Second Edition

Handbook of Simplified Solid-State Circuit Design

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PREFACE

This second edition of the HANDBOOK OF SIMPLIFIED SOLID-STATE CIRCUIT DESIGN carries through all of the features that made the first edition so successful. That is, the second edition provides a simplified, step-by-step approach to solid-state circuit design. All the chapters in the second edition have been expanded or enlarged to include new material. Existing data has been up-dated to reflect current design trends. Also, much of the existing material from the first edition has been revised for clarification and/or simplification. *No previous design experience is required* to use the design data and techniques described in this second edition.

As in the original, the basic approach of the second edition is to start all design problems with approximations or rules-of-thumb for the selection of components on a trial value basis, assuming a specific design goal and a given set of conditions. Then, using these approximate values in experimental test circuits, the desired results (gain, frequency response, impedance match, etc.) are produced by varying the test component values.

The second edition concentrates on simple, practical approaches to circuit design, not on circuit analysis or model circuits. Theory is kept to a minimum, and appears only where required to understand the design steps. Thus, the reader need not memorize elaborate theories or understand abstract mathematics to use the design data. With any solid-state circuit, it is possible to apply certain guidelines for the selection of component values. These rules can be stated in basic equations, requiring only simple arithmetic for their solution.

The component values will depend upon transistor characteristics, available power sources, the desired performance (voltage amplification, stability, etc.) and external circuit conditions (input/output impedance match, input signal amplitude, etc.). The transistor characteristics are to be found in the manufacturer's data, or from actual test. The circuit characteristics can then be determined, based on reasonable expectation of the transistor characteristics. Often, the final circuit is a result of many tradeoffs between desired performance and available characteristics. The second edition discusses the problem of tradeoffs from a simplified, practical standpoint.

It is assumed that the reader is familiar with solid-state basics at a level found in the author's HANDBOOK FOR TRANSISTORS (Prentice-Hall, Inc., Englewood Cliffs, N.J. 1976). It is especially important the reader be able to interpret solid-state datasheets. However, *no direct reference to any of the author's previous books is required to understand and use this second edition.*

The first chapter of this book is devoted to basic design rules, especially those related to transistor-bias techniques. This is essential since proper bias must be used in every transistor circuit. The second edition provides an expanded Chapter 1 that includes practical details of mounting techniques for metal-packaged power semiconductors.

Chapter 2 is devoted entirely to audio circuit design. The second edition provides an expanded section on transformerless audio amplifiers, as well as a revised section on transformer-coupling in audio circuits.

Chapter 3 covers operational amplifiers. The second edition assumes that today's designer will use commercial IC op-amps as the basic element for all op-amp design applications. With this in mind, the chapter concentrates on circuits external to the IC package that modify the op-amp to produce a given design function or characteristic (modification of frequency response, gain, etc.) and to interpretation of IC op-amp datasheets and/or test results.

Chapter 4 describes design of RF circuits, particularly RF power amplifiers which must be designed "from scratch". (Generally, RF circuits are not available in IC or package form.) The second edition is expanded to cover y-parameters (how y-parameters fit into simplified design), and includes examples of using y-parameters to design both VHF and UHF power amplifiers. An introduction to the Smith Chart is also included.

Chapter 5 covers waveforming and waveshaping circuits. The section on RF oscillators has been revised extensively to reflect current design trends.

Chapter 6 describes solid-state power supply circuits, including converters and regulators. A new section on switching regulators has been provided in the second edition.

Many professionals have contributed their talent and knowledge to the revision and enlargement of the new edition. The author gratefully acknowledges that the tremendous effort to make this second edition such a comprehensive work is impossible for one person, and he wishes to thank all who have contributed directly and indirectly. The author wishes to give special thanks to the following: the Semiconductor Products Division of Motorola Inc., the Semiconductor Products Department of General Electric, the Components Group of Texas Instruments, and the Solid State Division of Radio Corporation of America. The author also wishes to thank Mr. Joseph A. Labok of Los Angeles Valley College.

JOHN D. LENK

CONTENTS

1

BASIC DESIGN RULES

In this chapter, we shall establish a set of basic design rules. Generally, these rules will apply to all circuits discussed in remaining chapters. You need not commit these rules to memory. They will be referred to frequently in the remaining chapters. However, it is strongly recommended that you read this chapter in its entirety before attempting to design any solid-state circuit, even the simplest diode detector.

1-1. How To Use This Book

Once you have read this chapter, you may go directly to the section that describes the design procedures for a particular circuit. Use the Contents or Index to locate the first page of the section. All circuits of a given type (oscillators, low-frequency amplifiers, RF amplifiers, etc.) have been grouped into separate chapters. In turn, a separate section has been assigned to each circuit within the chapter. The sections are either complete within themselves or make reference to another specific section (by section number).

The same format or pattern is used in each section (where practical). First, a working schematic is presented for the circuit, together with a brief description of the operational theory. Where practical, the working schematic also includes the operational characteristics of the circuit (in equation form), as well as the rule-of-thumb relationship of circuit values (also in equation form).

Next, design considerations such as desired performance, use with external circuits, and available (or required) power sources are discussed. Each major design factor (supply voltage, amplification, operating frequency, transistor selection, operating point, etc.) is covered. This is followed by reference to the equations (on the working schematic) and procedures for determining component values that will produce the desired results.

Finally, a design example is given. A specific design problem is stated. The value of each circuit component is calculated, in step-by-step procedures, using the rules of thumb established in the design considerations.

Where applicable, procedures for testing the completed circuit are given in detail (generally at the end of each chapter).

1-2. Interpreting Data Sheets

Most of the basic design information for a particular transistor can be obtained from the data sheet. There are some exceptions to this rule. For extreme-high-frequency work, and in digital work where switching characteristics are of particular importance, it may be necessary to test a transistor under simulated operating conditions.

In any event, it is always necessary to interpret data sheets. Each manufacturer has its own system of data sheets. It would be impractical to discuss all data-sheet formats here. Instead, we shall discuss the typical information found on data sheets, and see how this information affects simplified design.

Figure 1-1 is the data sheet for a 2N332 transistor. This transistor is an industrial type, suitable for low-power audio or RF (up to about 10 MHz), as well as switching.

1-2.1. Maximum Voltage

The first specifications listed are those of *maximum voltage*. In Fig. 1-1, the maximum collector voltage is listed as V_{CBO} of 45 V. Actually, this is a test voltage rather than an operating design voltage. (V_{CBO} usually indicates collector–base breakdown voltage, with the emitter circuit open. Transistors do not operate in this way in circuits.) However, for design purposes, the 45-V figure can be considered as the *absolute maximum* collector voltage. Keep the following in mind on maximum collector voltage: Except for RF circuits used in transmitters, most transistors will be operated with their collector at some voltage value (V_C) less than the source voltage (V_{CC}). For example, in a typical class A circuit, the collector voltage will be half the source voltage, at the normal operating point. However, the collector voltage will rise to or near the source voltage when the transistor is at or near cutoff. Therefore:

Never design any circuit in which the collector is connected to a source higher than the maximum voltage rating, even through a resistance.

The next maximum voltage design problem to be considered is the type of source voltage. A battery power source will not deliver more than its rated

TYPICAL TRANSISTOR SPECIFICATION 2N332

ABSOLUTE MAXIMUM RATINGS (25°C.)

Voltages:		
Collector to base (emitter open)	V_{CBO}	45 volts
Emitter to base (collector open)	V_{EBO}	1 volt
Collector current	I_C	25 ma
*Power**		
Collector dissipation (25°C.)	P_C	150 mw
Collector dissipation (125°C.)	P_C	50 mw
Temperature range:		
Storage	T_{STG}	−65°C. to 200°C.
Operating	T_A	−55°C. to 175°C.

ELECTRICAL CHARACTERISTICS (25°C.)

(Unless otherwise specified, $V_{CB} = 5$ v; $I_E = -1$ ma; $f = 1$ kc)

		min.	*nom.*	*max.*	
Small signal characteristics:					
Current transfer ratio	h_{fe}	9	15	20	
Input impedance	h_{ib}	30	53	80	ohms
Reverse voltage transfer ratio	h_{rb}	.25	1.0	5.0	$\times 10^{-4}$
Output admittance	h_{ob}	0.0	.25	1.2	μmhos
Power gain					
($V_{CE} = 20$ v; $I_E = -2$ ma; $f = 1$ kc;					
$R_G = 1$ K ohms; $R_L = 20$ K ohms)	G_e		35		db
Noise figure	NF		28		db
High frequency characteristics:					
Frequency cutoff					
($V_{CB} = 5$ v; $I_E = -1$ ma)	f_{ab}		15		mc
Collector to base capacity					
($V_{CB} = 5$ v; $I_E = -1$ ma; $f = 1$ mc)	C_{ob}		7		μμf
Power gain (common emitter)					
($V_{CB} = 20$ v; $I_E = -2$ ma; $f = 5$ mc)	G_e		17		db
D-c characteristics:					
Collector breakdown voltage					
($I_{CBO} = 50$ μa; $I_E = 0$; $T_A = 25$°C.)	BV_{CBO}	45			volts
Collector cutoff current					
($V_{CB} = 30$ v; $I_E = 0$; $T_A = 25$°C.)	I_{CBO}		.02	2	μa
($V_{CB} = 5$ v; $I_E = 0$; $T_A = 150$°C.)	I_{CBO}			50	μa
Collector saturation resistance					
($I_B = 1$ ma; $I_C = 5$ ma)	R_{SC}		80	200	ohms
Switching characteristics:					
($I_{B_1} = 0.4$ ma; $I_{B_2} = -0.4$ ma;					
$I_C = 2.8$ ma)					
Delay time	t_d		.75		μsec
Rise time	t_r		.5		μsec
Storage time	t_s		.05		μsec
Fall time	t_f		.15		μsec

*Derate 1mw/°C increase in ambient temperature.

Fig. 1-1. Typical transistor data sheet (2N332).

voltage. However, *any electronic power source* is subject to some voltage variation. Therefore:

Always allow for some variation in source voltage when an electronic power supply is used.

Another factor that affects maximum voltage is temperature. Note that in Fig. 1-1 the maximum voltage is specified at 25°C. Usually, breakdown will occur at a lower voltage when temperature is increased. The topic of how operating temperatures affect transistor design is discussed further in Sec. 1-4.

In Fig. 1-1, the maximum base–emitter voltage is listed as V_{EBO} of 1 V. Again, this is a test voltage rather than an operating design voltage. Usually, the base–emitter junction has some current flowing at all times. The voltage drop across the junction is about 0.2 to 0.4 V for germanium and 0.5 to 0.7 V for silicon transistors. The lower voltage drops (0.2 V or 0.5 V) will produce some current flow, while the higher drops (0.4 V or 0.7 V) will produce heavy current flow. In Sec. 1-6, bias circuits designed to produce the desired drop are discussed. Either the higher or lower drops can be used, depending upon the desired results.

In general, the lower drops will produce less current drain and lower no-signal power dissipation. The higher drops may result in operation on a more linear portion of the transistor characteristics. For the purposes of standardization, the lower voltage drops will be used throughout this book. However, if desired, the higher drops can be used as an alternative by slight changes of the bias circuit values given in the design examples.

In practical design, it is often necessary to select a bias (base–emitter voltage) on the basis of *input signal* rather than on some arbitrary point of the transistor's characteristic curve. Keep in mind that the input signal to a transistor can come from an external source or a previous stage, or in the case of an oscillator or operational amplifier, can be *feedback*. Therefore:

Always consider any input signal that may be applied to the base–emitter junction, in addition to the normal operating bias.

1-2.2. Collector Current

In Fig. 1-1, the collector current is listed as I_C of 25 mA, at 25°C. As is discussed later, collector current will increase with temperature (and temperature increases as current increases). Therefore:

Do not operate any transistor at or near its maximum current rating.

Of course, if you could be absolutely certain that the transistor would dissipate any temperature increases (a practical impossibility), the circuit could be designed to operate near the maximum current.

In practical design applications, it is the *power* dissipated in the collector circuit (rather than a given current) that is of major concern. For example, assume that the collector operates at 45 V and 25 mA. This results in a power dissipation of over 1 W, far above the 150 mW specified for 25°C.

1-2.3. Power and Temperature Range

The power-dissipation capabilities of a transistor in any circuit are closely associated with the temperature range. As shown in Fig. 1-1, power dissipation is 150 mW at 25°C, 50 mW at 125°C, and must be *derated* 1 mW for each degree (°C) increase in ambient temperature. Because of the importance of temperature to power dissipation, the subject is discussed fully in Sec. 1-4.

1-2.4. Small-Signal Characteristics

Small-signal characteristics can be defined as those where the ac signal is small compared to the dc bias. For example, h_{fe} or *forward current transfer ratio* (also known as *ac beta* or *dynamic beta*), is properly measured by noting the change in collector alternating current for a given change in base alternating current, without regard to static base and collector currents.

Small-signal characteristics do not provide a truly sound basis for practical design. As discussed in related chapters, the performance of a transistor in a working circuit can be controlled by the circuit component values (within obvious limits, of course). There are two basic reasons for this approach.

First, not all manufacturers list the same small-signal characteristics on their data sheets. To further complicate matters, manufacturers call the same characteristic by different names (or even use the same name to identify different characteristics).

Second, the small-signal characteristics listed in data sheets are based on a set of *fixed operating conditions*. If the conditions change (as they must in any practical circuit), the characteristics will change. For example, beta changes drastically with temperature, frequency, and *operating point*. Therefore:

Use small-signal characteristics as a starting point for simplified design, not as hard-and-fast design rules.

1-2.5. High-Frequency Characteristics

High-frequency characteristics are especially important in the design of RF networks. As is discussed in later chapters, networks (such as RF stages in a transmitter) provide the dual function of frequency selection (tank circuit) and impedance matching between the transistor and a load. Unfortunately, the high-frequency information provided in many data sheets (such as Fig. 1-1) is not adequate for simplified design. To properly match impedances, both the resistive (real part) and reactive (imaginary part) components must be considered. The reactive component (either inductive or capacitive) changes with frequency. Therefore, it is necessary to know the reactance values over a wide range of frequencies, not at some specific test frequency (unless you happen to be designing for that test frequency only). The best way to show how resistance and reactance vary in relation to frequency for a particular transistor is by means of curves. Fortunately, manufacturers who are trying to sell their transistors for high-frequency use generally provide a set of curves showing the characteristics over the anticipated frequency range.

1-2.6. Direct-Current Characteristics

Direct-current characteristics, while important in the design of basic bias circuits, do not have too critical an effect on the operation of the final operating circuit. The dc characteristics shown in Fig. 1-1 are primarily test values rather than design parameters. The important point to remember regarding such dc characteristics is that they serve as a starting point for bias design, and that they will change with temperature.

1-2.7. Switching Characteristics

Switching characteristics are important in the design of all pulse circuity (multivibrators, gates, etc.). The switching times shown in Fig. 1-1 are defined in Fig. 1-2. These time factors (delay, storage, rise, fall) determine the operating limits for switching circuits. For example, if a transistor gate with a 20-ns rise time is used to pass a 15-ns pulse, the pulse will be hopelessly distorted. Likewise, if there is a 1.5-μs delay added to a 1-μs pulse an absolute minimum of 2.5-μs is required before the next pulse can occur. This means a maximum pulse-repetition rate (PRR) of 400 kHz ($1/2.5^{-6} = 400{,}000$ Hz). Actually, the prf is lower since there is some "off" time between pulses.

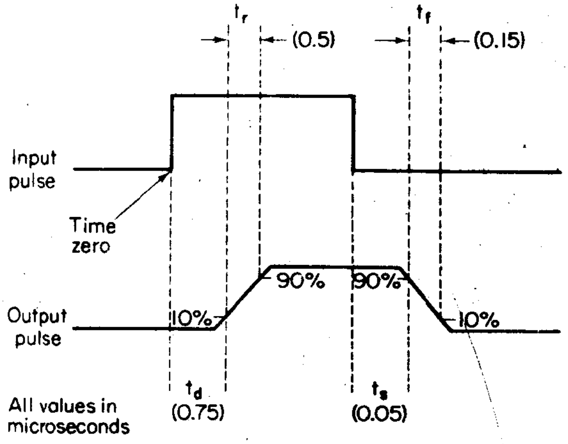

Fig. 1-2. Definition of switching-time characteristics.

1-3. Determining Parameters at Different Frequencies

Data sheets specify most parameters at some given frequency. Often, it is desired to know the parameter at another frequency. The following paragraphs describe methods for converting from one parameter to another at different frequencies.

1-3.1. Basic Parameter Relationships

One or both of two major parameters, h_{fb} (alpha) and h_{fe} (beta), are found on most data sheets. (Table 1-1 is a glossary of terms used in this section.)

Table 1-1. Glossary of Transistor Parameter 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_{ab}	Common-base current-gain cutoff frequency. Frequency at which h_{fb} has decreased to a value 3 dB below h_{fbo} (where $h_{fb} = 0.707h_{fbo}$).
f_{ae}	Common-emitter current-gain cutoff frequency. Frequency at which h_{fe} has decreased to a value 3 dB below h_{feo} (where $h_{fe} = 0.707h_{feo}$).
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	Phase-shift factor. (Phase shift of current in transistor base.)

1-3.1.1. Common-Base Parameters

The quantity h_{fbo} (the value of h_{fb} at 1 kHz) will remain constant as frequency is increased until a top limit is reached. After the top limit, h_{fb} begins to drop rapidly. The frequency at which a significant drop in h_{fb} occurs provides a basis for comparison of the expected frequency performance of different transistors. This frequency is known as f_{ab} and is defined as that frequency at which h_{fb} is 3 dB below h_{fbo}.

A curve of h_{fb} versus frequency for a transistor with an f_{ab} of 1 MHz is shown in Fig. 1-3. This curve has the following significant characteristics:

1. At frequencies below f_{ab}, h_{fb} is nearly constant and approximately equal to h_{fbo}.
2. h_{ab} begins to decrease significantly in the region of f_{ab}.

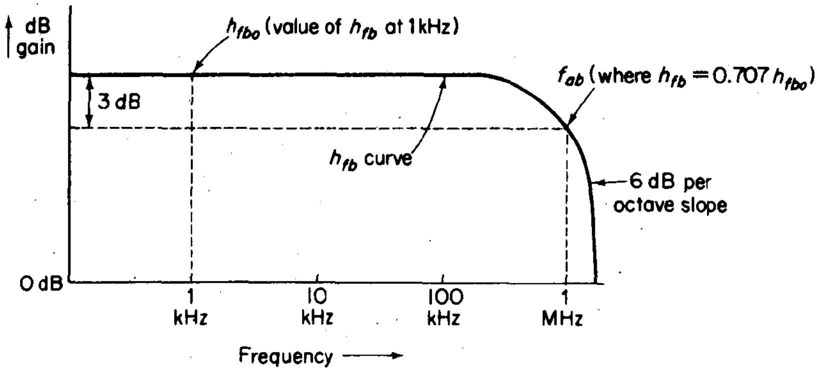

Fig. 1-3. Typical curve of common-base current gain versus frequency. Courtesy Motorola.

3. Above f_{ab}, the rate of decrease of h_{fb} (with increasing frequency) approaches 6 dB/octave.

The curve of common-base current gain versus frequency for any transistor has the same characteristics, and the same general appearance, as the curve of Fig. 1-3.

1-3.1.2. Common-Emitter Parameters

The common-emitter parameter which corresponds to f_{ab} is f_{ae}, the common-emitter current-gain cutoff frequency. This f_{ae} is the frequency at which h_{fe} (beta) has decreased 3 dB below h_{feo}. A typical curve of h_{fe} versus frequency for a transistor with an f_{ae} of 100 kHz is shown in Fig. 1-4. The curve of Fig. 1-4 has the same significant characteristics as those described for Fig. 1-3. That is, h_{fe} is considered to be decreasing at a rate of 6 dB/octave, at f_{ae}.

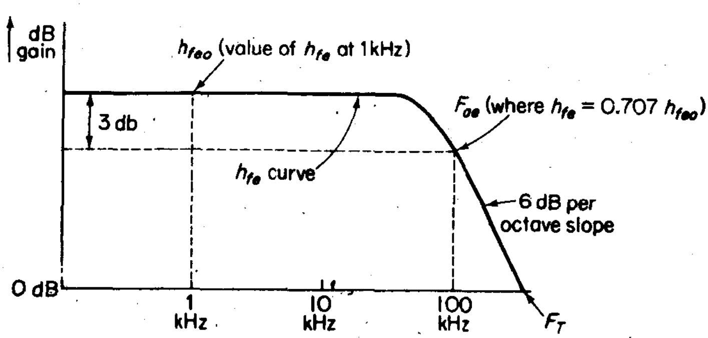

Fig. 1-4. Typical curve of common-emitter current gain versus frequency. Courtesy Motorola.