R. PAUL

MEASUREMENT OF TRANSISTOR PARAMETERS

MEASUREMENT OF

R. PAUL

MEASUREMENT OF TRANSISTOR PARAMETERS

Translated by Scripta Technica Ltd

English translation edited by
D. Llanwyn-Jones, B. Sc., Ph. D.
King's College, London

LONDON: ILIFFE BOOKS LTD

ILIFFE BOOKS LTD
42 RUSSELL SQUARE
LONDON WC1

First published by VEB Verlag Technik Berlin, under the title
TRANSISTORMESSTECHNIK

English edition first published in 1969 by Iliffe Books Ltd
Translated and prepared for press by Scripta Technica Ltd

592 02821 6

Printed in the German Democratic Republic

PREFACE TO THE ENGLISH EDITION

This translation of Prof. R. Paul's monograph from the original German edition should be of value both as a reference book to practising electrical and electronic engineers and as a textbook for final year undergraduates and postgraduates in physics and engineering.

It is not the intention of the author to give a complete description of the elementary basis of the analysis of the performance of the transistor as a circuit element in an academic way, but rather to extend considerably the coverage of the many elementary texts available on this subject. In particular, as suggested by the title, the main concern of the book is to deal with the principles of measurement of the various transistor leakage, saturation, switching, noise, thermal and quadripole parameters. The description of the methods of measurement is amply illustrated by numerous diagrams showing specific experimental results. The frequency range covered extends from d.c. frequencies to Gc/s frequencies.

As editor, I found this work illuminating in several respects. I think others will find this to be the case also.

D. Llanwyn Jones
January 1968

INDEX OF THE MOST IMPORTANT SYMBOLS

Print

Magnitudes of physical quantities: Italics (V, I).
Vectors: Italics in bold type ($\boldsymbol{V}, \boldsymbol{I}$); $\boldsymbol{V}^*$ is the conjugate complex number to $\boldsymbol{V}$ (etc.).

Voltage, current and power symbols

These symbols usually have subscripts. The instantaneous values, d.c. and a.c. parts are marked as follows.

1. Small (lower case) letters are used for instantaneous values of quantities varying in time (v, i) with small letter subscripts for periodic quantities (pure a.c. constituents) (v_{eb}, i_e) and with capital (upper case) letter subscripts for non-periodic quantities (pulse quantities) (v_{EB}, i_E).
2. Capital (upper case) letters are used for time-constant quantities (V, I) with small letter subscripts for the mean values of periodically varying quantities (V_{eb}, I_e) and capital letter subscripts for d.c. quantities (V_{EB}, I_E).

Impedances, admittances, capacitances, inductances

Small letters are used for the equivalent circuit quantities corresponding to the transistor itself (r_b, r_d, $r_{E'E}$, c_e); capital letter subscripts when the quantity corresponds to d.c. operation, small letter subscripts when the quantity corresponds to a.c. operation. Conductance S and several noise parameters are exceptions.

Capital letters are used for the elements lying outside the terminals of the transistor (R_{BE}, R_L, R_E).

Symbols generally used for admittances and impedances are $y = g + jb = g + j\omega c$, $z = r + jx$, $Y = G + jB$, $Z = R + jX$.

Inner transistor quantities are additionally marked by (h'_{21}, y'_{11}).

List of the most important mathematical symbols

These are the most important symbols used in mathematical expressions. If a symbol is used in several meanings, all its meanings are listed separately.

A	cross-section, area
$A_N(A_I)$	d.c. current amplification in grounded base circuit in forward (reverse) operation
$A_{N1}(A_{I1})$	d.c. current transport factor in normal (reverse) operation
$a_v(a_r)$	forward (reverse) voltage transfer
$B, b(B', b')$	as subscripts: base terminal (inner) grounded base circuit (in quadripole parameter symbols)
B	collector-base currents ratio
B_G	generator susceptance
B_L	load susceptance
B_N	susceptance of the standard
$B_N(B_I)$	d.c. current amplification in common emitter circuit in forward (reverse) operation
B_{NO}	d.c. current amplification B_N at the limit of overdrive
$C, c(C', c')$	as subscripts: collector terminal (inner)
C_{th}	thermal capacity
c	inner capacitance of the transistor (always with a subscript)
c	velocity of light
c_o, c', c_k	temperature coefficient of a saturation or leakage current
c_e, c_b, c_c	emitter, base, collector capacitance
c_{ed}, c_{cd}	emitter, collector diffusion capacitance
c_{eb}, c_{ec}, c_{cb}	leader capacitances between emitter, base and collector terminals
c_{es}, c_{cs}	emitter, collector junction capacitances
D_T	temperature slope reciprocal
$E, e(E', e')$	as subscripts: emitter terminal (inner), grounded emitter circuit (in quadripole parameter symbols)
e	electron charge
F	noise factor
F_e	additional noise factor
F_{tot}	total noise factor
F_{oo}	noise factor for white noise spectrum
f	frequency
Δf	bandwidth
Δf_e	equivalent bandwidth
f_b	upper cut-off frequency of $\|h_{21b}\|$
f_c	normalising frequency ($g_c = \omega_c c_c$)
f_e	normalising frequency ($g_e = \omega_e c_e$)
f_{hfb}	(lower) cut-off frequency of $\|h_{21b}\|$
f_{hfe}	cut-off frequency of $\|h_{21e}\|$
f'_{hfb}, f'_{hfe}	inner transistor cut-off frequencies f_{hfb}, f_{hfe}
f_o	centre frequency
f_o	normalising frequency
f_q	normalising frequency $g_c = \omega_q(c_c + c_{cb})$
f_{y21}	y_{21} cut-off frequency

f_T	transit frequency
f_s	normalising frequency $(\omega_s r_b c_e = 1 + r_b g_e)$
f_1	cut-off frequency at which $\lvert h_{21e} \rvert = 1$
f_{max}	maximum oscillation frequency
G	conductance (general symbol)
G	power amplification (general symbol)
G_G	generator conductance
G_L	load conductance
G_N	conductance of the standard
G_n	equivalent noise conductance $(G_n = g_n)$
G_t	transfer gain
G_a	available power amplification
$G_{a\ max}$	maximum available power amplification
g	inner conductance of the transistor (always with a subscript)
g_b, g_e, g_c	base, emitter, collector conductance $(g_b \neq \frac{1}{r_b})$
g_d	diffusion conductance
g_{ed}, g_{cd}	emitter, collector diffusion conductance
g_{er}	recombination conductance in the emitter zone
g_{cr}	recombination conductance in the collector zone (residual collector conductance)
g_n	equivalent noise conductance
h_{ik}	*h* parameter of the transistor (when referred to the transistor circuit configuration, provided with subscript: *b*, e, c)
h'_{ik}	*h* parameter of the inner transistor
I	current
I	as subscript: reverse operation
I_B, I_E, I_C	base, emitter, collector d.c. current
I_{BO}, I_{CO}	base, collector d.c. current at the limit of overdrive
I_{BS}	base excess current
I_R	leakage (residual) current, general symbol
I_{EBO}	emitter leakage current with open-circuited collector
I_{CBO}	collector leakage current with open-circuited emitter
I_{CEO}	collector leakage current with open-circuited base
I_{CBK}	collector leakage current with shorted emitter and base
I_{CBR}	collector leakage current with emitter and base joined via a resistance
I_e, I_c, I_b	emitter, collector, base a.c. current
i	as subscript: intrinsic
i	instantaneous value of the current (subscripts as with I)
i_n	noise current – general symbol
k	abbreviation
k	Boltzmann constant
k	switching-off factor
k	transformation factor
k_T $(k_{T\ eff})$	duty ratio (effective)
l_d	inner inductance of the transistor
l_r	inner inductance of the transistor, with the Early effect taken into account

l_b, l_c, l_e	lead inductance of the electrode shown by the subscript
M	multiplication factor (general symbol)
M_b, M_g, M_x	mutual inductance
m	matching factor
m	drift factor
m	abbreviation
m	overdrive factor
N, n	as subscripts: forward (normal) operation
N_A, N_D	donor density
P	power
P	power loss, dissipated power
P_o	available generator power
P_n	noise power (general symbol)
P_{nz}	additional noise power introduced by the noise quadripole
Q	amount of heat
Q_B	minority carrier charge stored in the base zone
Q_{BS}	excess charge
q	elementary charge of holes ($q = \|e\|$)
R	resistance (general symbol)
R_C, R_E, R_B	external collector, emitter, base resistance
R_G	generator resistance
R_L	load resistance
R_N	standard resistance
R_n	equivalent noise resistance
R_{th}	thermal resistance
R_{thi}, R_{the}	thermal resistance: inner, external
R_{thk}	thermal contact resistance
$R_{thi\ eff}$	effective inner thermal resistance
r	inner resistances of the transistor (always with subscripts)
r	abbreviation
r	reflection factor
r_d	diffusion resistance
r_b, r_B	base resistance
$r_{E'E}$, $r_{e'e}$	emitter path resistance
$r_{C'C}$, $r_{c'c}$	collector path resistance
r_n	equivalent noise resistance ($r_n \neq R_n$)
r_r	inner longitudinal resistance of the transistor, taking into account the Early effect
S_{sb}, S_{se}	total conductance in the base and emitter configuration
S_i	inner conductance
S_{io}	inner conductance at low frequencies
S_e	external conductance
T	absolute temperature (subscript denotes the actual point as for ϑ)
T	duration of one period
t	time
t_a	off-time
t_e	on-time
t_d	delay time

t_r	rise time
t_s	storage time
t_f	fall time
t_p	pulse duration
v	instantaneous value of the voltage (general symbol)
v_r	noise voltage (general symbol)
V	voltage (general symbol)
V_C, V_B, V_E	original voltage source
BV_{CEO}	collector-emitter breakdown voltage with open-circuited base
BV_{CBO}	collector-base breakdown voltage with open-circuited emitter
BV_{CER}	collector-emitter breakdown voltage with an arbitrary connection between emitter and base
V_D	diffusion voltage
V_{EB}, (V_{CB})	voltage between the (external) emitter and base terminals (collector and base terminals)
$V_{B'B'F}$	emitter floating voltage
$V_{C'B'F}$	collector floating voltage
V_{CES}, V_{CER}	collector-emitter saturation voltage, collector residual voltage
V_T	thermal voltage kT/q
V_{pt}	punch-through voltage
V_g	generator voltage
W	width of the base
Y	external admittance (general symbol)
Y_e (Y_a)	input (output) admittance
Y_G	generator admittance
Y_L	load admittance
Y_{cor}	correlation admittance
y	inner admittance of the transistor (always with a subscript)
y_{ik}	y parameter of the transistor (when pertaining to the transistor circuit configuration, with subscript b, c, e)
y'_{ik}	y parameter of the inner transistor
Z	external impedance (general symbol)
Z	wave impedance, characteristic impedance
Z_L	terminating impedance
Z_{ik}	z parameter of the transistor (when pertaining to the transistor circuit configuration, with subscript b, e, c)
α_b (α'_b)	short-circuit current amplification in the common base circuit in forward operation (inner transistor)
α_e (α_{oe})	short-circuit current amplification in the common emitter configuration in forward operation (at low frequencies)
α_o	short-circuit current amplification in the common base configuration at low frequencies
ϑ	temperature in degrees Celsius
$\Delta\vartheta$	junction temperature
ϑ_a	ambient temperature
$\vartheta_{j\,max}$	maximum permitted junction temperature (limit value)
ϑ_c	case temperature
ϑ_o	reference temperature

λ	wavelength
λ	attenuation factor
τ_B, τ_E, τ_C	base, emitter, collector time constant (switching time constants, time factors)
τ_{CO}	collector time constant at the limit of overdrive
τ_c'	collector time constant
τ_F	fall time constant
τ_L	delay time constant
τ_R	rise time constant
τ_S	saturation time constant
τ_{10}	general time constant
ϕ	phase angle
ω	angular frequency (pulsatance)

INTRODUCTION

The great advantages of transistors, as compared with electron tubes, have gained for them a steadily widening field of application, particularly in switching circuits. This makes it even more imperative that not only the manufacturer, but also the user, should be able to measure the electrical properties of these devices. This is necessary not only because of the greater variation of electrical parameters among devices of the same type (which the partisans of conventional electron tubes stress, and which indeed was a difficulty with some early circuits), but mainly because an understanding of the modes of operation of transistors requires knowledge of more parameters than in the case of electron tubes. It is also necessary to protect transistors from overloading. The relatively strong influence of various parameters (operating point, temperature, frequency) upon the characteristics requires many measurements by circuit designers, even though the manufacturing scatter of device parameters is being made narrower by technical progress.

Depending on the objectives, the requirements set for transistor measurements vary to a great extent. The development of devices requires, above all, measurement methods to be as accurate as possible and universally applicable, without regard to the expenditure of time and apparatus. Such methods are known simply as laboratory methods.

Circuit designers may be forced to use such methods, particularly when the circuit details must be based on characteristics that the data sheet produces only in general form, or not at all.

However, most circuit designers will be satisfied by a measurement of typical values in more stringent conditions than usual and by a fair accuracy of measurement, since either the data supplied by transistor manufacturers will be sufficient, or the user will have accumulated over a period of time a sufficiently great degree of experience; in either case, highly accurate measurements may be superfluous. Ordinary measurements require less time and instrumentation than laboratory methods but they may be applicable only to some specified types of transistors. Such methods will be called service methods.

Finally, in production or acceptance tests of transistors the question revolves not around absolute values of typical parameters but is only whether a certain limiting value, usually given in the data sheet, is exceeded or not achieved. In these tests, the speed of measurement, simple manipulations, constancy of the operating point and simplicity of instrumentation are primary considerations.

Transistor measurement techniques comprise all the above classified methods for determining the characteristics equally important to the manufacturer and to the user. The scope of transistor measurement techniques is not so much the development of new, more generally applicable methods, but rather the adaptation of well-known methods for measurements of active and passive devices to the specific character of transistors. The problems may consist in the use of relatively small amplitudes at very high frequencies of measurement (of the order of Gc/s), in setting the operating point without affecting the measurement result and in strict preservation of supplementary conditions during the measurement (quadripole termination, test jig), etc.

The great diversity of methods that have developed over the years is mainly occasioned by the great number of parameters that may be used for characterising transistor circuit performance for a given operational condition. These parameters can be divided into characteristic and effective classes; characteristic parameters depend solely on the transistor, effective parameters depend on the circuit conditions of application as well. The great advantage of the characteristic parameters is that, by definition, the method of measurement is uniquely determined and there is no need to describe in detail how the measurement is to be carried out. On the other hand, there are quite a few parameters, e.g. large signal parameters, that can be specified only as effective values since the amplitude of the driving signal must be specified. These parameters are little suited to serve as universal data, but are frequently used, nevertheless, particularly in pulse operation.

Some applications require information about the elements of an equivalent circuit and others information relating to thermal parameters, etc. [7.11, 7.21].

In accordance with the mode of operation the parameters can be divided into several groups.

1. Static parameters, which can be in most cases derived from the characteristic curves.
2. Dynamic parameters, comprising, for example, small signal values at low and high frequencies (quadripole parameters), cut-off and characteristic frequencies, and the elements of equivalent circuits.

3. Pulse parameters, which describe switching times and switching time constants;
4. Thermal parameters, which include the temperature of the junction, thermal resistances and a thermal time constant;
5. Noise parameters.

This classification is applied for describing appropriate measurement methods in Chapters 2 and 6; Chapter 1 describes the most important parameters and the limiting values of the junction transistor.

There will be no attempt to discuss in detail how some particular [7.27] physical and constructional parameters are determined, e.g. base width [1.100], diffusion constant, effective lifetime [1.40, 3.166, 3.119, 3.175], impurity density, drift factor [1.40, 3.174], junction surface area, etc. Such quantities are, in principle, included in the elements of an equivalent circuit, but specific points relating to the construction and type are also of importance and have to be taken into account in each case; see for example the following literature references: [3.57, 3.46, 3.93, 3.165, 1.40, 3.120, 3.172, 3.174, 3.173, 3.83, 3.54].

All the discussion in the following text refers, unless otherwise stated, to transistors.

CONTENTS

1

TRANSISTOR PARAMETERS

1.1 STATIC PARAMETERS

All applications of transistors are based, in one way or another, on their d.c. operation, be it by the setting of the operating point, in the amplification of very large signals with relatively slow variations, or in switching operations. The d.c. operation of an idealised transistor model (inner transistor) having current paths of no resistance ($r_B \approx r_{C'C} \approx r_{E'E} \approx 0$) can be described by the following system of equations which may be inferred by physical discussion [1.1, 1.4, 1.110]; directions of current flow are as shown in Fig. 1.1:

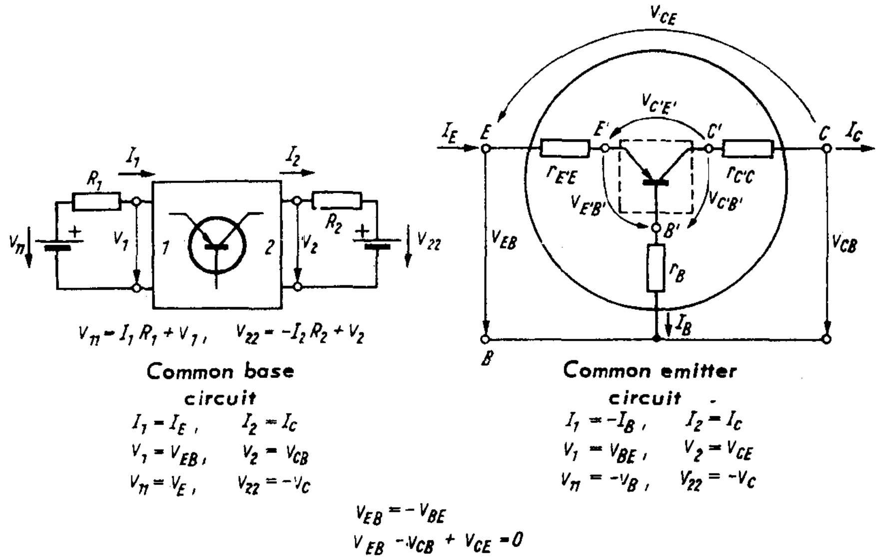
$$I_E = -\frac{I_{EBO}}{1 - A_N A_I}\left(\exp\frac{V_{E'B'}}{V_T} - 1\right) - \frac{A_I I_{CBO}}{1 - A_N A_I}\left(\exp\frac{V_{C'B'}}{V_T} - 1\right)$$
$$I_C = -\frac{A_N I_{EBO}}{1 - A_N A_I}\left(\exp\frac{V_{E'B'}}{V_T} - 1\right) - \frac{I_{CBO}}{1 - A_N A_I}\left(\exp\frac{V_{C'B'}}{V_T} - 1\right) \quad (1.1)$$

I_{EBC} - emitter leakage current (see Section 1.1.3);
i_{CBO} - collector leakage current (see Section 1.1.3);
A_N - d.c. amplification of the normal common-base circuit;
A_I - d.c. amplification of the inverse common-base circuit;
$V_T = kT/q$ - which may be termed the 'thermal voltage'.

The quantities above, I_{EBO}, I_{CBO}, A_N and A_I, will be regarded in our considerations as basic intrinsic properties of the transistor and will not be analysed further.

The 'thermal voltage' V_T has a value of about 26 mV at room temperature.

In modern transistors (mesa and planar types) and at the high loading which is frequent with these types, (1.1) are valid only when used with some additional fairly important limitations due to specific physical effects [1.1]. It is, therefore, more useful to



In a normally conducting *pnp* transistor I_E, I_B, I_C, V_{EB} and V_E have positive numerical values and V_{CE}, V_{CB}, V_C and V_B negative values. In *npn* transistors all numerical current and voltage values have signs opposite to those of *pnp* transistors

Fig. 1.1 Conventional directions of current flow in a transistor

start directly from the characteristic curves of the external transistor, i.e. from the graphical representation of the general relationships

$$I_E = f_1(V_{EB}, V_{CB})$$

$$I_C = f_2(V_{EB}, V_{CB})$$

with an implicit inclusion of these specific effects, and to consider such typical parameters and limiting values which describe and

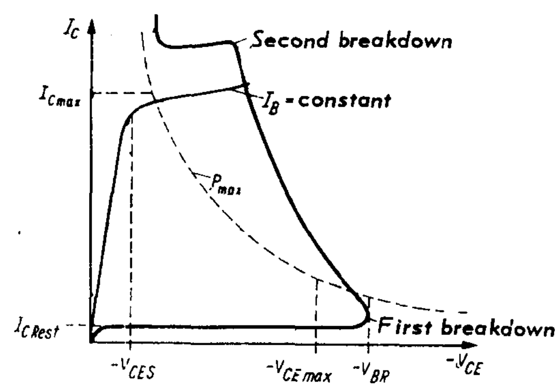


Fig. 1.2 Collector characteristics of transistor operating in common emitter circuit. (For further details, see text)

delineate the complete properties of a transistor [1.1].

Limiting values are dependent upon the operating point and can be given, as power, current or voltage limits. Since the power loss takes place mainly in the cut-off diode path (two-terminal path), i.e. in active normal operation in the collector diode, when the usual active operational range is considered, the effective parameters and limiting values can easily be found and interpreted by using the collector characteristics. An example of these for the common emitter circuit is given in Fig. 1.2.

1.1.1 POWER DISSIPATION. MAXIMUM CURRENT

The maximum permissible power dissipation is given by

$$P_{\max} = [I_E V_{EB} + I_C(-V_{CB})]_{\max} \approx I_C(-V_{CB})|_{\max}$$

and depends upon the maximum junction temperature $\vartheta_{J\max}$ which can be allowed and on the heat dissipation conditions which can be described in terms of a thermal resistance R_{th} where

$$P_{\max} = \frac{\vartheta_{J\max} - \vartheta_a}{R_{th}} = \frac{\vartheta_{J\max} - \vartheta_c}{R_{thi}} \tag{1.2}$$

In principle, it makes no difference whether in the above formula one uses the thermal resistance R_{th} (determined by the construction of the transistor, its envelope and cooling conditions, and the ambient temperature ϑ_a), or the inner thermal resistance R_{thi} where the case temperature ϑ_c is treated as the reference point.

The maximum power dissipation is determined by the manufacturer as a limiting value, and is not one of those parameters that are being checked by the user. The power limit is given either

1. directly as a function of the case (ϑ_c) or ambient temperature (ϑ_a) as a graph pertaining to certain thermal conditions (heat-sink surface-area geometry and heat-sink material; see Section 1.4.1),
2. indirectly, by producing figures for the thermal resistance R_{th}, or R_{thi}, maximum temperature of the junction, $\vartheta_{J\max}$, and the highest permissible temperature difference between the junction and the environment, or casing.

In the region of large current operation, the limit is given by manufacturer's maximum currents ($I_{C\max}, I_{B\max}, I_{E\max}$). These values apply at a reference temperature, ϑ_0 (see Section 1.4). The values of maximum currents are fixed by the manufacturer mainly from thermal considerations in conjunction with reliability trials.