_i)(1 + s_o) + s_r s_f}$
	h_f	h_o	$\frac{y_f}{y_i}$	$\frac{y_i y_o - y_r y_f}{y_i}$	$\frac{(1 - s_i)(1 + s_o) + s_r s_f}{(1 - s_i)(1 - s_o) - s_r s_f}$	$\frac{(1 - s_i)(1 + s_o) + s_r s_f}{(1 - s_i)(1 + s_o) + s_r s_f}$
[y]	$\frac{1}{h_i}$	$-\frac{h_r}{h_i}$	y_i	y_r	$\frac{(1 - s_i)(1 + s_o) + s_r s_f}{(1 + s_i)(1 + s_o) - s_r s_f}$	$\frac{-2s_r}{(1 + s_i)(1 + s_o) - s_r s_f}$
	$\frac{h_f}{h_i}$	$\frac{h_i h_o - h_r h_f}{h_i}$	y_f	y_o	$\frac{(1 + s_i)(1 + s_o) - s_r s_f}{(1 + s_i)(1 - s_o) + s_r s_f}$	$\frac{(1 + s_i)(1 + s_o) - s_r s_f}{(1 + s_i)(1 + s_o) - s_r s_f}$
[s]	$\frac{(h_i - 1)(h_o + 1) - h_r h_f}{(h_i + 1)(h_o + 1) - h_r h_f}$	$\frac{2h_r}{(h_i + 1)(h_o + 1) - h_r h_f}$	$\frac{(1 - y_i)(1 + y_o) + y_r y_f}{(1 + y_i)(1 + y_o) - y_r y_f}$	$\frac{-2y_r}{(1 + y_i)(1 + y_o) - y_r y_f}$	s_i	s_r
	$\frac{-2h_f}{(h_i + 1)(h_o + 1) - h_r h_f}$	$\frac{(1 + h_i)(1 - h_o) + h_r h_f}{(h_i + 1)(h_o + 1) - h_r h_f}$	$\frac{-2y_f}{(1 + y_i)(1 + y_o) - y_r y_f}$	$\frac{(1 + y_i)(1 - y_o) + y_r y_f}{(1 + y_i)(1 + y_o) - y_r y_f}$	s_f	s_o

Table 1.4 Conversion formulas for h parameters

		Converted h parameters		
		Common-base	Common-emitter	Common-collector
Known h parameters	Common-base	$\frac{h_{ib}}{1 + h_{fb}}$ $\frac{-h_{fb}}{1 + h_{fb}}$	$\frac{\Delta h_b - h_{rb}}{1 + h_{fb}}$ $\frac{h_{ob}}{1 + h_{fb}}$	$\frac{h_{ib}}{1 + h_{fb}}$ $\frac{-1}{1 + h_{fb}}$ $\frac{h_{ob}}{1 + h_{fb}}$
	Common-emitter	$\frac{h_{ie}}{1 + h_{fe}}$ $\frac{-h_{fe}}{1 + h_{fe}}$	$\frac{\Delta h_e - h_{re}}{1 + h_{fe}}$ $\frac{h_{oe}}{1 + h_{fe}}$	h_{ie} $- (1 + h_{fe})$
	Common-collector	$\frac{-h_{ic}}{h_{fc}}$ $\frac{-(1 + h_{fc})}{h_{fc}}$	$\frac{-\Delta h_{rc}}{h_{fc}} - 1$ $\frac{-h_{oc}}{h_{fc}}$	h_{ic} $1 - h_{rc}$ h_{oc}

$$\Delta h_e = h_{ie} h_{oe} - h_{re} h_{fe} \quad \Delta h_b = h_{ib} h_{ob} - h_{rb} h_{fb} \quad \Delta h_c = h_{ic} h_{oc} - h_{rc} h_{fc}$$

Table 1.5 Conversion formulas for y parameters

		Converted y parameters		
		Common-base	Common-emitter	Common-collector
Known y parameters	Common-base		$\sum y_b$ $-(y_{rb} + y_{ob})$ $-(y_{fb} + y_{ob})$ y_{ob}	$\sum y_b$ $-(y_{ib} + y_{rb})$ y_{ib}
	Common-emitter	$\sum y_e$ $-(y_{re} + y_{oe})$ $-(y_{fe} + y_{oe})$ y_{oe}		y_{ie} $-(y_{ie} + y_{re})$ $-(y_{ie} + y_{fe})$ $\sum y_e$
	Common-collector	y_{oc} $-(y_{fc} + y_{oc})$ $-(y_{rc} + y_{oc})$ $\sum y_c$	y_{ic} $-(y_{ic} + y_{rc})$ $-(y_{ic} + y_{fc})$ $\sum y_c$	

$$\Sigma y_e = y_{ie} + y_{re} + y_{fe} + y_{oe}$$

$$\Sigma y_b = y_{ib} + y_{rb} + y_{fb} + y_{ob}$$

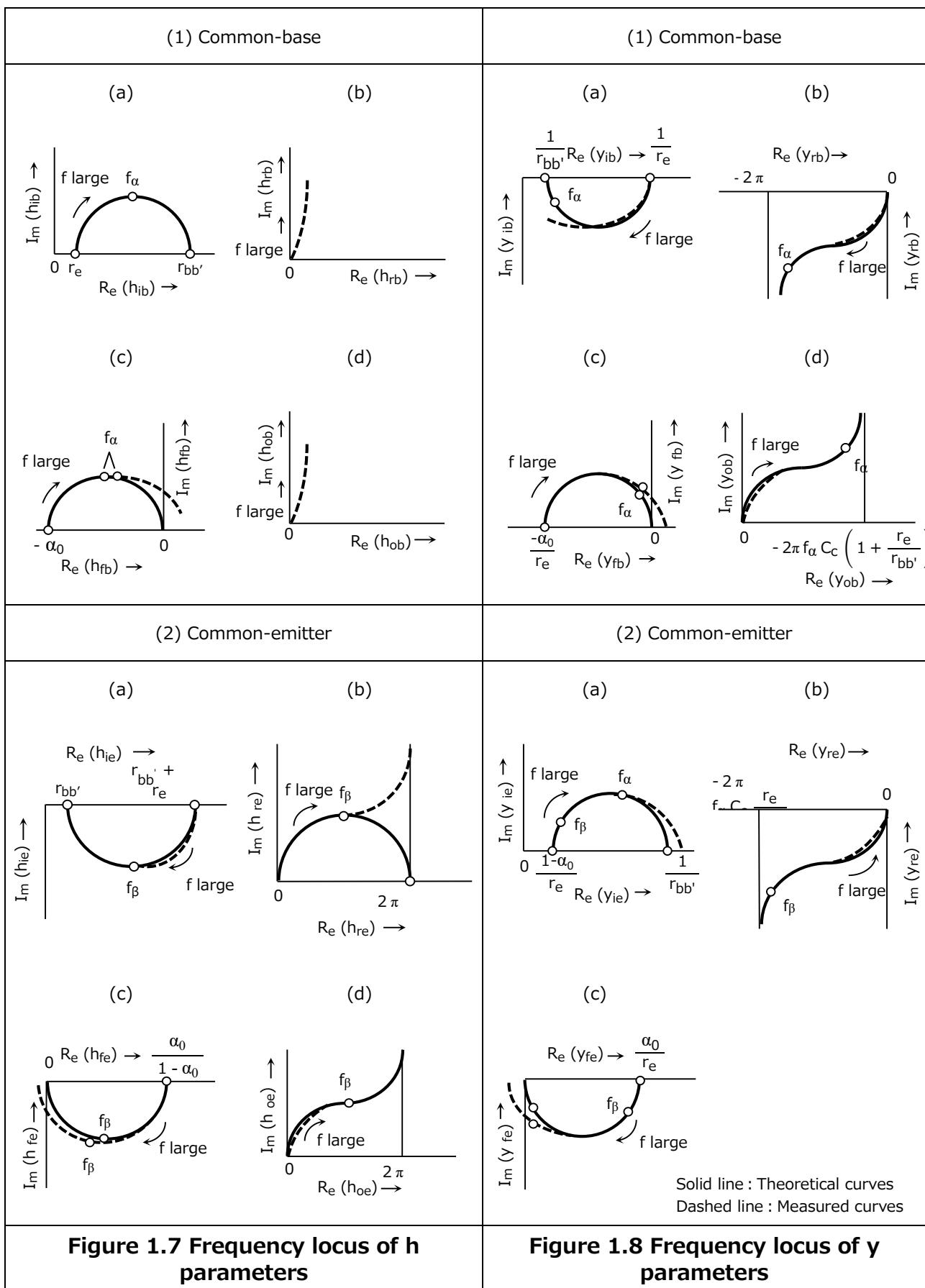
$$\Sigma y_c = y_{ic} + y_{rc} + y_{fc} + y_{oc}$$

Table 1.6 h parameters converted using T-type equivalent circuit

Common-base		Common-emitter	
h_{ib}	$\frac{r_e + r_{bb'} \left[(1 - \alpha_0) + j \frac{f}{f_\alpha} \right]}{1 + j \frac{f}{f_\alpha}}$	h_{ie}	$r_{bb'} + \frac{r_e}{(1 - \alpha_0) + j \frac{f}{f_\alpha}}$
h_{rb}	$j 2 \pi f C_c r_{bb'}$	h_{re}	$2 \pi f_\alpha C_c r_e \frac{j \frac{f}{f_\alpha}}{(1 - \alpha_0) + j \frac{f}{f_\alpha}}$
h_{fb}	$\frac{-\alpha_0}{1 + j \frac{f}{f_\alpha}}$	h_{fe}	$\frac{\alpha_0}{(1 - \alpha_0) + j \frac{f}{f_\alpha}}$
h_{ob}	$j 2 \pi f C_c$	h_{oe}	$2 \pi f_\alpha C_c \frac{j \frac{f}{f_\alpha} \left(1 + j \frac{f}{f_\alpha} \right)}{(1 - \alpha_0) + j \frac{f}{f_\alpha}}$

Table 1.7 y parameters converted using T-type equivalent circuit

Common-base		Common-emitter	
y_{ib}	$\frac{1 + j \frac{f}{f_\alpha}}{r_e + j r_{bb'} \frac{f}{f_\alpha}}$	y_{ie}	$\frac{(1 - \alpha_0) + j \frac{f}{f_\alpha}}{r_e + j r_{bb'} \frac{f}{f_\alpha}}$
y_{rb}	$-2 \pi f_\alpha C_c \frac{j \frac{f}{f_\alpha} \left(1 + j \frac{f}{f_\alpha} \right)}{\frac{r_e}{r_{bb'}} + j \frac{f}{f_\alpha}}$	y_{re}	$-2 \pi f_\alpha C_c \frac{r_e}{r_{bb'}} \frac{j \frac{f}{f_\alpha}}{\frac{r_e}{r_{bb'}} + j \frac{f}{f_\alpha}}$
y_{fb}	$-\frac{\alpha_0}{r_e + j r_{bb'} \frac{f}{f_\alpha}}$	y_{fe}	$\frac{\alpha_0}{r_e + j r_{bb'} \frac{f}{f_\alpha}}$
y_{ob}	$2 \pi f_\alpha C_c \frac{j \frac{f}{f_\alpha} \left(1 + \frac{r_e}{r_{bb'}} + j \frac{f}{f_\alpha} \right)}{\frac{r_e}{r_{bb'}} + j \frac{f}{f_\alpha}}$	y_{oe}	Same as for y_{ob}



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:

$$\begin{aligned} \text{NF} &= 10 \log \left(\frac{E_{si}}{E_{ni}} / \frac{E_{so}}{E_{no}} \right)^2 \\ &= 20 \log \left(\frac{E_{si}}{\sqrt{4 k T R_g B}} / \frac{E_{so}}{E_{no}} \right) \quad \dots \dots \dots \quad (1-12) \end{aligned}$$

E_{si} : Input signal voltage

E_{ni} : Input noise voltage

E_{so} : Output signal voltage

E_{no} : Output noise voltage

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

T : Absolute temperature (K)

R_g : Signal source resistance

B : Noise bandwidth (Hz)

or $E_{ni} = \sqrt{4 k T R_g B}$

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.

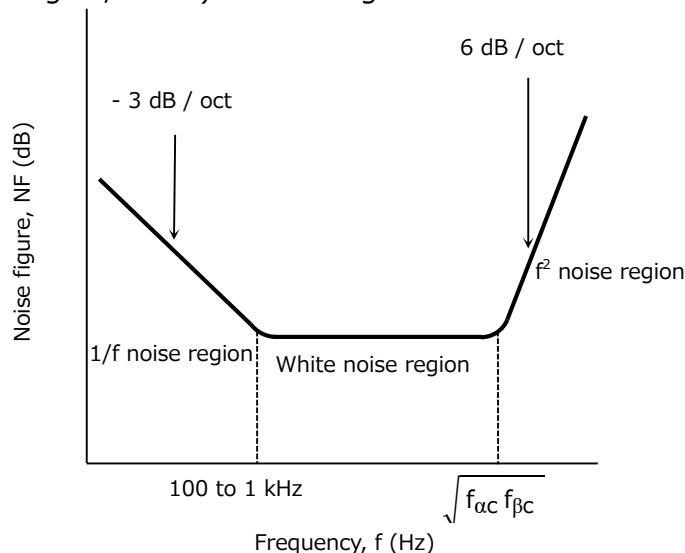


Figure 1.9 Relationship between NF and frequency

Table 1.8 Types of noise

Item \ Type	1/f noise region	White noise region	f^2 noise region
Description	Noise decreases at -3 dB/oct in proportion to frequency f.	Noise remains constant over a range of frequency.	Noise increases at 6 dB/oct in proportion to frequency f.
Cause	Surface fluctuation	Thermal noise caused by the base spreading resistance $r_{bb'}$	Fluctuation caused by current separation
Audio applications	Noise generated	Noise generated	Not noise generated

A transistor can be modeled with a voltage noise source (e_N) and a current noise source (i_N) as shown below.

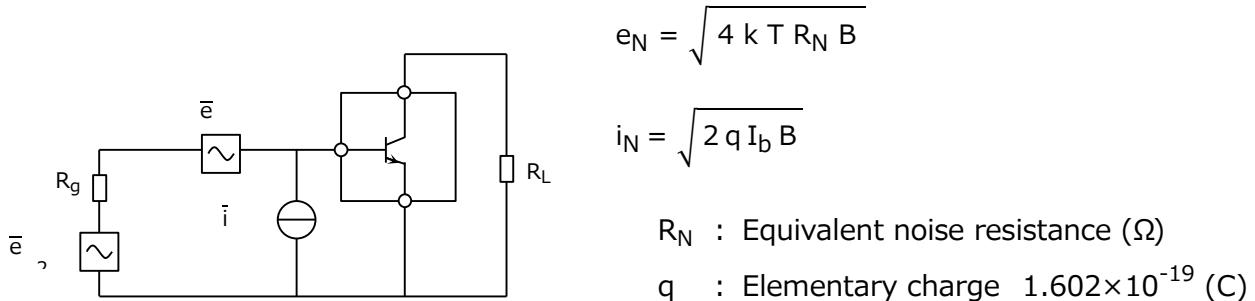


Figure 1.10 Noise source of transistor

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

$$NF = 10 \log \left(\frac{4 k T R_g + e_N^2 + i_N^2 + R_g^2 + 2 \gamma e_N i_N}{4 k T R_g} \right) \dots \dots \dots (1-13)$$

B : 1Hz

γ : Correlation function of e_N and i_N

Equation 1-13 shows that NF is a function of e_N and i_N .

It is evident from Equation 1-13 that the noise figure 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,

$$\bar{e}_{NT}^2 = 4 k T R_g + e_N^2 + i_N^2 R_g^2 + 2 \gamma e_N i_N \dots \dots \dots (1-14)$$

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

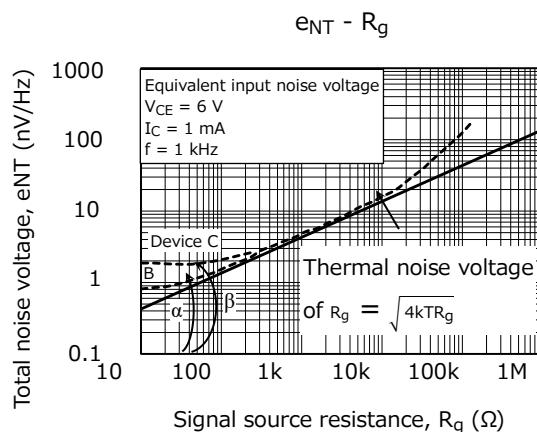


Figure 1.11 Total noise voltage – Signal source resistance

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 $R_g = 100 \Omega$.

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

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.

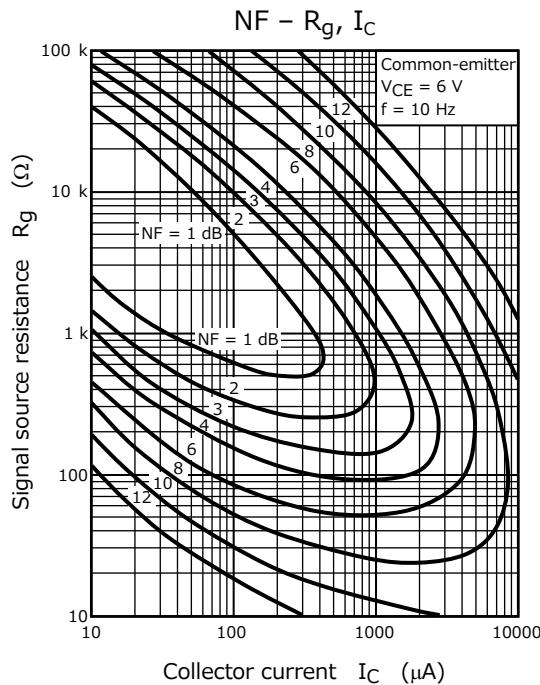


Figure 1.12 NF – R_g , I_C (1)

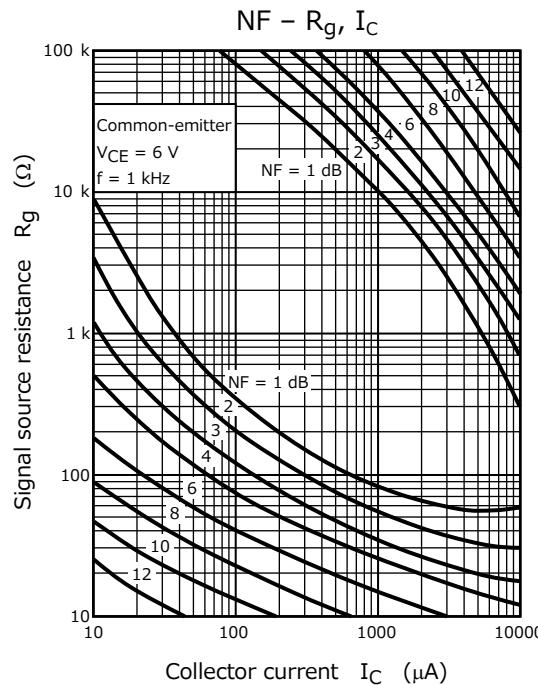


Figure 1.13 NF – R_g , I_C (2)

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 $f = 1$ kHz and $f = 10$ 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.

$$S/N = 20 \log \frac{\text{Rate output}}{\text{Output noise voltage}} \quad (\text{dB}) \quad \dots \dots \dots \quad (1-15)$$

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

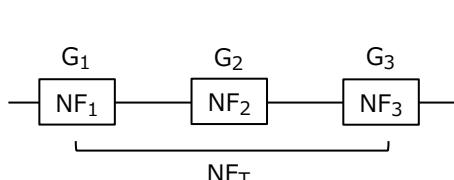
$$\begin{aligned} S/N &= 20 \log \frac{E_{so}}{E_{no}} \\ &= 10 \log \frac{E_{so}^2}{E_{no}^2} \\ &= 10 \log \left(\frac{E_{si}^2}{E_{no}^2} 10^{\frac{NF}{10}} \right) \\ &= 10 \log \frac{E_{si}^2}{4 k T R_g B} - NF \quad (\text{dB}) \quad \dots \dots \dots \quad (1-16) \end{aligned}$$

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

$$NF_T = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} \quad \dots \dots \dots \quad (1-17)$$



NF_T : Total noise figure
 NF_1 : Noise figure of the first amplifier
 NF_2 : Noise figure of the second amplifier
 NF_3 : Noise figure of the third amplifier
 G_1 : Power gain of the first amplifier
 G_2 : Power gain of the second amplifier
 G_3 : Power gain of the third amplifier

Figure 1.14 Noise figure of a multi-stage amplifier

The equivalent noise resistance (R_N) of this amplifier is:

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

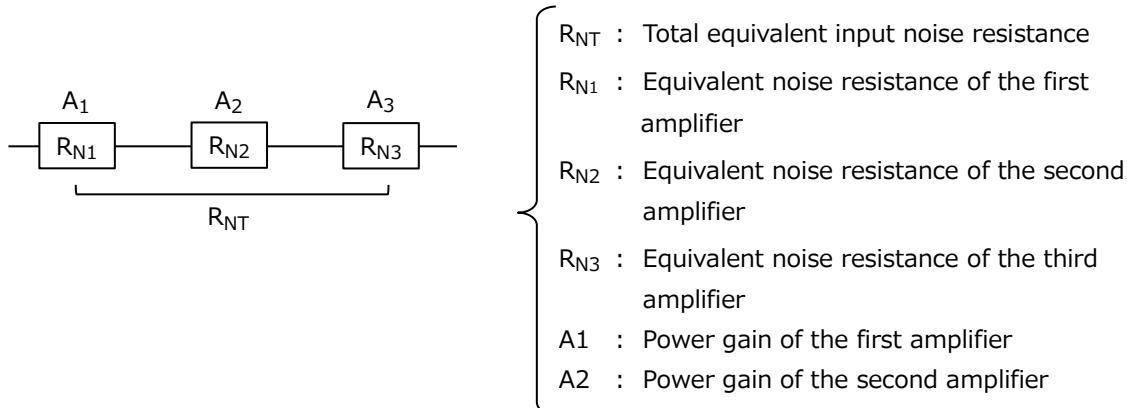


Figure 1.15 Equivalent noise resistance of a multi-stage amplifier

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:

$$NF_T \approx NF_1 \quad \dots \quad (1-19)$$

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:

$$\left. \begin{array}{l} \bar{e}_g^2 : \text{Mean square voltage of the thermal noise} \\ \text{generated by signal source resistance } R_g \\ \bar{e}_w^2 : \text{Mean square voltage of white noise} \\ e^{-2}_{1/f} : \text{Mean square voltage of 1/f noise} \end{array} \right\} \dots \quad (1-20)$$

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

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

$NF(1\text{kHz})$: NF at the 1-kHz spot frequency

\bar{e}_w^2 is calculated as follows from Equation 1-21:

$$\bar{e}_w^2 = (NF_{(1\text{kHz})} - 1) \bar{e}_g^2 \quad \dots \quad (1-22)$$

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

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

From Equation (1-22),

$$\bar{e}_{1/f}^2 = (NF_{(10\text{Hz})} - NF_{(1\text{kHz})}) \bar{e}_g^2 \quad \dots \quad (1-24)$$

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

$$\bar{e}_{1/f}^2 = (NF_{(10\text{Hz})} - NF_{(1\text{kHz})}) \bar{e}_g^2 \frac{10}{f} \quad \dots \quad (1-25)$$

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.

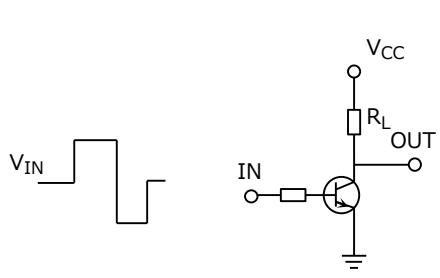


Figure 1.16
Switching time test
circuit

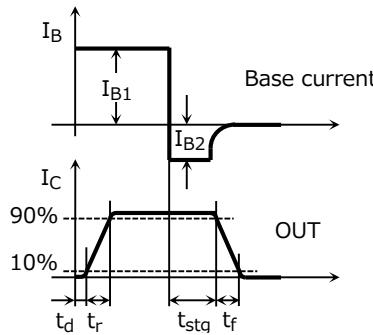


Figure 1.17
Switching waveforms
and the definitions of
switching times

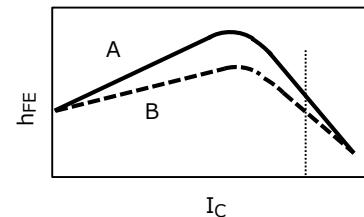


Figure 1.18
 I_C vs. h_{FE}

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:

$$t_r = \tau_R h_{FE} \ln \left(\frac{h_{FE} I_{B1}}{h_{FE} I_{B1} - 0.9 I_C} \right) \quad \dots \quad (1-25)$$

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

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

where,

$$\tau_R \approx \tau_F \approx \frac{1}{2 \pi f_T} + 1.7 R_L C_{TC} \quad \dots \quad (1-28)$$

$$\tau_S = \frac{0.6}{2 \pi f_b} + \frac{\tau_{nc}}{2} \quad \dots \quad (1-29)$$

C_{TC}	: Base-collector capacitance measured at V_{CC}
h_{FE}	: DC current gain at the end of the saturation region
f_T	: Transition frequency
f_b	: Base cut-off frequency
τ_{nc}	: Lifetime of minority carriers in the collector layer

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_f 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_f , 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, τ_{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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