PROPERTIES AND APPLICATIONS OF TRANSISTORS

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FOREWORD

JEAN-PIERRE Vasseur's book on the properties and applications of transistors is a synthesis which falls naturally into the collection of the *Annales de Radioélectricité*. The author was one of the first French engineers to study the applications of transistors. He has been entrusted, within the Compagnie générale de télégraphie Sans Fil, with the organization of a series of lectures in order to initiate his colleagues in the use of the transistor: this book takes advantage of the experience acquired by the author in the course of his many discussions with engineers, more particularly familiar with electron tube technique. The subject dealt with is both one of the oldest and most modern in radio. The detection of radio waves by means of galena crystals goes as far back as the beginnings of radio. Yet the operation of this detector was not understood at the time, due to the absence of exact information on solid state physics. No past inventor had thought of arranging close together two biased point contacts on a galena crystal, which could have produced a transistor effect; this effect would certainly have been inferior to that obtained today with germanium crystals, but would have placed electronics earlier on the road which it is about to follow.

So solid state electronics long remained latent. It appeared in technique only in the form of copper oxide or selenium rectifiers. During the second world war, detection of ultra-high frequencies once more focused attention on point-contact detectors using silicon, and, to a certain extent, germanium. It was from the thorough study of these elements that the transistor was to make its appearance, using the motions of electrons in an almost-perfect crystal, acting in a manner analogous to that of the vacuum in conventional tubes.

Transistors rapidly brought into action extensive facilities throughout the world and to this end specialists of very different disciplines were called upon, from "technologists" for solving problems such as the perfect sealing of casings, to theoreticians in pure physics for the mathematical determination of the electrical properties of crystals. Thus germanium has now become the solid which is understood both the best theoretically and the one which can be separated with the highest degree of purity and with the greatest perfection in crystal structure.

Solid state electronics has meanwhile developed in many other fields. Ferrites are now well known; some of their properties are used in "memories" and in ultra-high frequency work. Ferro-electric bodies are also the subject of considerable study, although they have not so far resulted in actual devices. Solid state "masers" raise considerable hope for low-noise amplification, and a beginning has been made in the development of applications based on the superconductivity of solids cooled down to near absolute zero.

All these new arrivals are accelerating the evolution of electronics. The introduction of semiconductors in equipment does, however, raise engineering problems and questions of definition of circuits, which have to be thought out afresh.

For, on the one hand, tube analogy is inadequate and, from habits contracted in dealing with tubes, it has been necessary to revise fundamentally the conceptions of tube users. M. Vasseur has done this most happily taking as a starting point the use of two-ports, which has provided him with the opportunity of giving a summary of their theory.

On the other hand, the use of transistors has had the effect of steadily transforming circuit engineering, by the "miniaturization" of components and by changing the orders of magnitude. The rapid progress of transistors towards ever higher frequencies is constantly opening up new domains of application for this branch of circuit theory.

M. Vasseur's book is thus most timely since it arrives at a moment when transistorized equipment is leaving the laboratory to enter the field of industrial design. It will most certainly be an effective contribution to the engineering literature on these new techniques.

MAURICE PONTE

INTRODUCTION

SINCE its appearance in 1948, the transistor has been the subject of a considerable amount of study and development work. It has become one of the essential elements of modern electronics, and its sphere of application, already vast, must certainly increase in the years to come. The performance of transistors has been considerably improved, in particular in the realms of high-frequency and high-power devices, and their quality is now comparable with that of the best vacuum tubes.

The evolution of the transistor was extremely rapid, and is indeed still going on. However, the essential principles of its working, manufacture and application are now well known, and it is most probable that it will, for many years to come, be applied more to the development of already known techniques rather than in the opening-up of new lines of approach.

Transistors have many similarities to vacuum tubes, which is rather surprising for two devices with such different structures. Equally, there are great differences between the two. There exist two types of complementary transistors working with currents and voltages of opposite sign, which make possible set-ups which have no equivalents with valves. On the other hand, transistors have more linear characteristics than valves, especially with low supply voltages, but their internal feedback is much greater and they are much more sensitive to the temperature at which they are operated. Another great difference lies in the fact that the input impedance of transistors is very much smaller than that of valves, which appreciably modifies certain circuits. Transistors have considerable advantages in their mechanical robustness, their high efficiency resulting from the lack of necessity for a heater, their small size and their long life. Transistor circuits are thus often quite comparable with valve circuits, but the orders of magnitude of the associated circuit elements and the methods for calculating circuit behaviour are rather different. Rather than reason by analogy, it is always preferable to think in terms of transistors only, and to derive circuits directly using their properties to the full.

The object of this book is to build up the essential elements which are necessary for the theory and practice of transistor circuits. It is addressed to students and engineers who wish to begin or to improve their present knowledge of this new branch of electronics. The point of view adopted is that of the practical man who is not interested in a purely theoretical approach, but who wants to understand the working of his apparatus and who wants to be able to design his own without copying existing circuits.

It is with this in mind that the subjects of the characteristics and properties of transistors and their basic circuits have been approached in this book. Many numerical examples are given to provide some idea of the orders of magnitude of all the quantities considered, and the best methods of measuring them are discussed.

It is assumed that the reader has a broad acquaintance with the fundamentals of electronics, and all the mathematics has been kept down to an elementary level. All intermediate algebra in the derivation of any formula has been eliminated, leaving only the initial assumptions and the results. So that they may be used quickly, the commonest formulae have been collected into tables or put into graphical form whenever possible.

This work is intended to deal only with well established general principles, which must form the foundation in any application, without considering any circuit in particular.

By far the largest part of the work is concerned with junction transistors, which are practically the only ones used nowadays. The special properties of point-contact transistors are mentioned in passing, partly because some junction devices have similar properties. In addition, radically different devices not yet developed commercially, such as the field-effect transistor, are briefly mentioned.

The first chapter explains briefly the physical principles of operation and the main methods of transistor manufacture. In particular, the natural equivalent circuit for the transistor is deduced from physical considerations, and its elements calculated in terms of the transistor's structure. These results allow a better understanding of the working of the transistor, but will not be used in the rest of the work, which does not assume any knowledge of solid-state physics.

The second chapter considers some fundamental ideas in the theory of linear two-ports in a form most suited to the analysis of transistor circuits.

The third chapter sets out the basic characteristics of the transistor, first its static characteristics and then its behaviour for small a.c. signals. In the latter case, the transistor may be replaced by an equivalent linear two-port whose possible forms are discussed. Finally, the variations of the equivalent network parameters with the working point and with temperature are considered.

The fourth chapter describes a single amplifying stage at low signal levels, applying the natural equivalent circuit to the transistor. Since the elements of this circuit are independent of frequency, the results obtained are valid for all frequencies at which the transistor gives any gain, and no arbitrary division is drawn between high- and low-frequency regions. The conditions under which a single transistor may oscillate by virtue of its internal feedback, and neutralizing circuits to overcome this effect, are first considered. The three methods of connexion of the transistor, common-emitter, common-base and common-collector, are then examined in turn. Their properties are studied as functions of frequency, and then, for low frequencies only, as functions of load and generator resistances.

The fifth chapter deals with the provision of bias, with stabilization of the working point and with the precautions to be taken to ensure correct operation at all temperatures.

The sixth chapter is devoted to an examination of the maximum power dissipation of a transistor, limited mainly by the thermal instability which can arise from the rapid growth of the cut-off current as a function of temperature. The results are presented in the form of universal curves and are applied to some of the commoner circuits.

Finally, the seventh chapter considers the noise level of transistors and the conditions to be fulfilled in building low-noise amplifiers.

The notations adopted are either those in common use, or those suggested in the international schemes for standardization. This has led to several quantities being given the same symbol, but only when no confusion is possible. The notations for two-ports and equivalent circuits must necessarily be complicated at first sight if all ambiguity is to be avoided. The paragraph devoted to this subject should be carefully read.

A certain number of results are new. This is particularly true of practically the whole of the sixth chapter and several passages in the fourth and fifth chapters. Also considerable use has obviously been made of existing literature. The references have been very carefully compiled, but it is almost impossible nowadays to quote all the authors who have contributed to the growth of our knowledge of transistors. References have therefore often been limited to a few recent articles in which the results obtained are given and extended further, and which themselves give a comprehensive bibliography.

The author finally has to thank Dr. M. Ponte, who suggested and encouraged this book, and who was responsible for seeing it through the press; M. L. Bouthillon, who read the manuscript and made many improvements upon it; Dr. C. Dugas, whose help in writing the first chapter was most valuable; Professor P. Aigrain and M. J. Riethmuller and his colleagues of the Semiconductor Department of CSF. Compagnie générale de Telegraphie Sans Fil, who made many helpful suggestions in the course of constructive discussion.

SYMBOLS AND NOTATION

1. MEANING OF SYMBOLS

Unless otherwise stated in the text, the principal symbols used will have the following meanings. The figures in brackets indicate the section where the symbol is defined or introduced for the first time.

a	Cooling coefficient or thermal resistance (6.3 and 6.4)
a	Parameter of a two-port (subscripts 11, 12, 21 or 22) (2.2)
A	Area of a junction (1.2.B)
A	Power amplification of a transistor (ratio between the power delivered to the load and the power dissipated at the input) (2.7)
b	Base connexion of a transistor (1.3.G and 3.1)
b'	Internal base of the transistor, connected to the external base terminal by the base resistance $r_{bb'}$ (1.3.G and 3.1)
b	Parameter of a two-port (subscripts 11, 12, 21 or 22) (2.2)
b, B	Susceptance
c	Collector of a transistor (1.3.A)
$c_{12} = r_{12} + js_{12}$	Correlation coefficient of two noise signals (7.1.C)
C	Capacity of a condenser
C	Thermal capacity (6.6)
d	Diameter of a junction (1.3.G)
D	Diffusion coefficient for minority carriers (D_n for electrons and D_p for holes) (1.1.F)
e	Emitter of a transistor (1.3.A)
e	Instantaneous or alternating e.m.f.
e, e	Base of natural logarithms (2.718)
E	D.c. e.m.f.
E_d	Emitter-collector voltage drop for fully conducting transistor (6.3.D, Fig. 3.7)

$\mathscr{E}$	Electric field
f	General symbol for a function
f	Frequency
f_c	Frequency at which an impedance or admittance takes a value which is the mean of its high and low frequency values (4.4.A)
f_y	Critical frequency for the y-parameters (4.4.A)
$f_\alpha; f_\beta; f_\mu$	Cut-off frequencies for α, β and μ parameters (4.4.C and 4.4.E) (for which the magnitude of these parameters is 3 dB below the low-frequency value)
F	Noise figure for narrow band width df (7.1.H)
$\mathscr{F}$	Noise figure for wide band (7.1.H)
g, G	Conductance
g_l	Leakage conductance on the surface of a transistor (1.3.G and 3.3.A)
G	Transducer gain of a transistor (ratio between the power delivered to the load and the maximum power available from the generator) (2.7)
G_{av}	Available gain (ratio between the power delivered to a matched load and the maximum power available from the generator) (7.1.H)
G_{max}	Maximum gain between matched impedances (2.7)
G_{inv}	Gain of transistor with collector and emitter interchanged (2.7)
G_I	Insertion gain (ratio of the power delivered to the load to the power delivered if the load were connected directly to the generator (2.7)
$\mathscr{G}$	Voltage gain (2.7)
$h = h^r + jh^i$	Parameter of a two-port (subscripts 11, 12, 21 or 22) (2.2)
i	Instantaneous or alternating current
I	D.c. current
$I_{eo}; I_{bo}; I_{co}$	D.c. current from the emitter, base or collector respectively, at a reference temperature T_0 (6.3)
$I_{oe}; I_{ob}; I_{oc}$	D.c. current from the emitter, base or collector respectively, at a temperature low enough for I_σ to be negligible (6.3)
I_m	Peak current
I_σ	Reverse current of the collector-base diode with the emitter on open-circuit (3.1)

I_s	Initial value of I_σ for a reverse collector voltage of the order of ten or twenty times $\left(\frac{KT}{q}\right)$ (1.2.A and 6.3)
I_{so}; $I_{\sigma o}$	Values of I_s and I_σ respectively, at a reference temperature T_0 (6.3)
$\mathscr{I}$	Imaginary part of a complex number
	$= \sqrt{-1}$
k	A constant
K	Boltzmann's constant ($1{\cdot}37 \times 10^{-23}$ J/°K or $0{\cdot}863 \times 10^{-4}$ eV/°K)
l	Thickness of the space-charge region near a p–n junction (1.2.B)
$j = l^r + jl^i$	Parameter of a four-terminal network (subscripts 11, 12, 21 and 22) (2.2)
l	Luminous flux (6.7.A)
L	Self-inductance
L	Diffusion length of minority carriers (L_n for electrons and L_p for holes) (1.1.G)
m	Effective mass (m_n for electrons and m_p for holes) (1.1.B)
n	Electron density, especially when electrons are minority carriers (1.1)
N	Turns ratio of a transformer
N	Electron density, especially when electrons are majority carriers (1.1)
N_b	Density of ionized atoms in the base region of a transistor (1.3.D)
p	Hole density, especially when holes are minority carriers (1.1)
P	Hole density, especially when holes are majority carriers (1.1)
q	Charge of an electron (1.6×10^{-19} C)
Q	Circuit magnification factor
Q	Electric charge
r, R	Resistance
$\mathscr{R}$	Real part of complex number
s	Surface recombination rate (1.1.G)
$S = \overline{\lvert u\rvert^2}$	Spectrum of a random signal (7.1.B)

$S = \dfrac{dI_c}{dI_\sigma}$	Stability factor of a transistor (5.2)
$\dfrac{S}{N}$	Signal-to-noise ratio (7.1.I)
t	Time
T	Symbol for a transistor
T	Period of a signal
T	Absolute temperature (expressed in degrees Centigrade for numerical applications)
T_A	Ambient temperature (6.3)
T_o	Reference temperature (6.3)
T_1	Equilibrium temperature (6.3.A)
$u(f)$	Complex amplitude of a random sine wave (7.1.B)
$U(t)$	Random function of time (7.1.A)
v	Instantaneous or alternating voltage
V	D. c. voltage
V_a	Avalanche voltage (for which $\alpha = 1$) (3.8)
V_p	Punch-through voltage (3.9)
V_φ	Constant voltage occurring in connection with the capacity of a reverse-biased junction (1.2.B and 3.3.B)
W	Base thickness of a transistor (1.3.C)
W	Power
W_d	Forward power (almost independent of temperature) (6.3.A)
W_L	Power dissipated in the load (2.7)
W_m	Maximum power
W_o	Thickness of the slice of semiconductor in an alloyed transistor (1.3.G)
W_s	Reverse power (increases rapidly with temperature) (6.3.A)
W_u	Useful output power from a push-pull circuit (6.3.D)
x, X	Reactance
y	Parameter of a two-port (subscripts 11, 12, 21 and 22) (2.2)
y, Y	Admittance
z	Parameter of a two-port (subscripts 11, 12, 21 and 22) (2.2)
z, Z	Impedance
α	Short-circuit current gain in the common-base connexion (1.3.C and 3.1.A)

β	Short-circuit current gain in the common-emitter connexion (1.3.C and 3.1.A)
γ	A characteristic temperature of a semiconductor such that I_o increases as $\exp\left(-\frac{\gamma}{T}\right)$ (3.1.A)
Δ	Symbol for a determinant (2.4)
Δf_n	Noise bandwidth of an amplifier (7.1.H)
ε	Energy gap in a semiconductor (1.1.A and 3.1.A)
η	Efficiency of a supply circuit (5.4.A)
θ	Lifetime of minority carriers (1.1.G)
θ	$= \frac{T_o^2}{\gamma}$ (6.5)
$\varkappa$	Permittivity
$\varkappa_o$	Permittivity of free space $\left(\frac{1}{9} \times 10^{-9}\ \text{m.k.s.}\right)$
λ	$= \frac{q}{KT}\left(\frac{1}{\lambda} = 0{\cdot}025\ \text{V at ambient temperature}\right)$ (3.1)
μ	Mobility (μ_n for electrons and μ_p for holes) (1.1.E)
μ	Attenuation of a passive two-port (5.4.C)
μ	Parameter h_{12} for a common-emitter transistor (3.2.A)
π	$= 3{\cdot}1416$
ϱ	Resistivity
ϱ	Effective value of all resistances connected between a transistor electrode and earth
ϱ	Forward resistance of a diode (6.7.C)
ϱ	Correlation function (7.1.C)
σ	Conductivity
φ	Phase angle
φ	$= \frac{f}{f_\alpha}$
ω	$= 2\pi f$, angular frequency.

2. MEANING OF SUBSCRIPTS

e, b, c	Refer respectively to emitter, base and collector of a transistor
b'	Refers to the internal base connexion (inaccessible)
i	Refers to the input circuit
o	Refers to the output circuit
G	Refers to the generator
L	Refers to the load
m	(sometimes *max*) indicates a maximum or peak value
min	Indicates a minimum value
mean	Indicates a mean value
opt	Indicates an optimum value
n	Refers to the elements in a neutralizing circuit, or to the parameters of a neutralized transistor
n	Refers to a noise voltage or current
n	Refers to electrons
p	Refers to holes
o	Indicates the low-frequency value of a parameter (e.g. α_o and h_{12co} are the low-frequency values of α and h_{12c})
o	Indicates the value of a d.c. current, a resistance or a power at the reference temperature T_o (e.g. I_{so}; W_{so} and r_{co} are the values of I_s, W_s and r_c at the temperature T_o)
*	Indicates the complex conjugate (e.g. $z^* = r - jx$ if $z = r + jx$)
$\overline{\quad}$	Indicates the mean value (e.g. $\overline{\|e_n\|^2}$ is the mean value of $\|e_n\|^2$).

Currents and voltages are denoted by capitals when they represent d.c. quantities and by small letters when they represent instantaneous or a.c. quantities.

The electrode currents of the transistor are marked by the corresponding subscripts, and, unless otherwise stated, are taken as positive when they flow towards the transistor.

The voltages between a transistor electrode and the common electrode are marked by the two corresponding subscripts. The subscript for the common electrode is placed second, and, unless otherwise stated, the positive sense is taken as from the common electrode to the electrode under consideration (e.g. v_{eb} is the instantaneous or a.c. voltage between emitter and base in the common base connexion. The positive sense is from b to e).

3. PARAMETERS OF A TWO-PORT OR EQUIVALENT CIRCUIT

For the purposes of calculation, a transistor working at a sufficiently low signal level may be replaced by an equivalent linear two-port (Section 2.1). Since the transistor has only three electrodes, one of these must always be common to both input and output circuits. Generally, the parameters of a two-port or equivalent circuit for the transistor and

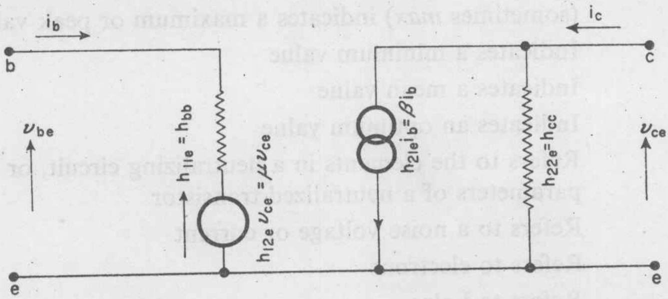


FIG. 1. Notation for the hybrid equivalent network, common-emitter connexion.

input and output impedances or admittances will be represented by small letters. The use of capitals will be reserved for elements of the external circuit.

Equivalent circuits with two generators are the natural representations of the characteristic equations of a two-port (Fig. 2.5). A parameter is represented by a letter (z, y, h or l) indicating the configuration used, two numerical subscripts (1 or 2) indicating the parameter's position in the system, and one subscript (e, b or c) indicating the common electrode (examples in Table 2.II).

The h-parameters for the common-emitter connexion are frequently used, and they will be expressed by the shorter notation given in Fig. 1.

The real and imaginary parts of the parameters are written as follows:

$$z = r + jx \qquad y = g + jb$$
$$h = h^r + jh^i \qquad l = l^r + jl^i . \tag{1}$$

The determinants are denoted by Δ, followed by the relevant parameter and a subscript to indicate the common electrode (e.g. $\Delta h_e = h_{bb}h_{cc} - \mu\beta$).

The main equivalent circuits with one generator are given in Fig. 2.6. The commonest of these, and the corresponding notations, appear in Table 2.II.

The parameters which are often used in practice are written more simply. Those so treated relate to the *T*-network for the common-base

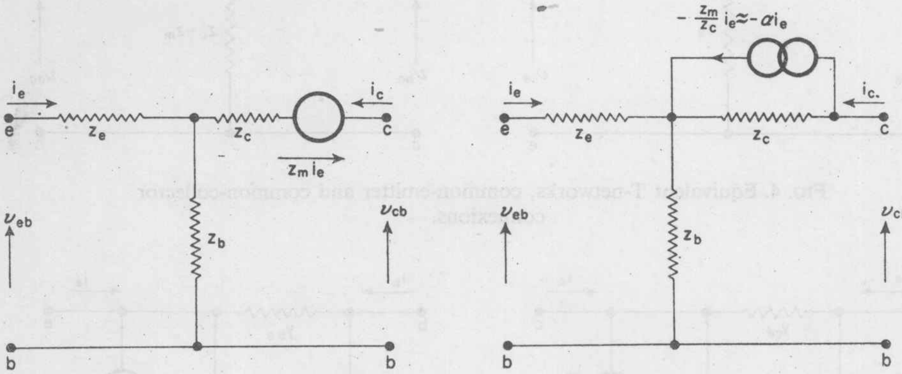


FIG. 2. Notation for the equivalent *T*-networks, common-base connexion.

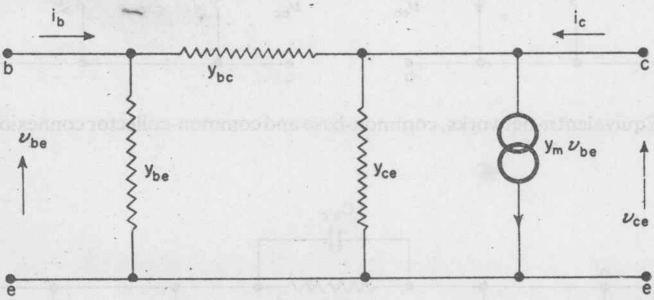


FIG. 3. Notation for the equivalent π-network, common-emitter connexion.

connexion (Fig. 2) and the π-network for the common-emitter connexion (Fig. 3). The parameters of networks of the same types for the other connexions are also given in Figs. 4 and 5.

We shall often have occasion to use the natural equivalent circuit, in which the base resistance $r_{bb'}$ is separated from the transistor proper. The parameters in Fig. 6 are for the common-emitter connexion; those for the other connexions may be obtained from them, using Fig. 5, and are given in Fig. 3.34.

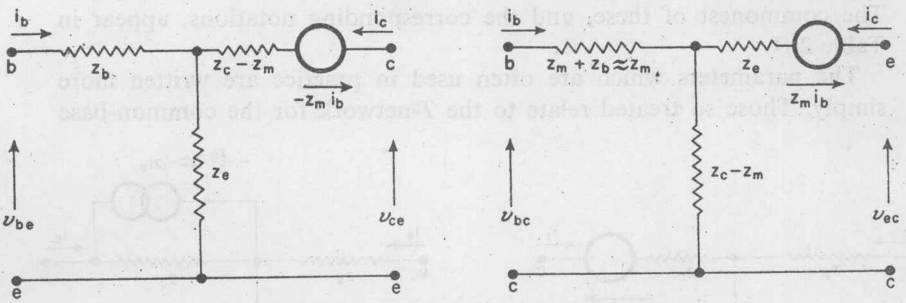


FIG. 4. Equivalent T-networks, common-emitter and common-collector connexions.

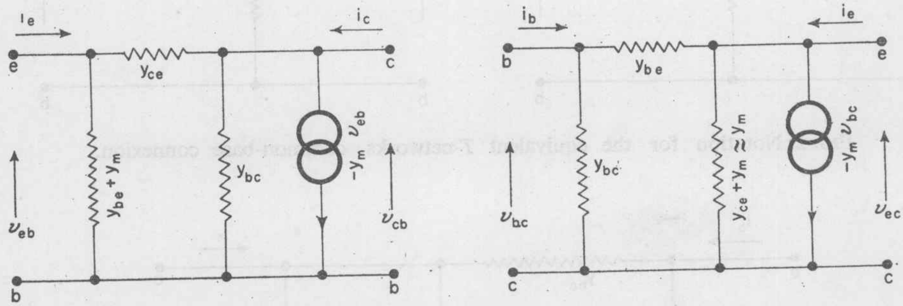


FIG. 5. Equivalent π-networks, common-base and common-collector connexions.

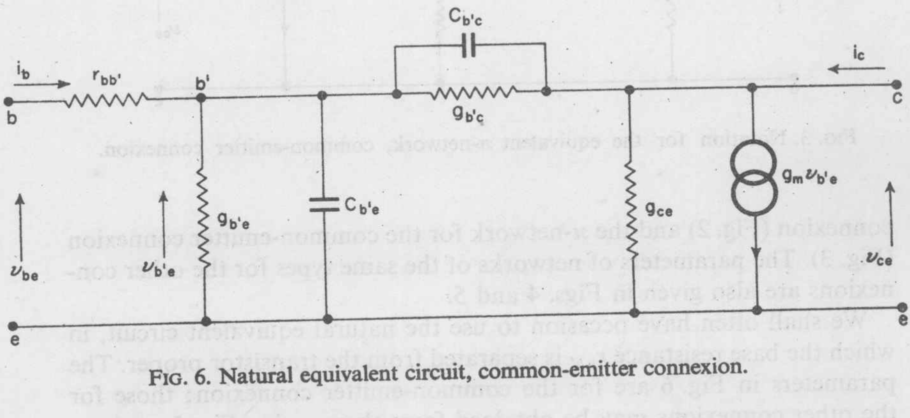


FIG. 6. Natural equivalent circuit, common-emitter connexion.

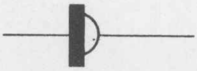
4. GRAPHICAL SYMBOLS

In addition to the usual symbols, the following will be used:

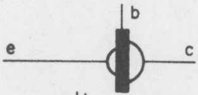
Voltage generator

Current generator

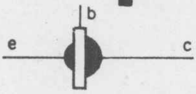
n p junction (the *n* region, in black, corresponds to the cathode)



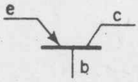
pnp junction transistor



npn junction transistor



Type *n* point-contact transistor



Type *p* point-contact transistor