Agilent Technologies
Innovating the HP Way

High-Frequency Transistor Primer

Part I

Silicon Bipolar Electrical Characteristics

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Preface

Transistors have been used at frequencies above 1 GHz since about 1960. The technology has increased such that both circuit and project engineers look to transistors for new system requirements at frequencies up to millimeter wave. The purpose of this primer series is to introduce microwave designers to the terminology used in describing the characteristics of high-frequency transistors. An understanding of the capabilities and limitations of these transistors should result in better performing, more reliable circuits.

This volume, Part I, covers general device electrical characteristics for silicon bipolar transistors. Volume II covers general noise and S-parameter characterization. Part III covers device thermal properties and Part IV covers GaAs FET device parameters and measurements.

Introduction

This primer is a short glossary and brief explanation of transistor terms commonly used in Agilent Technologies transistor data sheets, advertisements and other technical communications. Some of these terms are simple, virtually self-explanatory and are included here primarily for the sake of completeness. Others are more specialized and potentially ambiguous due to a lack of terminology standardization in the high-frequency transistor area. These latter types receive more treatment here.

I. Transistor Structure Types

All current Agilent Technologies silicon transistors are of the bipolar NPN planar epitaxial type. Briefly, the significance of each of these terms is as follows:

A. Bipolar

In its broadest sense it is the basic structure shown schematically in Figure 1, i.e., the familiar three semiconductor-region structure. Bipolar specifically means that the charge carriers of both negative (electrons) and positive (holes) polarities are involved in the transistor action. In way of contrast, unipolar types include the junction-gate and insulated-gate field-effect transistors which are basically one- or two-semiconductor-region structures in which carriers of a single polarity dominate.

B. NPN

An abbreviation for *negative-positive-negative* which identifies the regions of the structure as to polarity of the dominant or majority carrier in each region. The other polarity type is PNP. (See Figure 1.)

C. Silicon

Silicon is one of two elements from the fourth column of the periodic table which are in widespread use for transistor fabrication (the other is germanium). Other materials used include the compound gallium arsenide. Silicon is in predominant use because it results in the most favorable compromise among high-frequency, high-temperature, high-reliability and ease of use attributes of the usable semiconductor materials.

D. Planar

A term which denotes that both emitter-base and base-collector junctions of the transistor intersect the device surface in a common plane (hence, a better term might be co-planar). However, the real significance of the so-called planar structure is that the technique of diffusing dopants through an oxide mask, used in fabricating such a structure, results in junctions being formed beneath a protective oxide layer. These protected junctions are less prone to surface problems sometimes associated with other types of structures, such as the mesa.

E. Epitaxial

This term, as it is commonly used, is actually a shortening of the term epitaxial-collector. That is, the collector region of the transistor is formed by the epitaxial technique rather than by diffusion which is commonly used to form the base and emitter regions. The epitaxial layer is formed by condensing a single-crystal film of semiconductor material upon a wafer or substrate which is usually of the same material. Thus, an epitaxial (collector) transistor is one in

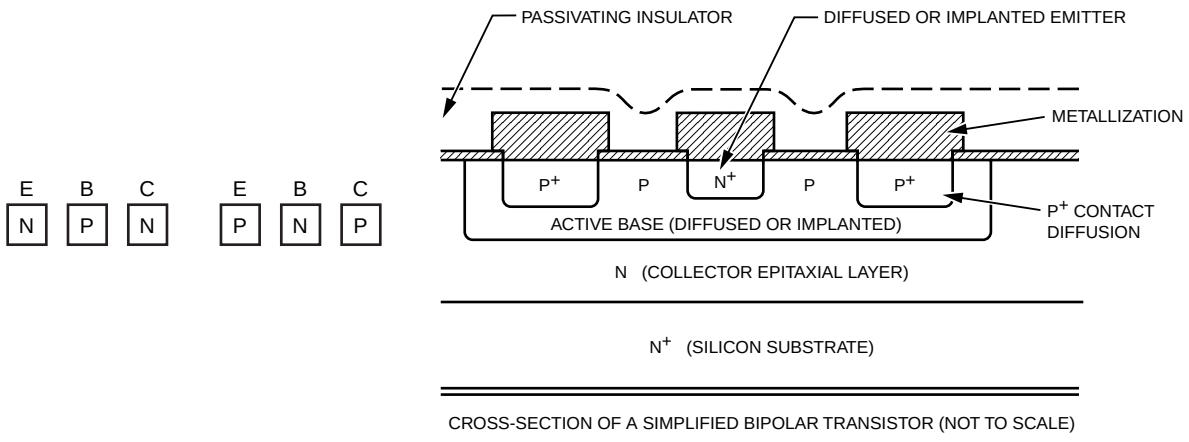

Figure 1. Transistor Structure Schematics

which the collector region is formed upon a low-resistivity silicon substrate. Subsequently, the base and emitter regions are diffused into the "epi" layer. The epitaxial technique lends itself to precise tailoring of collector-region thickness and resistivity with consequent improved device performance and uniformity.

II. Maximum Ratings

Maximum ratings may be defined as limiting values of externally applied stresses (voltage, current, temperature, etc.) normally under control of the user which if exceeded may result in irreversible damage to the device. The user who exceeds the maximum ratings does so necessarily at his own risk. These ratings are set by the manufacturer on the basis of many considerations such as life tests, breakdown voltages, etc., in order to define to the user certain operating conditions which are safe for each and every transistor of a given type.

Unfortunately, due to the cost of establishing certain ratings (which must eventually be reflected in product prices) the ratings given do not always encompass all conceivable operating conditions. For example, device dissipation ratings typically are complete only for the case of continuous dissipation (as opposed to peak dissipation in pulse applications). In practice, the ratings given should be sufficient for the majority of applications of a particular device. In certain applications, more information must be obtained by the user himself and/or through applications assistance from the manufacturer. The following ratings typically appear on Agilent Technologies transistor data sheets and provide adequate information for most applications of these devices.

A. Voltage Ratings

These ratings are usually derived from and usually coincide with the minimum device breakdown voltages. However, since this coincidence does not necessarily occur, it has become common practice to include both maximum voltage ratings and minimum breakdown voltages on data sheets.

It can be argued that such practice erodes the meaning of maximum ratings. Since, strictly speaking, maximum ratings should not be exceeded under any circumstances, strict adherence to voltage ratings would preclude measurement of breakdown voltage of any but marginal devices. In practice, voltage ratings are usually maximum operating voltages and no damage results if they are exceeded only to measure the breakdown voltages provided that care is taken to ensure that the specified low currents for these measurements are not exceeded.

B. Current Ratings

Maximum current ratings are arrived at from various considerations such as bonding-wire current-carrying ability, overall transistor performance degradation, etc. Maximum ratings are usually given only for collector current (except, in some cases for switching devices) since safely limiting collector current usually ensures that base and emitter currents are also safely limited.

C. Dissipation Ratings

In addition to the individual ratings on voltage and current discussed above, there is also a limit to the voltage-current products which can be safely handled by a transistor. That is, there is a power dissipation rating which must also be adhered to. Since the dissipation capabilities of a device are a function of the temperature of the external environment, this rating is a function of that temperature. For the DC case, this temperature dependence is usually the only significant functional dependence of this rating. In the AC case, that is when device dissipation varies significantly with time, dissipation capabilities become a generally complex function of waveshape. In the latter case, in addition to an average dissipation rating (which coincides with the DC rating) there exists a peak dissipation rating which is a function of waveshape (e.g., a function of pulse width and pulse period in the case of rectangular waveforms). Due to the complexity of the general AC case, transistors are seldom characterized completely enough to include complete AC rating information. Most transistors are rated only in terms of maximum continuous dissipation (i.e., the maximum DC and the maximum average dissipation). This rating is typically specified in terms of a maximum continuous dissipation at or below some stated reference temperature (usually 25°C) and a linear derating factor to be applied at higher temperatures. These two quantities define the maximum continuous dissipation rating curve shown graphically in Figure 2, or expressed analytically as shown in Equation 1.

Equation 1:

$$P_{T(max)}\,T_X = P_{T(max)}\,T_{XI};\,T_X \le T_{XI}$$

$$P_{T(max)}\,T_X = P_{T(max)}\,T_{XI} - K_{JX}\,\Delta T_X;\,T_{XI} < T_X < T_{X(max)}$$

Where

T_X = Temperature of the external reference point

$P_{T(max)}$ = Maximum Total Dissipation, a function of T_X

T_{XI} = Reference temperature below which $P_{T(max)}$ is constant

K_{JX} = Linear Derating Factor

$T_{X(max)}$ = Maximum Junction Temperature

ΔT_X = $T_X - T_{XI}$

Two external temperature reference points are commonly used:

1. Air ambient, T_A (or free-air; i.e., no forced air cooling), which is the air temperature in proximity to the transistor case as mounted in its "normal" manner and,

2. Case ambient, T_C, which is the temperature at the point on the transistor package at which it is most effective to heat sink the transistor.

Which reference point is used depends on the application.

In summary, the continuous dissipation rating (usually based on a V x I product), and the collector voltage and current ratings define a DC safe operating area as sketched in Figure 3.

D. Junction Temperature Rating

Another temperature reference point implicit in the above discussion of dissipation ratings is transistor junction temperature. The maximum external reference-temperature, $T_{X(max)}$, corresponds to the maximum internal junction

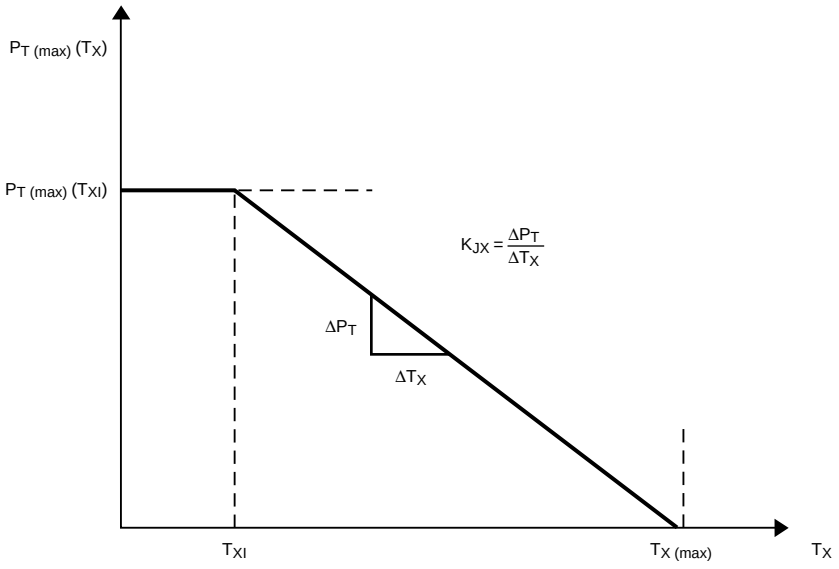

Figure 2. Continuous Dissipation Rating Curve

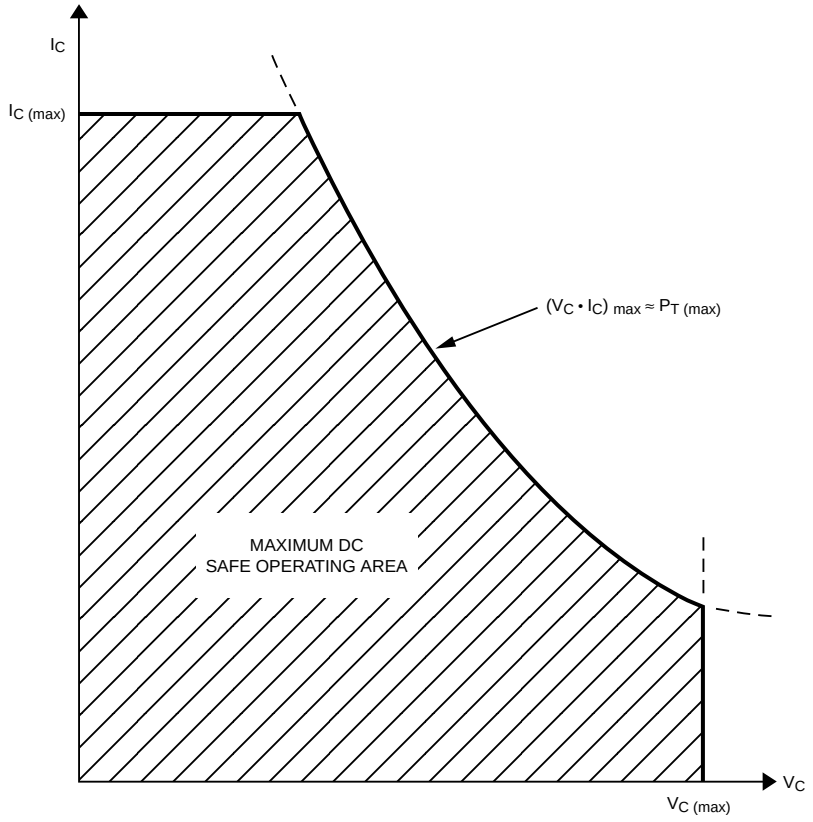

Figure 3. Maximum DC Safe Operating Area

temperature, since at $T_{X(max)}$ the power dissipation must be derated to zero. Strictly speaking, junction temperature does not properly classify as a maximum rating since it is not an external stress under direct control of the user (as opposed to power dissipation and external operating temperature which are). Thus, a more appropriate terminology for this rating would be maximum operating temperature. However, since it is a limiting factor in transistor dissipation capabilities and its use simplifies time-varying thermal analysis, the rating still appears on many transistor data sheets as a junction temperature rating.

E. Storage Temperature Rating

This rating defines the range of temperature over which the transistor may be stored (in the non-operating state) without damage. Because of possible electrical-temperature interactions, storage temperature range and operating temperature range do not necessarily coincide. However, in practice, they usually do coincide and in the absence of stated restrictions on operating range, storage temperature range may be taken as operating range also.

III. Electrical and Performance Characteristics

Electrical characteristics may be described as uniquely defined, measurable electrical properties of the transistor which are not a function of the measuring circuit or apparatus (except insofar as standard terminations and measurement accuracy are concerned). Performance, or operating characteristics are also electrical properties but they are, in general, not unique because their values depend upon the measuring circuit (in particular, the source and load impedance, which may be arbitrary). As might be expected, the terms are often used somewhat loosely (and sometimes interchangeably), especially in some cases where there are only subtle differences involved. The terms are generally used on transistor data sheets to segregate (for emphasis) under performance or operating characteristics those properties most directly applicable for the primary intended application.

A. Performance (Operating) Characteristics

Of the numerous performance characteristics which can be specified for high-frequency transistors, perhaps the most fundamental and pertinent characteristics are:

1. Power gain and noise figure, for small-signal applications;

2. Power gain, power output and efficiency, for large signal applications.

All of these characteristics are, of course, functions of frequency, bias temperature, etc., and to completely characterize a transistor over its full frequency, bias, and temperature ranges would be prohibitively costly. Consequently, characterization data is given only for restricted ranges of these variables. This data should portray sufficiently the capabilities of a particular device for its intended applications. As in the case of maximum ratings, some applications may require additional characterization by the user himself or through applications assistance from the manufacturer.

1. Power Gain

a. G_{max}

Of the various definitions for the measure of power flow in an active two-port device, such as a transistor, two are unique enough to allow specification without recourse to specifying the complete measuring circuit in detail. One of these definitions is termed Maximum Available Gain, G_{max}, and is the power gain obtained when the input and output ports are simultaneously conjugately matched to source and load impedances, respectively. Implicit in this definition is the assumption that the two-port is unconditionally stable, i.e., no combinations of input/output tuning can result in increasing gain to the point of oscillation.

b. $|S_{21}|^2$

The other unique power gain is the gain realized when the transistor is inserted between a source and a load with identical impedances (in practice usually 50 + j0 ohms). This particular insertion or transducer gain happens to coincide with the usual definition of the two-port forward scattering parameter, S_{21}. More precisely, it is equal to the magnitude squared of this parameter and is therefore often identified by the symbol

$|S_{21}|^2$.

For wideband applications,

$|S_{21}|^2$ is important since wideband terminations " not-too-different" from 50 ohms are more easily realized than are wideband transforming networks which provide the matching required for G_{max}.

2. Noise Figure

A common measure of the noise generated by an active two-port device, noise which sets a lower limit on amplifier sensitivity, is the noise factor, F. This is defined as:

$$F = \frac{\text{Input signal-noise ratio}}{\text{Output signal-noise ratio}} \quad (2)$$

or more generally as:

$$F = \frac{\text{Total output noise power}}{\text{Output noise power due to source resistance}} \quad (3)$$

At high frequencies, spot noise factor or noise factor for a small fractional bandwidth (say 1%) is used and is usually expressed as noise figure, NF, in decibels, i.e.,

$$NF = 10 \log F$$

As already discussed, noise figure is a function of source impedance (as well as functions of frequency, bias, etc.) and hence, there is an infinity of noise figures associated with a given device corresponding to the infinity of possible impedances which may be presented to the device input. The only unique one, in the sense that it does not involve arbitrary source impedances, is NF_{min}, the minimum noise figure obtained (at given bias and frequency) when the input is tuned to optimize this parameter. It is this noise figure which is usually given on Agilent Technologies data sheets.

In practical amplifiers, involving more than one stage, overall noise factor F_O is given by:

$$F_0 = F_1 + \frac{F_2 - 1}{G_1} + \cdots + \frac{F_n - 1}{G_{(n-1)}} \quad (4)$$

where

n = number of stages

G_n = gain of the nth stage

F_n = noise factor of the nth stage.

This expression emphasizes the important fact that for low noise amplifiers, the first stage must be designed for the lowest noise figure and highest gain possible. (Note that the noise contribution of the second stage is divided [reduced] by the gain of the first stage). Since the optimum source impedance and bias currents for optimum gain and noise figure do not often coincide, very careful circuit design is required to minimize overall noise figure.

3. Power Output

This characteristic is important for both amplifier and oscillator transistors. In both cases, it is extremely circuit sensitive. For amplifiers, maximum useful output is often limited to that power output level at which gain has compressed 1 dB, an indicator of the upper limit on the linearity range. For oscillators, it is merely a quantitative measure of RF power for a given DC input power.

4. Efficiency

In the most general sense, this characteristic expresses as a percentage, the ratio of RF power output to the total circuit input power, both DC and RF. That expression is total efficiency, η_t, defined as:

$$\eta_t = \frac{P_O}{P_i + P_{DC}} \times 100 \quad (5)$$

where

P_O = RF output power

P_i = RF input power

P_{DC} = total DC power input

Power transistors are often characterized in terms of power added efficiency, η_{add}, defined as:

$$\eta_{add} = \frac{P_O - P_i}{P_{DC}} \times 100 \quad (6)$$

Since for oscillator transistors there is no RF power input, and for amplifier transistors the maximum input RF power is calculable from the power gain and power output specifications, the inclusion of P_i in efficiency is redundant. Moreover, since the major portion of the DC power is dissipated by the transistor collector, a more restricted definition of efficiency is pertinent. This parameter, termed collector efficiency, η_c, is given by:

$$\eta_c = \frac{P_O}{P_{CC}} \times 100 \quad (7)$$

where

P_{CC} = V_{CC} x I_{CC}

V_{CC} = collector supply voltage

I_{CC} = collector supply current

B. Electrical Characteristics

Electrical characteristics may be conveniently classified into two main types, DC and AC.

1. DC Characteristics

The importance of DC characteristics of high frequency transistors lies primarily in biasing and reliability considerations. However, certain DC characteristics are also directly related to high-frequency performance. For example, high-frequency noise figure is affected by the DC current gain. The DC characteristics which are discussed here are those usually found on high frequency transistor data sheets.

a. $V_{(BR)CBO}$, I_{CBO}

These two parameters serve to characterize the reverse-biased collector-base p-n junction and are defined as follows (with the aid of Figure 4a). The collector-base breakdown voltage, $V_{(BR)CBO}$, identifies the voltage at which collector current tends to increase without limit, usually due to the high electric field developed across the junction. This voltage sets a limit on the maximum transistor operating voltage and, as mentioned before under maximum ratings, usually is the basis for the collector-base maximum voltage rating. $V_{(BR)CBO}$ should be specified at a value of $I_C = I_{C1}$ in the figure, which is within the avalanche (or high slope) region of the reverse characteristic. Typical values of I_{C1} are in the 1 – 10 μA region for high frequency transistors.

To further define the quality of the reverse V-I characteristic a specification is usually placed on collector cutoff current, I_{CBO}, measured at some value of collector-base voltage less than $V_{(BR)CBO}$. For a good quality silicon junction ("sharp" instead of soft, see Figure 4a), I_{CBO} is in the nano-ampere range.

b. $V_{(BR)EBO}$, I_{EBO}

These two parameters characterize the reverse-biased emitter-base p-n junction in an analogous manner to the collector-base junction parameters $V_{(BR)CBO}$, and I_{CBO}, given above and are shown in Figure 4b. No further discussion will be given here.

c. $V_{(BR)CEO}$, I_{CEO}

The collector-emitter breakdown voltage and cutoff current are somewhat more complex in nature than either the collector-base or emitter-base parameters. In the

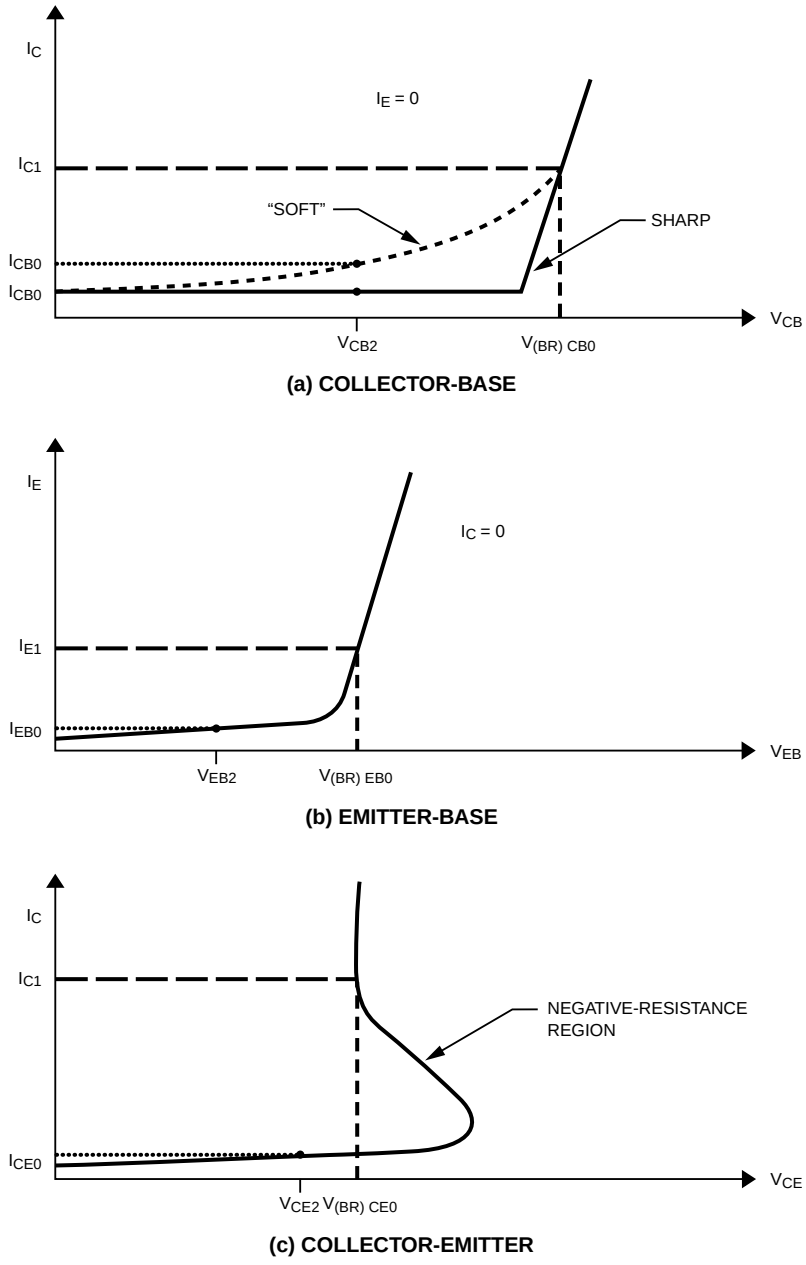

Figure 4. Transistor Reverse V-I Characteristics

latter two, only a single p-n diode is involved. In the collector-emitter case, two diodes are involved. Moreover, each is influenced by the other through transistor action, since the reverse current of the collector-base diode flows through the emitter-base junction as forward current. Thus the collector-base reverse current is amplified by the DC current gain of the transistor resulting in:

1) I_{CEO} being greater than I_{CBO} (for a given voltage).

2) Typically the familiar negative-resistance region in the V-I characteristic as shown in Figure 4c.

Consequently, $V_{(BR)CEO}$ is typically specified at collector currents one to three orders of magnitude higher than in the case of $V_{(BR)CBO}$ and $V_{(BR)EBO}$ in order to establish the minimum value of this characteristic.

d. h_{FE}

This parameter is simply the DC common-emitter current gain; i.e., the ratio of collector current to base current at some specified collector voltage and current.

2. AC Characteristics

Of the numerous AC characteristics which are defined for transistors, only relatively few are commonly used in characterizing high-frequency transistors. Some of the more pertinent parameters are briefly covered here.

a. S-Parameters

By far the most useful and conveniently measured set of two-port parameters for transistor high frequency (roughly 100 MHz and above) characterization is the S-parameter or scattering-matrix set. These parameters completely and uniquely define the small-signal gain and input/output immitance properties of any linear "black box". (By definition, a transistor or any active device is linear under small-signal conditions). However, these parameters reveal nothing (except possibly indirectly and approximately) about large-signal behavior or about noise behavior. Simply interpreted (more general definitions and other interpretations abound in the technical literature), the S-parameters are merely insertion gains, forward and reverse; and reflection coeffecients, input and output, with driven and non-driven ports both terminated in equal impedances, usually 50 ohms, real. Such an interpretation tends to make S-parameters very attractive, once some familiarity is gained, at high (especially microwave) frequencies, since the power flow or gain and reflection-coefficient concepts are more intuitively meaningful than voltage and current conceptual schemes. It should also be mentioned that S-parameters can be converted through straight-forward matrix transformations to other two-port parameter sets; e.g., h-, y-, or z-parameters.

Proceeding with more specific definitions, the S-parameters are defined analytically by:

$$b_1 = S_{11}a_1 + S_{12}a_2$$
$$b_2 = S_{21}a_1 + S_{22}a_2 \qquad (8)$$

or, in matrix form,

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11}S_{12} \\ S_{21}S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \qquad (9)$$

where, referring to Figure 5:

a_1 = (incoming power at port 1) $^{1/2}$

b_1 = (outgoing power at port 1) $^{1/2}$

a_2 = (incoming power at port 2) $^{1/2}$

b_2 = (outgoing power at port 2) $^{1/2}$

E_1, E_2 = Electrical stimuli at port 1, port 2

From the figure and defining linear equations, for $E_2 = 0$, then $a_2 = 0$, and (skipping numerous rigorous steps) refer to Equation 10 below.

Equation 10 :

$$S_{11} = \frac{b_1}{a_1} = \left[\frac{\text{Outgoing Input Power}}{\text{Incoming Input Power}}\right]^{1/2}$$
$$= \frac{\text{Reflected Voltage}}{\text{Incident Voltage}} = \text{Input Reflection Coefficient}$$
$$S_{21} = \frac{b_2}{a_1} = \left[\frac{\text{Outgoing Output Power}}{\text{Incoming Input Power}}\right]^{1/2}$$
$$= \left[\frac{\text{Output Power}}{\text{Available Input Power}}\right]^{1/2} = \left[\text{Forward Transducer Gain}\right]^{1/2}$$

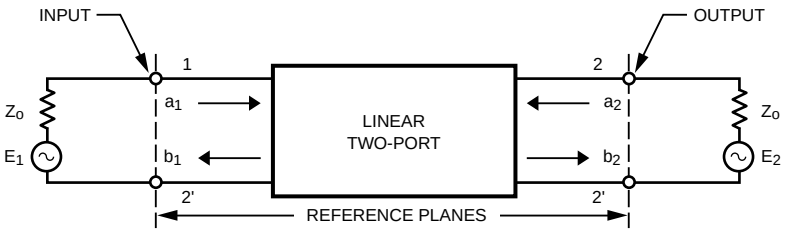

Figure 5. Two-port S-parameter Definition Schematic

or more precisely in the case of S_{21}:

Equation 11:

$$\text{Forward Transducer Gain} = G_{TF} = |S_{21}|^2 \quad Z_i = Z_o$$

Similarly at Port 2 for $E_1 = 0$, then $a_1 = 0$, and

Equation 12:

$$S_{22} = \frac{b_2}{a_2} = \text{Output Reflection Coefficient}$$

$$S_{12} = \frac{b_1}{a_2} = \text{Reverse Transducer Gain}^{1/2}$$

$$G_{TR} = |S_{12}|^2$$

Since many measurement systems actually "read out" the magnitude of S-parameters in decibels, the following relationships are particularly useful:

Equation 13:

$$|S_{11}|_{db} = 10\log|S_{11}|^2 = 20\log|S_{11}|$$

$$|S_{22}|_{db} = 20\log|S_{22}|$$

$$|S_{21}|_{db} = 10\log|S_{21}|^2 = 20\log|S_{21}| = 10\log|G_{TF}| = |G_{TF}|_{db}$$

$$|S_{12}|_{db} = 10\log|S_{12}|^2 = 20\log|S_{12}| = 10\log|G_{TR}| = |G_{TR}|_{db}$$

b. Transition Frequency

One of the better known, but perhaps least understood, figures-of-merit for high-frequency transistors is the so-called transition frequency, f_T. Part of the misunderstanding which appears to exist is due to the use of a misleading (but common, for historical reasons) terminology of "short-circuit gain-bandwidth product" for this parameter.

By definition, f_T is that characteristic frequency described by the equation:

$$f_T = h_{fe} \times f_{meas} \qquad (14)$$

where

h_{fe} = magnitude of small-signal common-emitter short-circuit current gain, h_{fe}

f_{meas} = Frequency of measurement, chosen such that:

$$2 \le h_{fe} \le \frac{h_{feo}}{2} \qquad (15)$$

h_{fe} = the low frequency value of h_{fe}

To varying degrees of approximation, depending on transistor type, f_T is the frequency at which h_{fe} approximates unity. It is not, in general, the frequency at which h_{fe} is precisely equal to unity. To clarify these points further, consider the plot of h_{fe} against frequency sketched in Figure 6.

At low frequencies, $f << f_B$, h_{fe} is constant and equal to h_{feo}.

At f_B, h_{fe} has decreased to 0.707 h_{feo}; i.e., f_B is the 3 dB cutoff frequency for common-emitter short-circuit current gain, h_{fe}.

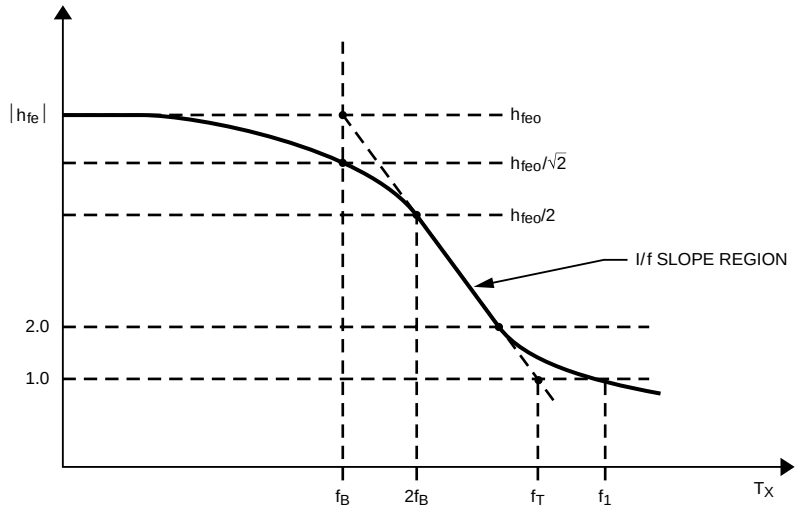

Figure 6. $|h_{fe}|$ Frequency Characteristics

For frequencies such that

$$2f_B < f < f_T$$

h_{fe} varies inversely proportional to frequency. That is, the f_T defining relationship holds:

$$h_{fe} \times f_{meas} = \text{constant} = f_t \qquad (16)$$

At frequencies approaching f_T, other parameters, especially package parasitics, can cause $|h_{fe}|$ to depart significantly from this 1/f variation. Therefore, the frequency, f_1, at which $|h_{fe}|$ actually equals unity can be somewhat different from f_T.

Applying this frequency-gain characteristic to common-emitter wide-band, low-pass amplifiers gives rise to the terminology of f_T being a "gain-bandwidth product". However, this is an optimistic approximation at best, since the product of low frequency circuit gain and the 3 dB cutoff frequency is reduced from f_T by an amount depending on circuit impedances. The real significance of f_T lies in the fact that it is a measure of certain internal transistor parameters which do, in fact, affect high-frequency performance; for example, gain (though not in the convenient quantitative manner implied by the gain-bandwidth product terminology). In particular, good high-frequency noise performance requires that f_T be high. Thus, f_T is included on transistor data sheets as a figure of merit primarily, not as a parameter to be used directly in design.

c. Collector-Base Time Constant, $r_b'C_c$

This is an internal device parameter which relates only indirectly to high frequency performance. It is primarily a measure of internal feedback within the transistor. It also relates to transistor high-frequency impedance. As the name says (in symbols), it is a measure of transistor base resistance and collector capacitance in combination; however, except for certain low-frequency transistors, it cannot be considered the simple two-element lumped R-C time constant implied by the terminology. (In high frequency transistors, both base resistance and collector capacitance must be considered distributed when considered in detail). As a figure of merit, it is included on transistor data sheets to indicate how well base resistance and collector capacitance have been minimized. It also allows the estimation of certain gain properties of the transistor (see f_{max} parameter, following).

d. Collector-Base Capacitance, C_{cb}

This parameter is simply the total collector-base p-n junction capacitance measured at a low frequency (typically, 1 MHz) where it can be considered a single lumped element. For high-frequency transistors it is, of course, desirable that C_{cb} be small from bandwidth and stability considerations as well as from gain considerations alone.

e. Maximum frequency of Oscillation, f_{max}

This is another figure-of-merit parameter, as opposed to measurable parameters directly usable in the applications of transistors. Its importance stems from the following approximate relationships (which will not be derived here):

$$f_{max} \approx \left(\frac{f_T}{8\pi r_b' C_c} \right)^{1/2} \qquad (17)$$

$$G_{max} \approx \left(\frac{f_{max}}{f_{oper}} \right)^2 \qquad (18)$$

These expressions illustrate in a quantitative way the importance and the interrelationship between high f_T and low $r_b'C_c$ insofar as high frequency gain is concerned. However, since they are approximations and since their derivation

involves several assumptions not always valid, they must be interpreted with caution. For example, the expression for G_{max} is obviously not applicable at low frequencies since as $f \rightarrow 0$, $G_{max} \rightarrow \infty$, according to this expression. As a rule of thumb, the G_{max} expression is a reasonable approximation for frequencies such that,

$$5 > \frac{f_{max}}{f_{oper}} > 1 \qquad (19)$$

For accurate analysis of transistor gain and stability, a complete set of two-port parameters must be employed in exact expressions, such as those from which the approximations shown above were derived.

IV. Glossary of Microwave Transistor Terminology

$V_{(BR)CBO}$
Breakdown voltage of a reverse biased collector-base junction measured with the emitter open.

$V_{(BR)EBO}$
Breakdown voltage of a reverse biased emitter-base junction measured with the collector open.

$V_{(BR)CBO}$
Breakdown voltage between the collector and emitter terminals measured with the base open.

I_{CBO}
Leakage current of a reverse biased collector-base junction measured with the emitter open.

I_{EBO}
Leakage current of a reverse biased emitter-base junction measured with the collector open.

h_{fe}
DC common-emitter current gain.

C_{cb}
Collector-base junction capacitance measured with the emitter connected to the guarded terminal of a three terminal measurement system.

f_T
Transition Frequency. The frequency at which the magnitude of the small-signal common-emitter short-circuit current gain approximates unity.

$r_b'C_c$
The collector-base time constant.

f_{max}
Maximum frequency of oscillation. The frequency at which G_{max} approaches unity.

$P_{T(max)}$
Maximum continuous power dissipation below a reference temperature (usually 25°C).

$T_{J(max)}$
Maximum allowable transistor junction temperature.

$I_{C(max)}$
Maximum allowable collector current without destruction or degradation of the transistor.

NF
A measure of the noise generated by the transistor.

G_{max}
The maximum available power gain (MAG) when the transistor is unconditionally stable and input and output ports are sumultaneously conjugately matched.

S_{11}
Input reflection coefficient.

S_{12}
Reverse transfer coefficient.

S_{21}
Forward transfer coefficient.

S_{22}
Output reflection coefficient.

P_O
Amplifier – The power output at the one (1) db gain compression point.
Oscillator – A measure of the RF power output.

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