NOTE: The theory in this application note is still applicable, but some of the products referenced may be discontinued.

AN139A

Understanding Transistor Response Parameters

**Prepared by: Roy Hejhall
Applications Engineering**

This note explains high–frequency transistor response parameters and discusses their interdependance. Useful nomograms are given for determining h_{fe}, f_T, $f_{\alpha e}$, f_{max}, and many other parameters.

ABSTRACT

The range of frequencies over which a transistor performs a useful circuit function is limited by inherent parameters. Manufacturers' data sheets often specify only one or two of these parameters, and questions concerning others often arise. Therefore, a clear understanding of these parameters is of value in attempting to answer such questions from the data given.

PARAMETER CHARACTERISTICS AND INTERRELATIONSHIPS

One parameter is h_{fb} (alpha, the common base ac short–circuit forward current gain). As frequency is increased, h_{fb} remains approximately equal to h_{fbo} (the value of h_{fb} at 1 kHz). After the upper frequency is reached, h_{fb} begins to decrease rapidly.

The frequency at which a significant decrease in h_{fb} occurs provides a basis for comparison of the expected high frequency performance of different transistors. The common base current gain cutoff frequency, $f_{\alpha b}$, is defined as that frequency at which h_{fb} is 3 dB below h_{fbo}. Expressed in magnitude, h_{fb} at $f_{\alpha b}$, is 70.7 percent of h_{fbo}. Power gains, current gains, and voltage gains for a few common decibel values are found in Table 1. A curve of h_{fb} versus frequency for a transistor with an $f_{\alpha b}$ of 1 MHz is shown in Figure 1.

This curve has the following significant characteristics: (1) at frequencies below $f_{\alpha b}$, h_{fb} is nearly constant and approximately equal to h_{fbo}, (2) h_{fb} begins to decrease significantly in the region of $f_{\alpha b}$, (3) above $f_{\alpha b}$, the rate of decrease in h_{fb} with increasing frequency approaches 6 dB per octave in the limit.

The curve of common base current gain versus frequency for any transistor has these characteristics, and the same general appearance as the curve of Figure 1.

The common emitter parameter which corresponds to $f_{\alpha b}$, is $f_{\alpha e}$, the common emitter current gain cutoff frequency.

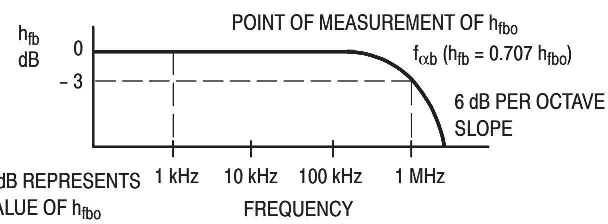

Figure 1. Graph Represents a Curve of a Common Base Current Gain Plotted Against Frequency Variations

* Circuit diagrams are included as a means of illustrating typical semiconductor applications, consequently, complete information sufficient for construction purposes is not necessarily given. The information in this application note has been carefully checked, and is believed to be entirely reliable. However, no responsibility is assumed for inaccuracies. Furthermore, such information does not convey to the purchaser of the semiconductor devices described any license under the patent rights of Motorola Inc. or others.

Reprinted from ELECTRONIC PRODUCTS

REV 0

© Motorola, Inc. 1993

Freescale Semiconductor, Inc.

Freescale Semiconductor, Inc.

GLOSSARY OF SYMBOLS

Symbol	Definition
h_{fb}	Common base ac forward current gain (alpha)
h_{fbo}	Value of h_{fb} at 1 kHz
h_{fe}	Common emitter ac forward current gain (beta)
h_{feo}	Value of h_{fe} at 1 kHz
$f_{\alpha b}$	Common base current gain cutoff frequency. Frequency at which h_{fb} has decreased to a value 3 dB below h_{fbo}. ($h_{fb} = 0.707\ h_{fbo}$)
$f_{\alpha e}$	Common emitter current gain cutoff frequency. Frequency at which h_{fe} has decreased to a value of 3 dB below h_{feo} ($h_{fe} = 0.707\ h_{feo}$)
f_T	Gain bandwidth product. Frequency at which $h_{fe} = 1$ (0 dB)
G_{pe}	Common emitter power gain
f_{max}	Maximum frequency of oscillation. Frequency at which $G_{pe} = 1$ (0 dB)
K_θ	Excess phase shifter factor. Factor which is a function of excess phase shift of current in the base of a transistor.

By definition, $f_{\alpha e}$ is the frequency at which h_{fe} (beta, the common emitter of ac short–circuit current gain), has decreased 3 dB below h_{feo} (the value of h_{fe} at 1 kHz). A typical curve of h_{fe} versus frequency for a transistor with an $f_{\alpha e}$ of 100 kHz is shown in Figure 2.

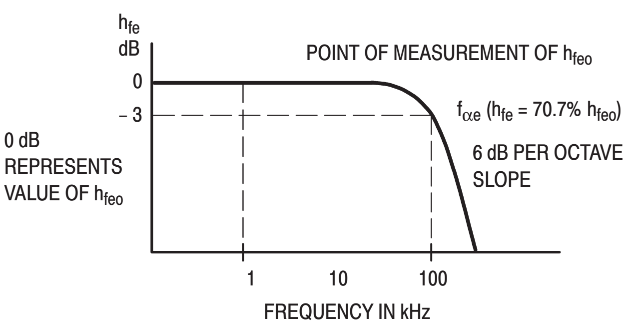

Figure 2. Common Emitter Current Gain is Plotted Against Frequency in the Curve Shown

This curve also has the significant characteristics listed for Figure 1. These characteristics allow such a curve to be constructed for a particular transistor by knowing only h_{feo} and $f_{\alpha e}$. From the curve, h_{fe} at any frequency could be determined. Furthermore, if $f_{\alpha e}$, is not known, a curve could also be constructed if h_{feo} and h_{fe} at any frequency above $f_{\alpha e}$ were known. Thus to determine h_{fe} at any frequency, it is necessary to know only h_{feo} and either $f_{\alpha e}$ or h_{fe} at some frequency f, where f is greater than $f_{\alpha e}$.

Sometimes h_{feo} is needed and only h_{fbo} is given, or vice versa. The quantities h_{fbo} and h_{feo} are related by the following:

$$h_{feo} = \frac{h_{fbo}}{1 - h_{fbo}} \tag{1}$$

$$h_{fbo} = \frac{h_{feo}}{h_{feo} + 1} \tag{2}$$

Equations 1 and 2 are plotted in Figure 3. To further facilitate computations, the low frequency current gain scales of Figures 7–8 contain both an h_{fbo} and an h_{feo} scale, and may be entered with a knowledge of either quantity.

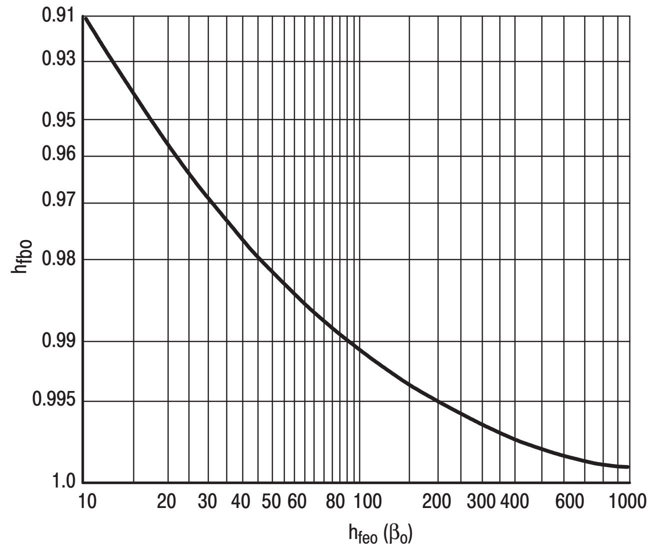

Figure 3. The Relationship Between h_{feo} and h_{fbo} is given by the Graph Shown

RELATIONSHIPS BETWEEN $f_{\alpha e}$ AND $f_{\alpha b}$

Suppose two transistors are considered for a particular application where performance at high frequencies is of interest. The data sheets are compared and it is discovered that one specifies $f_{\alpha b}$ and the other $f_{\alpha e}$. What preliminary comparisons can be made from this without making any laboratory measurements?

Phillips[1] gives a discussion of the relationships between $f_{\alpha e}$ and $f_{\alpha b}$ with the following result:

$$f_{\alpha e} = K_\theta\,(1 - h_{fbo})\,f_{\alpha b} \tag{3}$$

where K_θ is a function of excess phase shift in the base region and has some value between 0.5 and 1.0.

Most transistors have a K_θ in the 0.8 to 1.0 range. Alloy transistors have a K_θ of 0.82.

The nomograms provide solutions for values of K_θ of 0.9 and 0.8. If more specific information on K_θ is not available, a value of 0.8 is recommended.

The quantity $f_{\alpha e}$ is normally a much lower frequency than $f_{\alpha b}$ for the same transistor. For example, consider the Motorola 2N1141 germanium transistor. The data sheets give typical values $f_{\alpha b}$ = 1,000 MHz and h_{fbo} = 0.98. Substituting in Equation 3 yields $f_{\alpha e}$ = 0.80 (1 – 0.98) 1,000 = 16 MHz. This result is in approximate agreement with the h_{fe} versus frequency curve of the manufacturer's 2N1141 data sheet.

For the practical application of Equation 3, refer to Figure 7. When any two of the quantities $f_{\alpha e}$, $f_{\alpha b}$, h_{fbo}, or h_{feo} are known, use the nomograms to find the third quantity.

Freescale Semiconductor, Inc.

For More Information On This Product,
Go to: www.freescale.com

Freescale Semiconductor, Inc.

Table 1. Conversion Table for Power, Voltage, and Current Ratios into Decibels

dB	Power Ratio	Voltage or Current Ratio	dB	Power Ratio	Voltage or Current Ratio
0	1.00	1.00	10	10.0	3.2
0.5	1.12	1.06	15	31.5	5.6
1.0	1.26	1.12	20	100	10
1.5	1.41	1.19	25	316	18
2.0	1.58	1.26	30	1,000	32
3.0	2.00	1.41	40	10,000	100
4.0	2.51	1.58	50	10^5	316
5.0	3.16	1.78	60	10^6	1,000
6.0	3.98	2.00			
7.0	5.01	2.24			
8.0	6.31	2.51			
9.0	7.94	2.82			

A common high–frequency parameter is f_T, the gain bandwidth product and is defined as that frequency at which h_{fe} = 1 (0 dB).

The value f_T is sometimes specified indirectly on high–frequency transistor data sheets. This is done by specifying h_{fe} at some frequency above $f_{\alpha e}$, thus f_T is then obtained by multiplying the magnitude of h_{fe} by the frequency of measurement. This relationship arises from the 6 dB per octave characteristic of the h_{fe} versus frequency curve above $f_{\alpha e}$. Since 6 dB represents a current gain magnitude of 2, h_{fe} is halved each time frequency is doubled, and vice versa. Therefore, the product of h_{fe} and frequency of the sloping portion of the curve yields f_T.

For example, consider the Motorola 2N2218 silicon annular transistor. The data sheet gives a typical h_{fe} of 4.0 at 100 MHz. Multiplication of h_{fe} times the frequency of measurement yields f_T = 4.0 x 100 = 400 MHz. This is in agreement with the data sheet which specifies a typical f_T of 400 MHz.

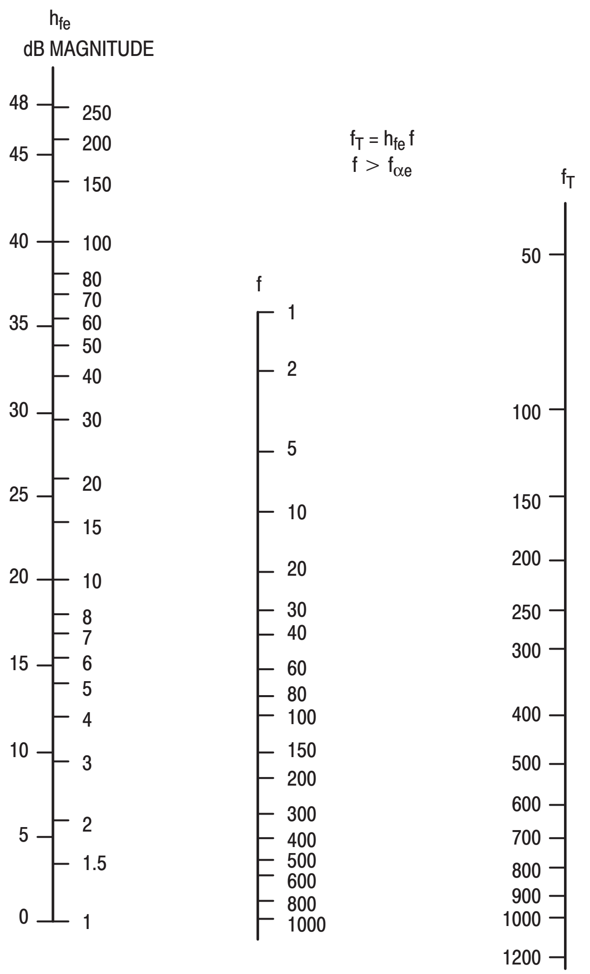

Figure 4. This Nomogram is Useful in Finding h_{fe}, when a Frequency f > $f_{\alpha e}$

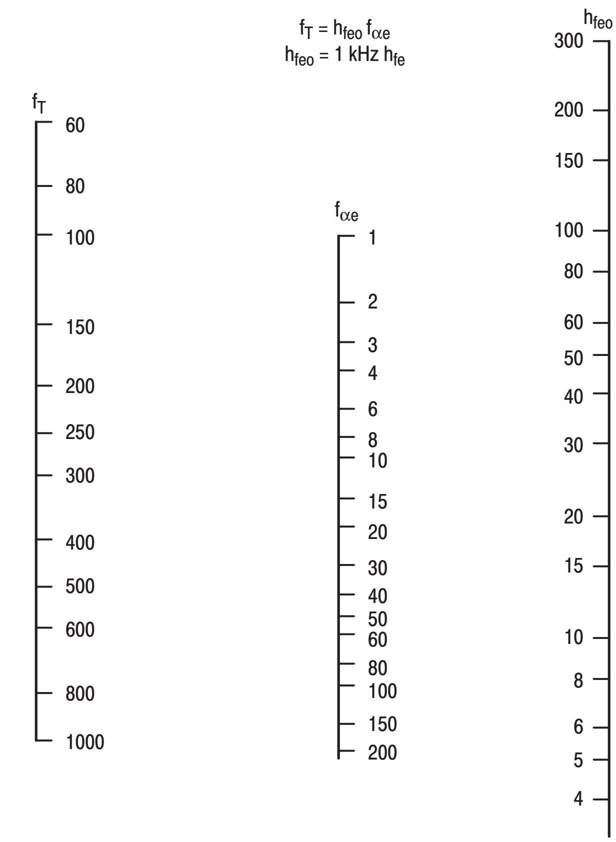

Figure 5. The Quantity f_T is Found from this Nomogram Once $f_{\alpha e}$ and h_{feo} are Known

For More Information On This Product,
Go to: www.freescale.com

Freescale Semiconductor, Inc.

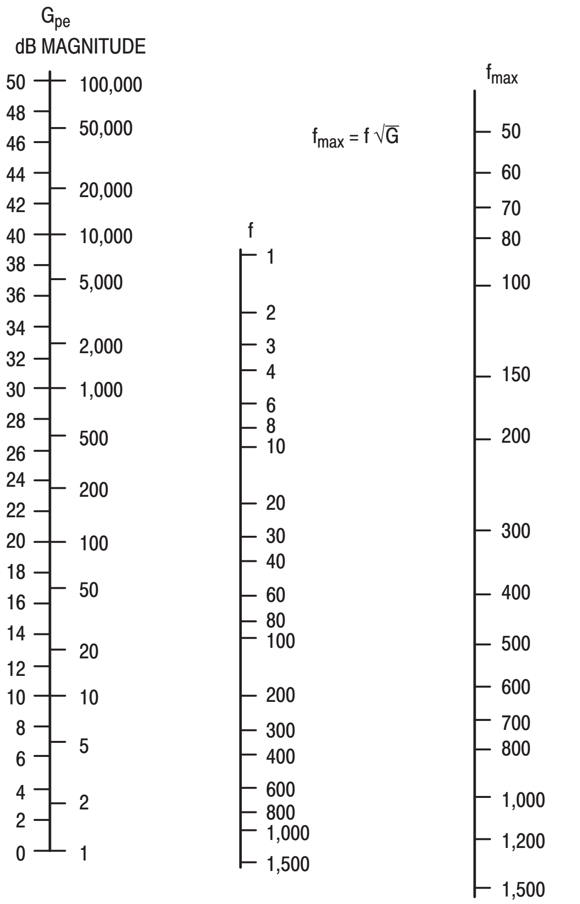

Figure 6. Maximum Frequency is Found from this Nomogram Knowing the Frequency and Power Gain

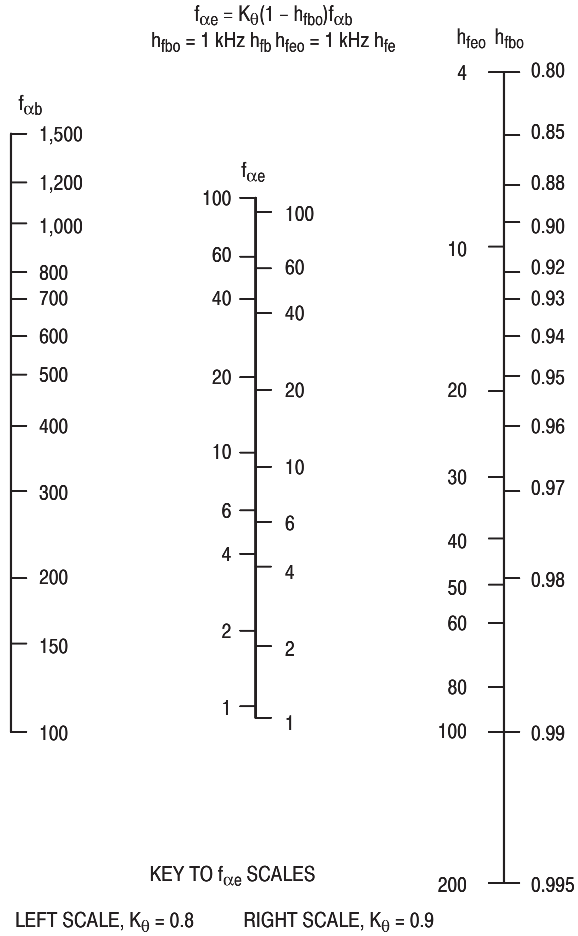

Figure 7. Once $f_{\alpha b}$ is Known this Nomogram is Used to Find $f_{\alpha e}$

The parameter f_T is also equal to the product of h_{feo} and $f_{\alpha e}$, expressed by

$$f_T = h_{feo} \times f_{\alpha e} \quad (4)$$

with h_{feo} known, Equation 4 provides a simple means of finding $f_{\alpha e}$ when f_T is known or vice versa. (See Figure 5.)

Phillips also develops the following relationship between $f_{\alpha b}$ and f_T:

$$f_T = K_\theta\, h_{fbo}\, f_{\alpha b} \quad (5)$$

where K_θ is the same quantity as in Equation 3. Notice that since K_θ lies between 0.5 and 1.0, the f_T of a transistor is approximately equal to or slightly less than its $f_{\alpha b}$. (See Figure 8.)

RULES FOR DETERMINING h_{fe}

The following rules summarize how to determine h_{fe} at some frequency f:

Rule 1: When $f < f_{\alpha e}$, $h_{fe} \approx h_{feo}$

Rule 2: When $f \approx f_{\alpha e}$, $h_{fe} \approx 0.7\ h_{feo}$

Rule 3: When $f > f_{\alpha e}$, consider h_{fe} to be decreasing at 6 dB per octave at frequency f and use Figure 4 to find h_{fe}.

Rule 4: (A) If h_{fbo} not h_{feo} is known, use Figure 3 to find h_{feo}.

(B) If h_{feo} and $f_{\alpha e}$ are known, use Figure 5 to find f_T. Use Figure 8 to find f_T if $f_{\alpha b}$ is known.

(C) If f_T is known, use Figure 5 to find $f_{\alpha e}$. Use Figure 7 to find $f_{\alpha e}$ if $f_{\alpha b}$ is known.

Though common emitter current gain is equal to 1 at f_T, there may still be considerable power gain at f_T due to different input and output impedance levels. Thus, f_T is not necessarily the highest useful frequency of operation of a transistor, and an additional parameter, the maximum frequency of oscillation (f_{max}), is sometimes encountered. The term f_{max} is the frequency at which common emitter power gain is equal to 1, and is related to f_T by

$$f_{max} \approx \sqrt{\frac{f_T}{8\pi\, r'_b C_c}} \quad (6)$$

where r'_b is the base resistance and C_c is the collector capacitance.

A plot of common emitter power gain versus frequency also has the characteristics shown in Figure 1. This leads to another gain bandwidth product

$$f_{max} \approx f\sqrt{\text{Power Gain}} \quad (7)$$

where f is the frequency of measurement and power gain is expressed in magnitude not in decibels. Hence, f_{max} may be found by measuring power gain at some frequency

For More Information On This Product,
Go to: www.freescale.com

on the 6 dB per octave portion of the power gain versus frequency curve, and multiplying the square root of the power gain with the frequency of measurement (see Figure 6). The symbol for common emitter power gain is G_{pe}.

The parameters are voltage and current dependent, and operating point must be considered in all cases. For example, the high–frequency h_{fe} measurement at one collector voltage and current must not be used to calculate f_T directly at another voltage and/or current without considering the added effects of the different operating point.

The parameter $f_{\alpha e}$ for present high frequency transistors usually lies in the region between 100 and 500 MHz. The term h_{fe}, measured at any frequency above this region is assumed on the 6 dB per octave portion of h_{fe} versus frequency curve and is used to calculate f_T directly.

Power gain measured at any frequency above 500 MHz is assumed on the 6 dB per octave portion of the power gain versus frequency curve and is used to calculate f_{max} directly.

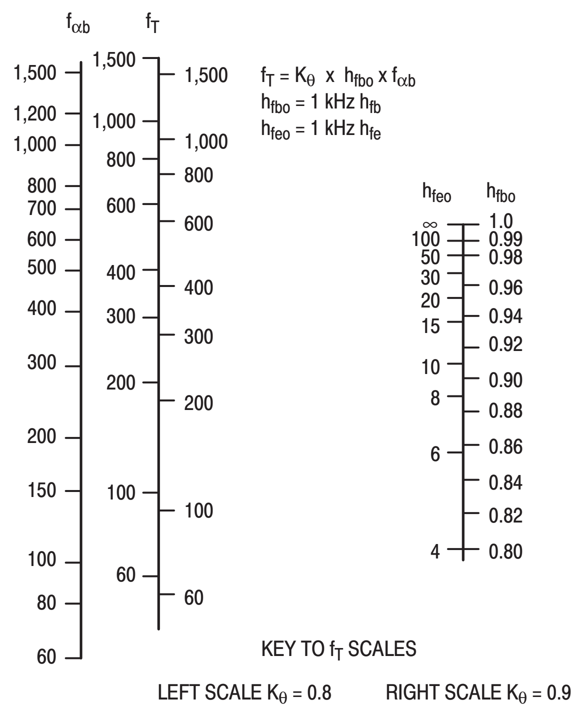

Figure 8. This Nomogram Represents f_T, $f_{\alpha b}$, and Either h_{fbo} or h_{feo}

INSTRUCTIONS FOR CURVES AND NOMOGRAMS

The nomograms assume no shift in operating point. Known parameters used to find an unknown must be measured at the same collector voltage and collector current as the desired unknown.

Frequency scales on the nomograms are calibrated in numbers only without units. Furthermore, all nomograms contain two frequency scales. Decimal points may be shifted on the frequency scales of any nomogram as long as they are shifted the same amount on both scales (i.e., both frequency scales of a nomogram must be multiplied by 10 to the same power). This enables the same nomogram to be used for both high and low–frequency transistors.

The nomograms assume that both power gain and current gain decrease with increasing frequency at a rate of 6 dB per octave at high frequencies.

All power gain and current gain scales (except h_{fbo} and h_{feo}) are calibrated in both actual magnitudes and decibel values for convenience.

EXAMPLE 1

To find h_{feo} when h_{fbo} is known or vice versa, enter Figure 3 with the known value and read the unknown directly. Given: h_{fbo} = 0.96. Find: h_{feo}. Answer = 24.

EXAMPLE 2

Figure 4 is a nomogram of f_T and h_{fe} at some frequency f, where $f > f_{\alpha e}$. Given: h_{fe} at 100 MHz is 6 dB. Find: h_{fe} at 75 MHz. Answer: 4, or 12 dB.

EXAMPLE 3

There are no special instructions for the nomogram of Figure 5, merely use it to find the unknown parameter when any two are known. Given: h_{feo} = 40 and f_T = 400 MHz. Find: $f_{\alpha e}$. Answer: 10 MHz.

EXAMPLE 4

Figure 6 is a nomogram of f_{max} and common emitter power gain measured at some frequency f where power gain is known to be decreasing at 6 dB per octave. Given: power gain at 500 MHz is 6 dB. Find f_{max}. Answer: 800 MHz. Given: f_{max} = 1000 MHz. Find: power gain at 250 MHz. Answer: 12 dB.

EXAMPLE 5

Figure 7 is a nomogram of $f_{\alpha b}$, $f_{\alpha e}$, and either h_{fbo} or h_{feo}. To account for variations in this relationship with different transistor types, there are two $f_{\alpha e}$ scales, one for K_θ = 0.8 and one for K_θ = 0.9. Given: $f_{\alpha e}$ = 1 MHz and h_{fbo} = 0.90. Find: $f_{\alpha e}$. Answer: 80 kHz (assuming K_θ = 0.8).

EXAMPLE 6

Figure 8 is a nomogram of f_T, $f_{\alpha b}$, and either h_{fbo} or h_{feo}. To account for variations in this relationship with different transistor types, there are two f_T scales, one for K_θ = 0.8 and one for K_θ = 0.9. Given: f_T = 400 MHz and h_{fbo} = 0.90. Find: $f_{\alpha b}$. Answer: 555 MHz (assuming K_θ = 0.8).

REFERENCE

1. A. B. Phillips, "Transistor Engineering", McGraw–Hill Book Company, Inc., New York, N.Y., Chapter 14.

Freescale Semiconductor, Inc.

For More Information On This Product,
Go to: www.freescale.com

Freescale Semiconductor, Inc.

NOTES

Freescale Semiconductor, Inc.

For More Information On This Product,
Go to: www.freescale.com

NOTES

Freescale Semiconductor, Inc.

For More Information On This Product,
Go to: www.freescale.com

Freescale Semiconductor, Inc.

Motorola reserves the right to make changes without further notice to any products herein. Motorola makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does Motorola assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation consequential or incidental damages. "Typical" parameters can and do vary in different applications. All operating parameters, including "Typicals" must be validated for each customer application by customer's technical experts. Motorola does not convey any license under its patent rights nor the rights of others. Motorola products are not designed, intended, or authorized for use as components in systems intended for surgical implant into the body, or other applications intended to support or sustain life, or for any other application in which the failure of the Motorola product could create a situation where personal injury or death may occur. Should Buyer purchase or use Motorola products for any such unintended or unauthorized application, Buyer shall indemnify and hold Motorola and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that Motorola was negligent regarding the design or manufacture of the part. Motorola and Ⓜ are registered trademarks of Motorola, Inc. Motorola, Inc. is an Equal Opportunity/Affirmative Action Employer.

Literature Distribution Centers:
USA: Motorola Literature Distribution; P.O. Box 20912; Phoenix, Arizona 85036.
EUROPE: Motorola Ltd.; European Literature Centre; 88 Tanners Drive, Blakelands, Milton Keynes, MK14 5BP, England.
JAPAN: Nippon Motorola Ltd.; 4-32-1, Nishi-Gotanda, Shinagawa-ku, Tokyo 141, Japan.
ASIA PACIFIC: Motorola Semiconductors H.K. Ltd.; Silicon Harbour Center, No. 2 Dai King Street, Tai Po Industrial Estate, Tai Po, N.T., Hong Kong.