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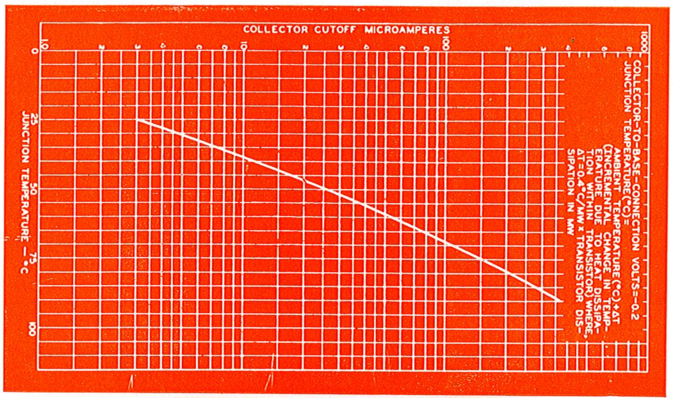
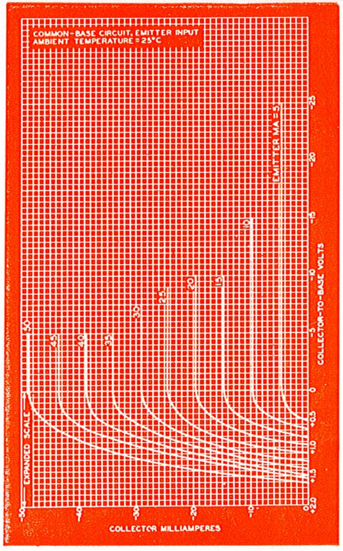
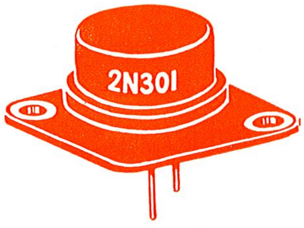




Transistor

SPECIAL ISSUE NO. 2



AMALGAMATED WIRELESS VALVE COMPANY PTY. LTD.

TRANSISTORS AND THEIR PARAMETERS

by H. R. Wilshire, A.S.T.C., S.M.I.R.E., A.M.I.E. (Aust.)

(Applications Laboratory, A.W.V.)

SUMMARY

The basic principles of operation of the transistor, which is a comparatively recent addition to the family of crystal valves, are discussed. It is compared with its counterpart the thermionic valve and the need for the methods used to describe its properties are noted. The various circuit configurations in which transistors are used and tables relating the various systems of parameters with each other and with the circuit are set down. A list of circuit design equations and an example of their use are given.

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1. INTRODUCTION

A relatively short time has elapsed since the first announcement in 1948 of the work on semi-conductors by J. Bardeen and W. H. Brattain (¹) and by W. Shockley (²) in which they described a new version of the crystal valve — the semi-conductor amplifier triode or "transistor".

Before the development of the transistor, the crystal valve family comprised only one member — the semi-conductor diode. As happened in the case of the thermionic valve, the addition of a control electrode converted the diode to a triode, made signal amplification possible and added the second member to the family of crystal valves.

Since the early days much has been learned concerning the design of transistors and their application to the many problems for which previously the evacuated thermionic valve was the only answer.

As the reader of transistor literature will verify, an enormous amount of work has been carried out on transistors in the intervening years by the world's scientists and engineers. One result of this work is that use has been made of a large number of symbols, diagrams, equations and methods of presenting and specifying their characteristics and performance.

The properties of any device can be expressed using a suitable system of parameters, e.g., for a thermionic valve, the most important are its transconductance (g_m) in μA/V or mA/V, plate resistance (r_p) in ohms or megohms, amplification factor (μ) and electrode currents for particular values of electrode voltages. The transistor version of the crystal valve although it carries out the same function of signal amplification as the thermionic valve, operates in a fundamentally different way and requires a different and generally more complex system of parameters. Unfortunately, and perhaps unavoidably so in the development of such a device, different workers have at times used different symbols and terms to describe the same characteristics. Different ways of calculating transistor performance have also been used by various authors and a certain amount of confusion has been caused thereby, even to those familiar with the peculiarities of transistor action. The main purpose of this article is to attempt to reduce the number of points about which confusion now exists.

Before dealing with the parameters in detail, it may be interesting and informative to discuss some fundamentals of transistor operation and to see how this crystal valve compares with the thermionic valve.

2. BASIC PRINCIPLES OF TRANSISTOR ACTION

(a) Characteristics of Semi-conductors:

The development of the transistor was due to the realisation by the Bell Laboratory workers that in an appropriate material — the semi-conductor — an electric current could be carried by a mechanism other than that of electron flow. The theory of current flow in the opposite direction to the normal by means of the movement of "holes", which behave like positive charges, was the foundation stone upon which the transistor was built.

Students of physics, and in particular those familiar with the structure of matter, will know that the big difference between a metal and an insulator is that the latter have no 'free' electrons, i.e., all the electrons in each of their atoms are very rigidly tied to their fixed orbits in the atoms. The relatively "free" electrons of a metal can be easily dislodged from their regular paths or orbits by the application of an electrostatic force or voltage and thus can be made to progress from one end of the material to the other. The metal has a "low resistance", while the insulator, which requires a considerable force to cause electrons to move, has a "high resistance". Semi-conductors are solid materials which are midway between these two extremes. They have an atomic structure in which the bonds between the outer or valence electrons and the atom are relatively easily broken. Germanium and silicon are such materials.

It was found by the early workers that the properties of the semi-conductor germanium could be profoundly affected by the introduction of small amounts of certain impurities. The effect of impurities is governed by the behaviour of the valence electrons of their atoms. These are the electrons which are held by relatively weak forces to the atomic nucleus and which take part in chemical action and move under the effect of an electric force or voltage. Germanium (Ge) has 4 valence electrons, a material such as arsenic or antimony has 5, and one like indium has 3. When an impurity like arsenic is introduced to Ge, the crystal lattice is formed from Ge atoms having 4 valence electrons and those of the impurity having 5. Four of these five are required to form the link with the Ge atoms in the crystal, leaving one surplus which becomes free and can easily be moved through the material. These impurities are called "donors" and because the current conduction is by **negative** electrons or carriers the semi-conductor is called an "n" type.

When an impurity such as indium, whose atoms have three valence electrons, is added to germanium, only 3 electrons are available to satisfy the four bonds required by the germanium crystal lattice. This leaves a vacancy and is said to form a "hole". The hole may be filled by the movement of an electron from a nearby lattice, leaving a hole in that lattice. The action is repeated from one lattice to another, and the hole can be considered as moving in the opposite direction to that of the electron. Such an impurity is called an "acceptor", since it causes the crystal lattice to accept electrons. The current conduction is by positive carriers or holes which behave like positive charges and the semi-conductor is called a "p" type.

(b) Diodes — Point Contact and Junction:

If a pointed metal contact is made to a semi-conductor of the "n" type, the combination becomes a point contact diode and has the special voltage-current relationships shown in Fig. 1.

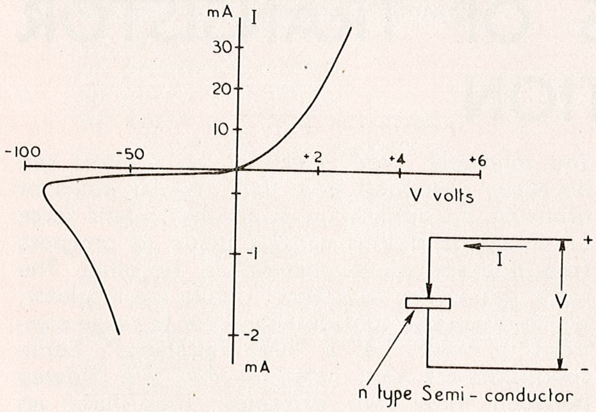

Fig 1

A similarly shaped characteristic can be obtained when a junction is made between a "p" type and an "n" type of semi-conductor. The resulting curve, which is shown by the full line in Fig. 2, reveals some important differences over that of the point contact diode.

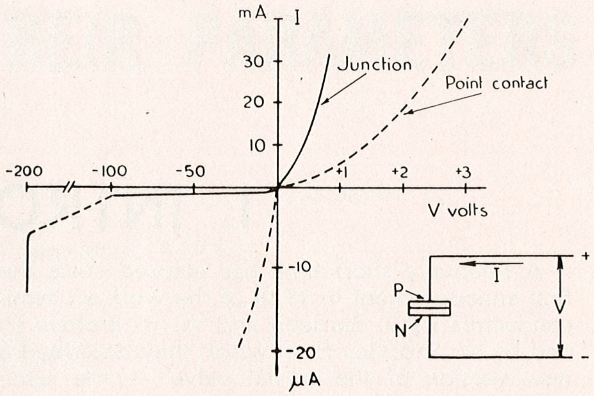

Fig. 2

Note the steepness of the curve of forward current versus voltage and the very small reverse current that flows for quite high reverse voltages. In other words the junction diode has a much lower forward resistance and a higher reverse resistance than the point contact type. The characteristic of the latter, drawn to the same scale as that used for the junction diode, is indicated by the dotted line of Fig. 2.

(c) Transistors — Point Contact:

Transistor action came about when it was discovered that, if a second point was brought into contact with the semi-conductor material of the diode near to the first contact and biased appropriately, a current flowing in the forward direction across the first diode, could profoundly affect the current flowing across the second diode. This was the point contact transistor. Its general characteristics are shown in Fig. 3.

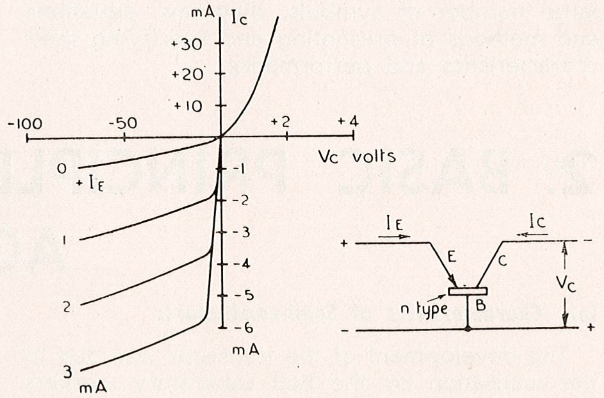

Fig. 3

The point contact transistor may have a current amplification of between 2 and 4 in contrast to that of the simple junction type which theoretically cannot exceed unity. The reason for the high current gain of the point contact transistor is not exactly understood and several theories exist concerning its behaviour. An additional feature of this type is that due to the physical nature of its point contact, the emitter—base contact area is small and hence it has a low internal capacitance and relatively good high frequency response. On the debit side are the following characteristics:—
(i) is fairly non-linear over the operating region,

(ii) has low output resistance, and (iii) may develop a negative resistance or internal positive feedback over the operating region. The feedback becomes more positive as the resistance in the base circuit increases and if this resistance is high enough the feedback will be sufficient to cause the circuit to oscillate. For this reason the base resistance must always be low when using a point-contact transistor. Every effort is made when manufacturing these types to keep the internal base resistance so low that it is stable in all types of circuits. This inherent instability generally limits the use of point-contact types to grounded base circuits since in this type of circuit the external resistance added in series with the base is a minimum.

Fig. 3 shows the characteristics of the more commonly available type of point contact transistor which has an "n" type of semi-conductor for the body. They may also be made from "p" type material and then will have a somewhat better high frequency response. This is brought about by the fact that the electrons, which are the charge carriers making up the collector current in a transistor of this type, have about twice the mobility or speed of movement of holes and it is thus easier for them to follow high frequency signals. The operation is otherwise similar except that the polarity of the emitter bias and the collector voltage is reversed.

(d) Transistors — Junction:

Action similar to that of the point contact transistor can be obtained by manufacturing a unit in such a way that a region having either "p" or "n" type characteristics is sandwiched between regions having the opposite characteristic (i.e., "npn" or "pnp"). See Fig. 4. If contacts are made to each of these regions and the polarity of the voltage applied across each other of the junctions is arranged to bias, say the left hand junction in the direction of easy current flow and the right hand junction in the high resistance direction, then a variation of current into the emitter or across the emitter-base junction will control the current flowing from the collector or across the base-collector junction. Since the emitter-base junction represents a low resistance and the collector-base junction a high resistance a power and a voltage gain is obtained between emitter and collector. (Power = I^2R and, since the collector current ≈ the emitter current, the higher collector circuit resistance through which this current flows gives a power and voltage gain.)

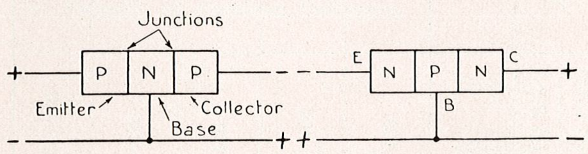

Fig. 4

As in the case of the point contact types the two forms of junction transistor are similar in operation except that the polarities of the direct supply voltages are reversed. (See Fig. 4.)

In the junction transistors, as distinct from the point-contact type, most of the current carriers — either electrons or holes — released by the emitter, reach the collector. The base current is therefore small compared to either of the currents flowing in the other circuits. In other words the near equality between emitter and collector currents (both direct and small signal alternating values), means that α_{fb} — the emitter to collector current amplification factor — is near unity. The low base current means that the base to collector current amplification factor α_{fe} is high.

If the junction transistor was perfect the emitter current would equal the collector current with base current = 0. The resultant high input impedance would give the transistor in the grounded emitter circuit the characteristics of a high performance thermionic valve. Due mainly to the combination of holes and electrons in the base region the ratio of these two currents can never equal unity. Values of 0.98 are commonly achieved in modern transistor manufacture.

The voltage-current characteristics of a typical junction transistor are shown in Fig. 5.

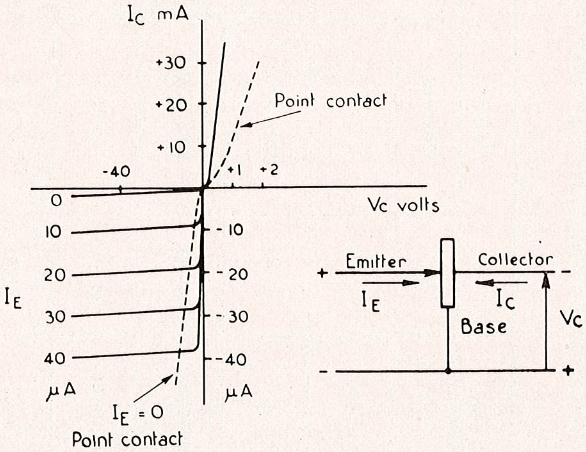

Fig. 5 Characteristics of Typical "pnp" Junction Transistor.

The curves of Fig. 5 show some of the important differences between the junction and the point-contact transistors. One of the most striking is the different slope of the collector voltage-current characteristic both in the forward and reverse directions. This means of course that the dynamic resistance of the collector under operating conditions, i.e., with the collector biased in its reverse direction is very much higher than for the point-contact type. In fact it has a value one order of magnitude higher. The dashed curve of Fig. 5 shows the characteristic for $I_E = 0$ of the point-contact transistor represented by Fig. 3 drawn to the same scale as the junction type. Note the flatness of collector characteristics and the small values of collector currents.

TABLE I.* Characteristics of Various Types of Crystal Valve

Type	Cut-off Freq. Mc/s.	Power Dissipation mW.	GAIN			BIAS		IMPEDANCE	
			Power dB	Current	Voltage	Emitter mA.	Collector Volts	Input ohms	Output kΩ.
Point Contact Triode	1–>100	100–400	20–30	2·0–4·0	30–50	≑1 (0·3v.)	≑30	0–200	10–50
N.P.N. Grown Junction Triode	1–20	20–50	30–40	0·98–0·99	100–200	≑1 (0·2v.)	≑5	50–100	500–2000
P.N.P. Alloy Junction Triode	0·5–>20	20–30,000	30–40	0·96–0·99	100–200	1–10 (0·2–2·0v.)	5–40	50–100	200–1000
P.N.P. Alloy Junction Triode (Common Emitter)	0·05–>1	20–10,000	35–45	25–100	≑500	— (I_B = 1·0mA.)	≑5	≑1000	≑50
P.N.P. Diffused Junction Triode (Drift)	1–600	20–50	20–30	0·95–0·99	≑100	≑1	≑10	≑50	100–500
Point Contact Variable-alpha Tetrode	Emitter (1) 1–100 Emitter (2) 0·3–3	100–400	20–30	2–4 Both emitters 2–20 (variable)	30–50	Emitter (1) ≑ 1 Emitter (2) ≑ 10	≑30	0–200	2–50
P.N.P.N. Grown Junction Triode (Hook Collector)	0·1	20–50	30–40	≑100	≑100	0·02	≑5	50–100	≑100
N.P.N. Double Base Junction Tetrode	10–100	20–50	20–30	0·85–0·90	≑100	≑1	≑5	50–100	100–500
Surface Barrier Triode	30–>100	2–10	20–30	0·85–0·95	≑100	≑0·5	3	≑30	≑100
Field Effect (unipolar)	≑100	300	15–25	10	—	Gate ≑10v.	Drain ≑30	$\doteqdot 10^6$	≑100
P.N.I.P. Junction Triode (Intrinsic Region)	100–250	—	—	—	—	—	—	—	—
"SPACISTOR"	1,000–10,000	—	>70	—	3,000	—	—	$>20 \times 10^6$	>20,000

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* This table has been extracted from "Handbook of Semi-Conductor Electronics" edited by Lloyd P. Hunter. and acknowledgment is hereby given.

The difference between the current amplification factor for the two types is also shown by these two sets of curves. The current amplification-emitter to collector — is the change in collector current caused by a change in emitter current with the collector voltage maintained constant. Fig. 5 shows this to be <1 for the junction transistor whereas Fig. 3 shows a value ≈ 2 for the point-contact type.

There are other important differences: e.g., due to the junction type of union between the dissimilar semi-conductors in this type of transisfor the capacitance effects are much greater and good high frequency response is harder to achieve. For the same reason the currents that the junction type can carry without overheating are much higher than can be used in the point-contact types.

A vast amount of time and money has been spent on the improvement of the junction transistor since the first was announced in 1951. Many different types all based on the junction principle, have been introduced and some of these are capable of useful performance up to frequencies of hundreds of Mc/s.

A comparison of the characteristics of the majority of transistor types is shown in Table 1.

(e) Summary of General Transistor Data:

A summary of the main points discussed above is given below:—

(i) General Properties of Semi-conductors.

"n" type — current conduction by electrons.
"p" type — current conduction by holes.
Impurities giving "p" type conduction — antimony, arsenic, phosphorus, etc.
Impurities giving "n" type conduction — boron, indium, gallium, aluminium, etc.

(ii) Polarity of Applied Voltages.

Transistor Type	Type of Semi-conductor	Emitter	Collector
Point Contact	n p	Positive Negative	Negative Positive
Junction	pnp npn	Positive Negative	Negative Positive

Emitter is biased in forward direction, i.e. direction of easy current flow.
Collector is biased in reverse direction, i.e., direction of difficult flow or high resistance.

(iii) General Properties of Transistors.
The junction type has lower noise, better stability and uniformity, can dissipate higher power and has poorer frequency response than the point contact type. A comparison of other features follows:—

Feature	Point Contact	Junction
Year Developed	1948	1951
Type of semi-conductor	Base — "n" or "p"	pnp or npn
Most common type	n	pnp
Output Resistance	10-50 KΩ	100-2000 KΩ
Current Amplification (emitter to collector)	2-4	<1 (0.85-0.99)

(f) Convention for Sign of Currents and Voltages and Transistor Symbols:

Before considering in detail the various ways of representing the characteristics and performance of a crystal valve it is necessary to formulate a set of rules which will fix the sign or direction of currents flowing in and applied to every element of the device.

The convention which has been generally adopted is the standard one applied to thermionic valve circuits and to the analysis of networks of all kinds.

Current is assumed to flow in a direction opposite to that of the movement of electrons. This is in agreement with established practice and is illustrated in Fig. 6.

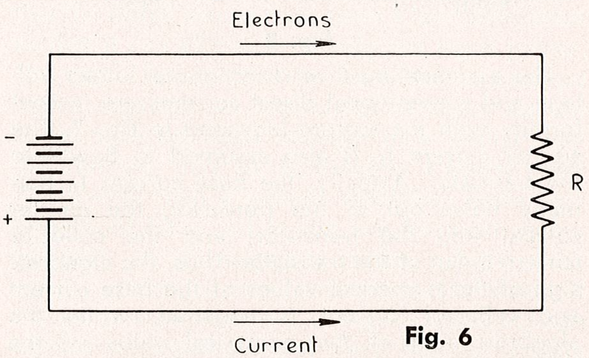


Fig. 6

The movement of the electrons and the current can be considered as a flow of charge carriers from one terminal of the battery to the other. The electrons are negative charge carriers and flow from the negative terminal of the battery through the external circuit to the positive terminal. The current can be considered as a flow of positive charge carriers in the opposite direction from the positive to the negative terminals as indicated in Fig. 6.

Another way of looking at this is to consider that the e.m.f. existing across the battery is set up internally by chemical action which causes electrons to accumulate at the negative end. The negative electrons are then attracted through the external circuit towards the positive end of the battery. The action is reversed for the current since it is assumed to be due to a flow of positive charges.

It has been the custom for many years when analysing the behaviour of networks, of which the transistor is an example, to consider that the positive direction of current is the one in which the current flows into the device. The sign for the voltage applied to any electrode gives its polarity with respect to the reference electrode. Fig. 7 indicates the convention for the sign of both current and voltage.

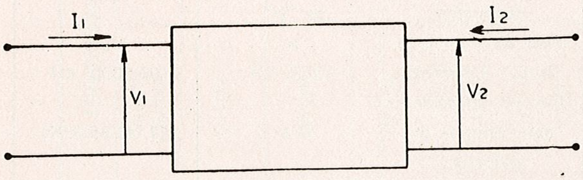


Fig. 7

In accordance with this convention, a junction transistor of the pnp type, would be connected into a common emitter circuit in the manner indicated in Fig. 8.

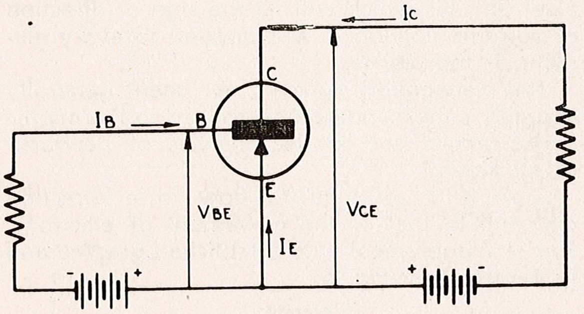


Fig. 8

The assumed positive directions of direct voltage and conventional direct currents are in conformity with the custom indicated in Fig. 7. The emitter current I_E is also assumed to flow into the transistor. Actually, the base current I_B normally flows out of the transistor; the emitter current into the transistor; and the collector current I_C out of the transistor. Thus, the algebraic sign of the numerical values of the base current and collector current is negative, while the algebraic sign of the numerical value of the emitter current is positive. For certain special operating conditions, such as high temperature and low base current, the base current can reverse in direction and then, since it flows into the transistor, the numerical value will be given a positive sign. Also, as indicated by Fig. 8, the base and collector voltages are negative with respect to the emitter, i.e., the algebraic sign of the numerical value of V_{BE} and V_{CE} is negative. These conventions require, that, for a pnp transistor, the signs of the numerical values shown on the characteristic curves, i.e., I_C, V_{CE}, I_B and V_{BE}, be negative. An example of the use of this sign convention is given below:—

Since we have assumed that all the currents flow into the transistor, by applying Kirchhoff's first law, which states "the algebraic sum of all currents flowing toward any junction point in a circuit is zero", we can write:—

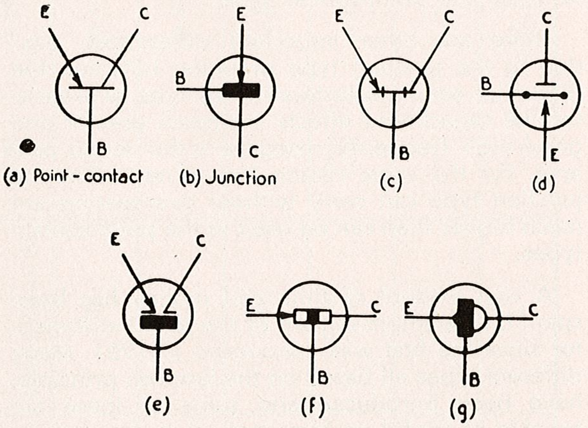
$$I_B + I_E + I_C = 0.$$

$$\therefore I_E = - I_B - I_C.$$

Assume numerical values for I_B and I_C of —0.05 mA and —7.0 mA respectively and substituting both value and sign in this equation, we have:—

$$\begin{aligned} I_E &= -(-0.05) - (-7.0) \\ &= + 0.05 + 7.0 \\ &= 7.05. \end{aligned}$$

The two points to be noted from this result are (1) I_E is positive in sign and therefore the original direction assumed is correct, and (2) I_E is larger than I_C by an amount I_B.



(a) Point - contact (b) Junction (c) (d)

(e) (f) (g)

Fig. 9

The setting up of a system of rules and the strict adherence to them is essential if one looks upon a crystal valve or transistor as a "black box" which behaves in a special way when connected into a suitable circuit. The properties of this circuit element can be evaluated by the ordinary methods of network analysis which, if the proper network is chosen, will specify accurately the performance of the transistor.

Various symbols have been used to represent a transistor in a circuit diagram. The more important of these for the pnp type are shown in Fig. 9.

Radiotronics in future will use the forms (a) and (b) of Fig. 9, to represent the pnp version of the point contact and junction types respectively. The npn will be shown with the arrow on the emitter reversed as shown in Fig. 10.

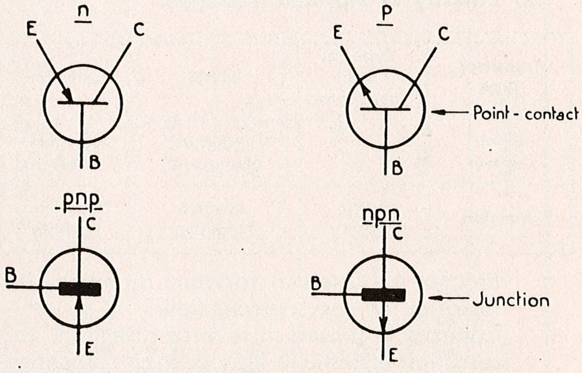


Fig. 10

The main reasons for preferring these forms are (1) they clearly differentiate the point contact from the junction type, and (2) they are easy to draw. This is true, particularly for the junction type which on present trends looks like being the most commonly used.

3. THE CRYSTAL VALVE COMPARED WITH THE THERMIONIC VALVE

(a) **General:**

Since the crystal valve or transistor was introduced as an electronic amplifier, its users have fallen into two groups — those who feel that it is easier dealt with using the same circuit theory as applied to thermionic valves and those who insist that although the two devices carry out the same functions, the extra complexity of the crystal version requires the use of new methods. The latter people believe that the use of the methods of analysis previously used for thermionic valve circuits increases the difficulties of understanding and applying transistors.

What the individual does on first meeting transistors will depend on his background of training and experience. It is hoped to show here that the similarity between the crystal valve and the thermionic valve is such that probably the best approach is to treat the extra and new problems of the transistor as merely an extension of those met with in the use of the thermionic valve.

The transistor, which is one form of the crystal valve, can be considered to be a thermionic valve with rather unusual properties. Many of these special properties and most of the complexity of the transistor circuit design equations are caused by the fact that the transistor has built-in feedback which is effective from d.c. up to the highest frequency handled. With thermionic valves it is normally necessary to take into account feedback across the valve only at fairly high frequencies. As will be shown in Section 4, a comparison of the two devices in terms of similar units can be made by calculating for the transistor equivalent characteristics such as transconductance (g_m) and plate resistance (r_p).

In Table 2, the main characteristics of the familiar 6AU6 are compared to the equivalent properties of a typical junction transistor, the 2N105. These equivalent valve parameters have been calculated from the transistor's "h" parameters as indicated in Section 4. The table shows the transistor's high effective g_m (approx. 4 times that of the thermionic valve), low power requirement (approximately 1/1000th that required by the valve) and small volume of space occupied (approx. 1/200th that of the valve). The high g_m is, of course, largely counterbalanced by the fact that the input impedance of the transistor is very much lower than that of the valve, with the result that an appreciable amount of power is required to drive the transistor. It also means that the signal source must have a low impedance so that it can efficiently supply the input power. The signal source for the transistor is perhaps better regarded as supplying an input current rather than an input voltage. In a similar way the transistor may be regarded as a power amplifier rather than a voltage amplifier. These considerations have led to the use by most manufacturers of characteristic curves which show input current as one parameter. However, if these curves are plotted, using the input voltage instead of input current, they become exactly the same as for thermionic valves. The transistor has been described[4] as an "superlatively good

TABLE 2.

Valve Parameter		Typical Thermionic Valve (Type 6AU6)		Typical Crystal Valve* (Transistor Type 2N105)
		Pentode Connected	Triode Connected	
g_m	mA/V	4·5	4·8	19·1
r_p	KΩ	1500	7·5	183
μ	—	$\doteqdot$6700	36	3480
R_{g-k}	Ω	$>10^7$	$>10^7$	2880
R_{g-p}	MΩ	>100	>100	5·4
Heater Power	Watts	1·89	1·89	zero
B+ Supply	Volts	250	250	4·5
	mA	10·6	12·2	1·0
	mW	2650	3050	4·5
Volume (exc'l socket)	Ins³.	—	0·658	0·0036

* Common Emitter Circuit

valve spoilt by a very low input resistance — so much so in fact that the overall gain is no better than that of quite an ordinary valve".

(b) Input Impedance:

As noted above, the input impedance of the transistor is low and there is feedback between the output and input electrodes. The latter characteristic causes the input impedance to be very dependent on the value of load resistance and thereby complicates the equations expressing the circuit performance.

(c) Output Impedance:

The transistor's output impedance can be high — comparable to that of the valve. It is generally between the values normally associated with a triode and pentode valve. See Tables 1 and 2. In the same way, as with the input impedance, the value of the signal source impedance affects the output impedance, and as before, makes the circuit equations more complicated.

(d) Gain:

The very much higher "g_m" of the transistor, compared to the thermionic valve has already been noted. Transconductance or g_m is defined as the ratio of an increment in output current to the increment in input voltage causing the change. Since in a transistor the input impedance is low, a very small change in input voltage will cause a large change in input current. A small change in input voltage will therefore cause a large change in output current and the g_m will be high. This does not always represent a high overall voltage gain however. Since it is normally necessary in any transistor amplifier to step down from a relatively high impedance to the low impedance required to match the transistor's input impedance, the overall gain of the stage may be quite low. In the same way, the high "g_m" of the transistor does not indicate a high current gain. A very low current gain or even a current loss will produce a high voltage gain if the output impedance of the device is very high compared to the input impedance. Most types of junction transistors have a current gain of <1 — typical values being 0.95 to 0.99. Point contact types have values between 2 and 4. (See Table 1.)

(e) Feedback:

As discussed earlier, it is the built-in feed-back which complicates the behaviour of the crystal valve. The equivalent effects are present in the thermionic valve only for very much higher frequencies where the reactance of the grid-plate capacitance allows a proportion of the output voltage to appear across the input circuit.

In addition to the internal feedback, there is another effect which may add to the awkardness of the transistor equations. This is the presence of a small amount of "signal feed-through". Generally the component of the output signal due to this effect is very small and may be neglected.

For certain specialised conditions, the signal appearing at the input due to the internal feedback also is sufficiently small to allow considerable simplification of the circuit equation.

(f) Maximum Operating Frequency:

In thermionic valves the limit on the maximum frequency at which satisfactory performance can be obtained is set chiefly by the interelectrode capacitances. However, for very high frequencies, two other factors become evident. These are the cathode and grid lead inductance and the transit time of the electrons. As the frequency increases, these finally become important enough to set the top limit of frequency at which the valve is useful. For transistors, the interelectrode capacitances are relatively unimportant compared to other effects caused by the physics of transistor action.

(g) "Knee" Voltage:

The very low voltage between collector and base or collector and emitter required for the maximum collector current is one of the most striking differences between the transistor and the thermionic valve. This voltage, the "knee" voltage of the pentode valve, is the voltage existing at the collector when the maximum signal current is flowing and since it is nearly equal to zero for the junction transistor, the overall efficiency is high. Curves of a 6AU6, showing plate voltage versus plate current, with the plate voltage expressed as a percentage of the plate supply voltage (taken as 250V), are compared in Fig 11, to the equivalent curves for an 2N105 transistor. The very great difference in the slope of the curves when the plate or collector voltage is lower than say 10% of the supply voltage can be seen.

(h) Other Features:

The crystal and thermionic valves have been compared considering their main characteristics. In general, the two are capable of similar performance in appropriate circuits; the transistor can perform some tasks better, while for others, the valve is superior. The applications for which one is better suited depend, of course, on the requirements, e.g., the transistor's smaller physical size, lower operating voltages and currents, very much greater resistance to shock and vibration and very much smaller change in characteristics in the presence of magnetic fields, make it particularly attractive for certain special types of equipment. These features of the transistor have been treated thoroughly in the literature and will not be dealt with in further detail.

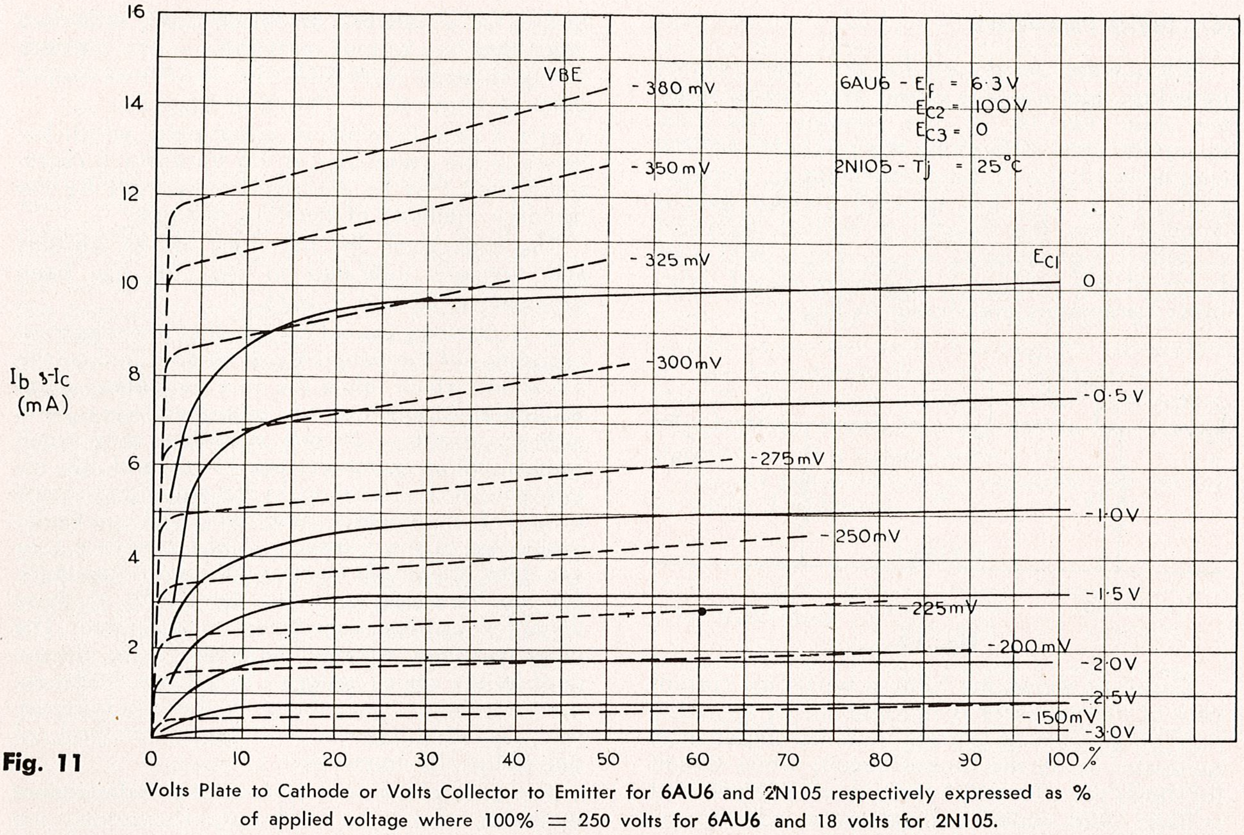


Fig. 11

4. SURVEY OF PARAMETER SYSTEMS

(a) General:

Since the transistor was introduced in 1948, a number of methods of describing its properties and behaviour have been proposed. Each of the methods has some advantages and at the same time disadvantages compared to the others.

The choice of the proper constants or "parameters" with which to specify the transistor will allow the devising of a more or less simple circuit which behaves in the same way as the transistor. This "equivalent" circuit is necessary to the user of the device to allow him to predict its performance in equipment.

The set of parameters selected to describe the transistor should preferably meet the following main requirements:—

(i) be directly connected to the physical constants or structure of the device;

(ii) allow the setting up of simple equivalent circuits;

(iii) be easily measured.

It is perhaps useful at this point to differentiate between the two fundamental systems of parameters. One represents the transistor's characteristics, using the "device" parameters and the other using the "circuit" parameters.

The device parameters are preferred by the designer and manufacturer of the transistor since they can be directly related to the physical constants of the device and are independent of the circuit in which it is used.

The circuit parameters on the other hand describe the relationships existing between the input and output voltages and currents and because of this are more valuable to the circuit designer. They are obtained by measurements made at the terminals of the device and do not bear any obvious relation to the structure of the transistor.

Due to the large variations in the operating point and in the internal characteristics experienced in the transistor when the amplitude of the signal varies, both the device and circuit parameters are normally restricted to small signal conditions. For large signals, such as are met with in the output stages of audio frequency amplifiers, it is more accurate to specify the transistor's performance by means of appropriate characteristic curves. The parameters considered from this point on will therefore be considered as applying only when the transistor is operating under small signal conditions.

(b) Device Parameters:

These were developed for the point contact transistor and are the oldest and undoubtedly the most familiar of the systems. The four quantities used to describe the transistor are the emitter resistance r_e, base resistance r_b, collector resistance r_c and the forward current gain α Another term, the transfer or mutual resistance r_m, which is given by $r_m = \alpha r_c$, is also used. Two forms of the familiar T equivalent circuit using these parameters are shown in Fig. 12.

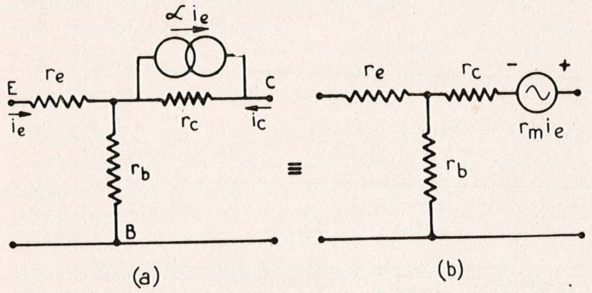


Fig. 12

Circuit (a) shows the form in which the current gain of the transistor is represented by the addition of a constant current (infinite impedance) generator αi_e to the output circuit; while Circuit (b) shows the alternative form in which a constant voltage (zero impedance) generator adds a voltage r_m i_e to the output circuit.

The two real disadvantages of the device parameters are (a) in general they cannot be measured directly, but must be determined from a number of measurements of the circuit parameters; and (b) they are suited only for a narrow frequency range. When attempts are made to extend them to provide an accurate model for high frequency use, they become complex and more difficult to use than certain forms of the circuit parameters.

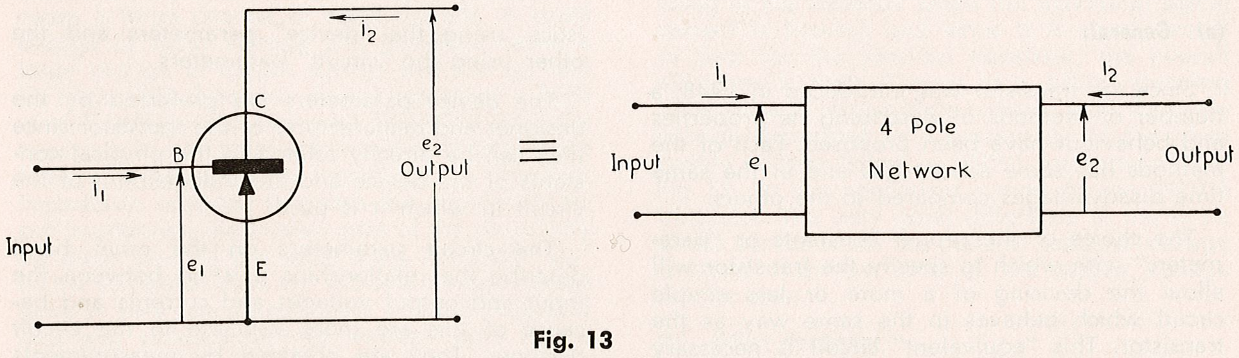


Fig. 13

(c) Circuit Parameters:

The second system of parameters, since they describe the properties of the transistor in terms of the currents and voltages at its terminals and are therefore dependent on the circuit configuration, are called the circuit parameters.

For the purpose of mathematical analysis, the transistor, a three terminal device, may be regarded as a network or "black box", with two input and two output terminals — one element being common with both the input and output pairs of terminals as shown in Fig. 13.

The 4 pole network of quadripole, which behaves in the same way as the transistor it represents, then may be described completely by the ordinary methods of network analysis.

The convention for the signs of the currents and voltages indicated in Fig. 13, has been discussed in Section 2, para. f.

It is obvious from Fig. 13, that the electrical properties of the network will be specified by the equations which relate the four variables—input voltage e_1, input current i_1, output voltage e_2, and output current i_2. If one considers only small signals, these equations are linear and the coefficients of the variables in the equation become a set of parameters describing the particular properties of the transistor. Since there are four variables, there will be four different parameters. For the transistor, only two (any two) of these variables can be considered independent. The other two then become "dependent", i.e., dependent on the values assigned to the two "independent" variables. Each choice of the two independent variables gives a different method of describing the transistor.

For example, if we take as the **independent** variables, the input and output currents, the **dependent** variables become the input and output voltages. There are six possible ways of combining these pairs, and as a result, there are six sets (or matices) of four parameters which will completely describe the performance of the network. In addition, any one of the three elements of the transistor—base, emitter or collector—may be used as the common connection between the input and output circuits. There are therefore, 18 possible ways of specifying the transistor's performance.

(d) Types of Circuit Parameters:

When one writes the equation for each selection of independent variables, one finds that the parameter so obtained has the properties of a circuit element such as a resistance, impedance, conductance, admittance or a simple ratio such as current gain.

Taking the case where the input and output currents are selected as the independent variables, we have the following equations^5 —

$e_1 = z_{11}\, i_1 + z_{12}\, i_2$ .... (1)

$e_2 = z_{21}\, i_1 + z_{22}\, i_2$ .... (2)

In these equations the coefficients of the currents each have the characteristics of an impedance, since the voltage e_1 or e_2 is made up of two terms each representing a voltage. For example the two components of e_1 are (a) the product of an impedance z_{11} and the current i_1; and (b) the product of impedance z_{12} and current i_2. This then is the "impedance" representation.

Equations (1) and (2) use the conventional notation of network analysis where the subscripts of each symbol indicate the points with which the quantity is related, i.e., in Fig. 13 "1", refers to the input and "2" to the output circuit, z_{11} and z_{22} are the impedances between the input terminals and output terminals respectively. In the interests of simplicity and clearness it is proposed from this point on, to use the alternative convention for subscripts as set out in the I.R.E. Standard on Semi-Conductor Symbols $(^6)$ Parameters connected with the input circuit will carry the subscript "i" instead of "11", and with the output circuit "o" instead of "22". The transfer impedance z_{21} (forward) and z_{12} (reverse) become z_f and z_r respectively. Equations (1) and (2) then become:

$e_i = z_i i_i + z_r\, i_o$ ....(3)

$e_o = z_f i_i + z_o\, i_o$ ....(4)

For the case where the input current and output voltage are taken as the independent variables and equations^5 are:

$e_i = h_i\, i_i + h_r\, e_o$

$i_o = h_f\, i_i + h_o e_o$

To make each of the terms $h_i\, i_i$ and $h_r\, e_o$ a component of a voltage, the parameter h_i must have the dimensions of an impedance and the parameter h_r must be dimensionless, i.e., a simple ratio. Similarly for $h_f\, i_i$ and $h_o\, e_o$ to be components of the current i_o, the parameter h_f requires to be a simple ratio and h_o to have the dimensions of an admittance, i.e., the reciprocal of an impedance. The term $h_o\, e_o$ then becomes $\frac{1}{z}.\, e_o$ and is a component of current. In a similar way, the coefficients of the equations relating the admittance or "y" parameters have the characteristics of an admittance. Although all the above parameters have been quoted in their general form, in practice the more restricted low frequency terms are used. The reactive component of the impedance then can be neglected and the "z" parameters become the "r" parameters. Similary, the y or admittance terms assume the dimensions of a conductance.

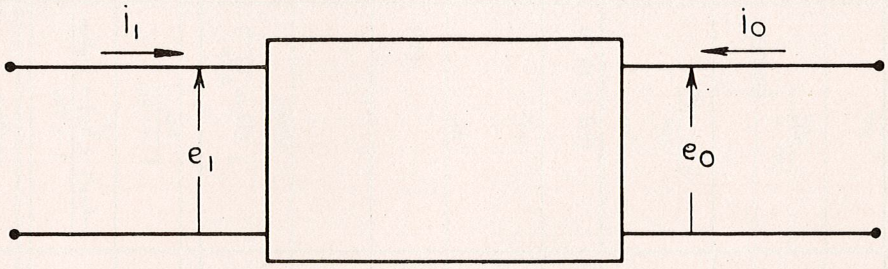
The six combinations or variables are set out in Table 3 below:—

TABLE 3

REPRESENTATION	INDEPENDENT VARIABLES	DEPENDENT VARIABLES
Impedance or "z"	Input Current Output Current	Input Voltage Output Voltage
Hybrid or "h"	Input Current Output Voltage	Input Voltage Output Current
Admittance or "y"	Input Voltage Output Voltage	Input Current Output Current
"g"	Input Voltage Output Current	Input Current Output Voltage
"a"	Output Voltage Output Current	Input Voltage Input Current
"b"	Input Voltage Input Current	Output Voltage Output Current

Of these six combinations, only three, the impedance, hybrid and admittance, have found much use.

The three sets of parameters are defined in terms of the network of Fig. 13, which is reproduced below:—



Impedance Parameters:

$z_i = \left(\frac{e_i}{i_i}\right)_{i_o = 0}$ = Input impedance with output **open** circuit to a.c.
(r_i)

$z_r = \left(\frac{e_i}{i_o}\right)_{i_i = 0}$ = Reverse transfer impedance with the input **open** circuit to a.c.
(r_r)

$z_f = \left(\frac{e_o}{i_i}\right)_{i_o = 0}$ = Forward transfer impedance with the output **open** circuit to a.c.
(r_f)

$z_o = \left(\frac{e_o}{i_o}\right)_{i_i = 0}$ = Output impedance with input **open** circuit to a.c.
(r_o)

TABLE 5

Conversions between "h" and "T" Parameters for the Three Circuit Configurations

SYMBOLS			'h' SYSTEM			T Circuit	Hybrid-π
New	Old		Common Emitter	Common Base	Common Collector		Common Emitter
h_{ie}	h_{11e} $\frac{1}{y_{11e}}$	h'_{11}	h_{ie} (2000Ω)	$\frac{h_{ib}}{1 + h_{fb}}$	h_{ic}	$r_b + \frac{r_e r_c}{r_c - r_m}$ or $r_b + (1 + \alpha_{fe}) r_e$ or $r_b + \frac{r_e}{1 - \alpha_{fb}}$	$r_{bb'} + r_{b'e}$
h_{re}	h_{12e} μ_{bc}	h'_{12}	h_{re} $(9{\cdot}3 \times 10^{-4})$	$\frac{h_{ib} h_{ob}}{1 + h_{fb}} - h_{rb}$	$1 - h_{rc}$	$\frac{r_e}{r_c - r_m}$ or $\frac{r_e(1 + \alpha_{fe})}{r_c}$ or $\frac{r_e}{(1 - \alpha_{fb}) r_c}$	$\frac{r_{b'e}}{r_{b'c}}$
h_{fe}	h_{21e} α_{cb} β	h'_{21}	h_{fe} (49)	$\frac{-h_{fb}}{1 + h_{fb}}$	$-(1 + h_{fc})$	$\frac{r_m}{r_c - r_m}$ or α_{fe} or $\frac{\alpha_{fb}}{1 - \alpha_{fb}}$	$g_m r_{b'e}$
h_{oe}	h_{22e} $\frac{1}{z_{22e}}$	h'_{22}	h_{oe} (33×10^{-6}) A/V	$\frac{h_{ob}}{1 + h_{fb}}$	h_{oc}	$\frac{1}{r_c - r_m}$ or $\frac{1 + \alpha_{fe}}{r_c}$ or $\frac{1}{r_c(1 - \alpha_{fb})}$	$\left(\frac{1 + g_m r_{b'e}}{r_{b'c}}\right) + \frac{1}{r_{ce}}$
h_{ib}	$\frac{1}{y_{11}}$	h_{11}	$\frac{h_{ie}}{1 + h_{fe}}$	h_{ib} (40Ω)	$\frac{h_{ic}}{-h_{fc}}$	$r_e + \frac{r_b}{1 + \alpha_{fe}}$ or $r_e + (1 - \alpha_{fb}) r_b$	$\frac{r_{bb'} + r_{b'e}}{1 + g_m r_{b'e}}$
h_{rb}	μ_{ce}	h_{12}	$\frac{-h_{re}(1 + h_{fe}) + h_{ie} h_{oe}}{1 + h_{fe}}$	h_{rb} (4×10^{-4})	$\frac{h_{ic} h_{oc}}{-h_{fc}}$	$\frac{r_b}{r_c}$	$\frac{r_{bb'}}{r_{b'c}} + \frac{r_{bb'} + r_{b'e}}{(1 + g_m r_{b'e}) r_{ce}}$
h_{fb}	α_{ce}	h_{21}	$\frac{-h_{fe}}{1 + h_{fe}}$	h_{fb} $(-0{\cdot}98)$	$\frac{1 + h_{fc}}{-h_{fc}}$	$-\frac{\alpha_{fe}}{1 + \alpha_{fe}}$ or $-\alpha_{fb}$	$-\frac{g_m r_{b'e}}{1 + g_m r_{b'e}}$
h_{ob}	$\frac{1}{z_{22}}$	h_{22}	$\frac{h_{oe}}{1 + h_{fe}}$	h_{ob} $(0{\cdot}67 \times 10^{-6}$ A/V)	$\frac{h_{oc}}{-h_{fc}}$	$\frac{1}{r_c}$	$\frac{1}{r_{b'c}} + \frac{1}{r_{ce}(1 + g_m r_{b'e})}$

TABLE 5. *(Cont'd)*

SYMBOLS			'h' SYSTEM			T Circuit	Hybrid-π Common Emitter
New	Old		Common Emitter	Common Base	Common Collector		
h_{ic}	h_{11c} $\left(\frac{1}{y_{11c}}\right)$	h''_{11}	h_{ie}	$\frac{h_{ib}}{1+h_{fb}}$	h_{ic} (2000Ω)	$r_b + \frac{r_e r_c}{r_c - r_m}$ or $r_b + (1+\alpha_{fe})r_e$ or $r_b + \frac{r_e}{1-\alpha_{fb}}$	$r_{bb'} + r_{b'e}$
h_{rc}	h_{12c}	h''_{12}	$1 - h_{re}$ ($\doteqdot 1$)	$\frac{1}{1-h_{rb}}$ ($\doteqdot 1$)	h_{rc} (1)	$1 - \frac{r_e(1+\alpha_{fe})}{r_c}$ or $1 - \frac{r_e}{(1-\alpha_{fb})r_c}$ $\doteqdot 1$	$1 - \frac{r_{b'c}}{r_{b'e}}$ $\doteqdot 1$
h_{fc}	h_{21c} α_{eb}	h''_{21}	$-(1+h_{fe})$	$\frac{-1}{1+h_{fb}}$	h_{fc} (−50)	$-\frac{r_c}{r_c - r_m}$ or $-(1+\alpha_{fe})$ or $-\frac{1}{1-\alpha_{fb}}$	$-(1+g_m r_{b'e})$
h_{oc}	h_{22c} $\frac{1}{z_{22c}}$	h''_{22}	h_{oe}	$\frac{h_{ob}}{1+h_{fb}}$	h_{oc} (33×10^{-6} A/V.)	$\frac{1}{r_c - r_m}$ or $\frac{1+\alpha_{fe}}{r_c}$ or $\frac{1}{(1-\alpha_{fb})r_c}$	$\frac{1}{r_{b'c}}\left(1+g_m r_{b'e}\right) + \frac{1}{r_{ce}}$
α			$\frac{h_{fe}}{1+h_{fe}}$	$-h_{fb}$	$\frac{1+h_{fc}}{h_{fc}}$	$\frac{r_m}{r_c}$ or $\frac{\alpha_{fe}}{1+\alpha_{fe}}$ or α_{fb} (0·98)	$\frac{g_m r_{b'e}}{1+g_m r_{b'e}}$
r_c			$\frac{h_{fe}+1}{h_{oe}}$	$\frac{1}{h_{ob}}$	$\frac{-h_{fc}}{h_{oc}}$	r_c (1·5 MΩ)	$\frac{r_{b'c}r_{ce}(1+g_m r_{b'e})}{r_{b'c} + r_{ce}(1+g_m r_{b'e})}$
r_e			$\frac{h_{re}}{h_{oe}}$	$h_{ib} - (1+h_{fb})\frac{h_{rb}}{h_{ob}}$	$\frac{1-h_{rc}}{h_{oc}}$	r_e (28 Ω)	$\frac{r_{b'e}}{(1+g_m r_{b'e}) + \frac{r_{b'e}}{r_{ce}}}$
r_b			$h_{ie} - \frac{h_{re}(1+h_{fe})}{h_{oe}}$	$\frac{h_{rb}}{h_{ob}}$	$h_{ic} + \frac{h_{fc}(1-h_{rc})}{h_{oc}}$	r_b (600 Ω)	$r_{bb'} + \frac{r_{b'e}}{1 + \frac{r_{ce}}{r_{b'c}(1+g_m r_{b'e})}}$

These are the "open circuit" parameters, i.e., they are measured with the input or the output terminals **open circuit** as far as a.c. is concerned. For d.c., the circuit is closed and the transistor works under the proper applied direct voltages. NOTE: The "r" symbols are the low frequency equivalents of the general impedance form "z".

(ii) Hybrid Parameters:

$h_i = \left(\frac{e_i}{i_i}\right) e_o = 0$ = Input impedance with output **short** circuited to a.c.

$h_r = \left(\frac{e_i}{e_o}\right) i_i = 0$ = Reverse voltage amplification factor with input **open** circuit to a.c.

$h_f = \left(\frac{i_o}{i_i}\right) e_o = 0$ = Forward current amplification factor with output **short** circuit to a.c.

$h_o = \left(\frac{i_o}{e_o}\right) i_i = 0$ = Output admittance with input **open** circuit to a.c.

Since these are a mixture of open and short circuit conditions they are called the "hybrid" parameters. Once again the open or short circuit refers only to a.c. signals.

(iii) Admittance Parameters:

$y_i = \left(\frac{i_i}{e_i}\right) e_o = 0$ = Input admittance with the output **short** circuit to a.c.

$y_r = \left(\frac{i_i}{e_o}\right) e_i = 0$ = Reverse transfer admittance with the input **short** circuit to a.c.

$y_f = \left(\frac{i_o}{e_i}\right) e_o = 0$ = Forward transfer admittance with the output **short** circuit to a.c.

$y_o = \left(\frac{i_o}{e_o}\right) e_i = 0$ = Output admittance with the input **short** circuit to a.c.

The "y" system parameters are each measured with the opposite end short-circuited to a.c., and have the dimensions of an admittance, i.e., the reciprocal of an impedance. They are thus the "short-circuit" or "admittance" parameters.

Each of these sets of parameters has some advantages and disadvantages compared with the others. They fit the requirements for the ideal system with a varying degree of success. For example, the T parameters fully meet requirement (i) of Section 4(a), because they are directly related to the device. However, they are impossible to measure directly and must be calculated from other measurements. They make the circuit design equations complicated, and for junction transistors particularly, vary a great deal with frequency.

The "z" or open circuit parameters suffer from the main disadvantage that for the case of the junction transistor with its high output impedance or resistance, they are difficult to measure. An output circuit which has a very much higher a.c. impedance than that of the collector (i.e., the a.c. open circuit condition), is required. The high collector resistance of the modern transistor makes this very difficult. On the other hand, the hybrid "h" parameters avoid this difficulty since both h_i and h_f (the only two parameters which specify the condition of the output circuit) are measured with an a.c. short circuit across the collector or output circuit. The resultant greater ease and precision of measurement and the fact that they vary less with temperature and operating point has brought the "h" parameters into more and more common use. In addition, under some conditions, their use results in a simplification of amplifier design equations.

(iv) Short Circuit "z" Parameters:

A variation of the normal open circuit z or r parameters has been suggested[7],[8], as a means of simplifying the circuit design equations. In these modifications r_i and r_o remain unchanged as the open circuit input and output resistances respectively, and r_r and r_f are replaced by r_{11}' or r_{is} and r_{22}' or r_{os}. In reference 8, the symbols r_{in} and r_{out} are used for r_{is} and r_{os} respectively. The two new parameters are measured in the same way as r_i and r_o except that the far end is short circuited instead of open circuited to a.c. signals. In accordance with the I.R.E. standard, the subscripts "i" and "o" are used to indicate the input and output parameters respectively and the subscript "s" to indicate the short circuit condition.

Short circuiting the output to a.c. makes the measurement of the input parameter r_{is} easier and more accurate. As will be shown in Section 6, the use of r_{is} and r_{os} makes the circuit design equations almost as simple as those used for thermionic valves and at the same time makes the effects of varying the source and load resistances easier to see.

Table 4 lists the formulae relating the short circuit r parameters r_{is}, r_{os} to the open circuit r parameters r_i, r_o and the T circuit parameters.

TABLE 4

Conversion Formulae Relating Short-circuit r, Open circuit r and T Circuit Parameters.

Short Circuit r	Open Circuit r	T Circuit
r_{is}	$r_i - \frac{r_r\ r_f}{r_o}$	$r_e + r_b\ (1 - \alpha_{fb})$
r_{os}	$r_o - \frac{r_r\ r_f}{r_i}$	$r_c\left(1 - \frac{\alpha_{fb}\ .\ r_b}{r_b + r_e}\right)$

(v) High Frequency Parameters:

All the equivalent circuits and their respective parameters considered above have been suitable for low frequencies only. Accurate high frequency performance can not be determined unless the equivalent circuit is made more complicated by adding say one or more resistive terms and one or more capacitive terms.

The operation and characteristics of the transistor at higher than audio frequencies is a subject of some magnitude, and outside the scope of this article. The only reference that will be made here concerns the use of the "Hybrid-π" equivalent circuit and its components.

Fig. 14 shows this circuit (common emitter connection) to be a modified form of the low frequency π circuit.

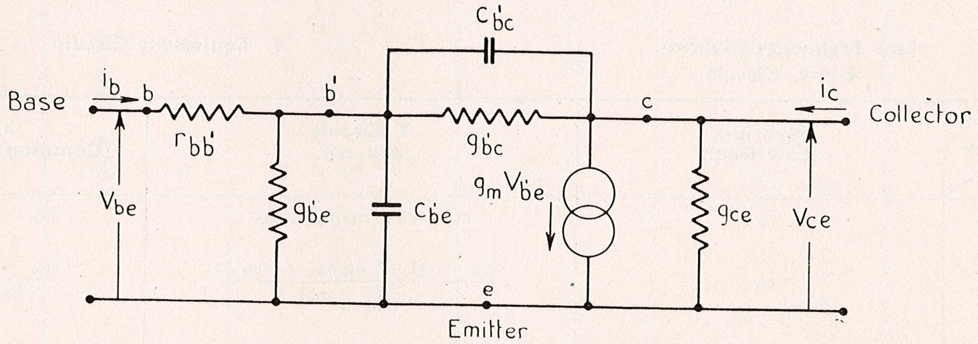


Fig. 14

b' - Internal base connection of device

The terms in the above circuit are defined as follows:—

$r_{bb'}$	is the resistance between base lead and the artificial internal point b'.
$g_{b'e}$	is the conductance between point b' and the emitter lead.
$g_{b'c}$	is the conductance between point b' and the collector lead.
g_{ce}	is the conductance between collector and emitter.
$c_{b'c}$	is the capacitance between point b' and the collector lead.
g_m	is the intrinsic transconductance.

The main advantages of this circuit are that it accurately represents the performance of the transistor over the whole of its useful frequency range and all its parameters are both relatively independent of frequency and easily measured.

For more information on this circuit and its use, the reader is referred to the literature[9],[10].

(e) Relations between Types of Parameters:

Providing any one of the 18 possible sets of parameters is known for a particular transistor each of the other 17 may be calculated[11] for the same d.c. operating conditions.

Conversion formulae relating the h parameters for the common base, emitter and collector configurations, the T and the hybrid π circuit parameters are listed in Table 5.

The numerical values in parentheses are typical and apply to a particular junction transistor.

Table 6 shows formulae connecting the hybrid-π, T circuit and the h parameters.

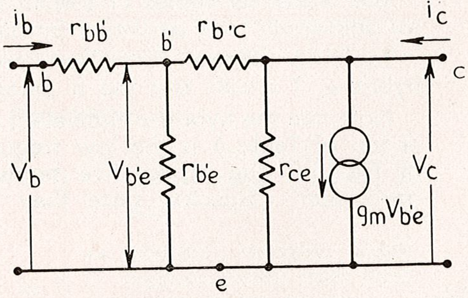
Note that the hybrid-π equivalent circuit shown at top of Table 6 is the low frequency version of Fig. 14. The capacitative terms of Fig. 14 have been neglected since they will have a negligible effect at low frequencies. The terms $r_{b'e}$, $r_{b'c}$, etc., are the resistive counterparts of the conductances $g_{b'e}$, $g_{b'c}$, etc., i.e., $r_{b'e} = \frac{1}{g_{b'e}}$. The extra information represented by the resistive term $r_{bb'}$ of the high frequency hybrid-π circuit is strictly not required for the low frequency representation. However, as shown in Table 6, a simple conversion from either the T or h parameters cannot be made unless the extra term $r_{bb'}$ is known.

Table 7 shows formulae enabling the sets of r(low frequency z), h and y parameters to be determined from each other. Since these are network equations, they hold for any of the three configurations. Each of the terms for any particular conversion must, of course, be the ones applying to a particular circuit configuration, e.g., if r_{ie} is required, then the "h" or "y" parameters used in the equation must be the ones appropriate to the common emitter circuit.

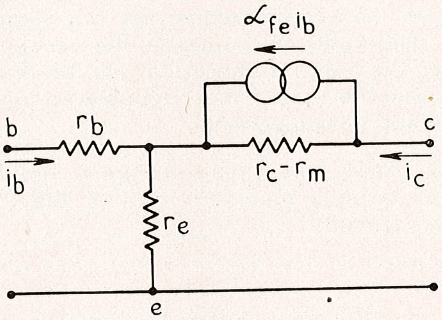
(f) Thermionic Valve v. Transistor Parameters:

Reference was made in Section 3, Para. (a), to the conversion of transistor parameters to those for an equivalent thermionic valve circuit. Table 8 lists the formulae relating the common base, common emitter and the T parameters with the valve parameters g_m, r_p, r_{gk}, r_{gp} & μ. Using these equations, the characteristics of a transistor can be expressed in terms of those normally used to describe a thermionic valve.

TABLE 6
Conversion Formulæ—Hybrid-π, T and h Parameters



Low Frequency Hybrid-π Equiv. Circuit



T Equivalent Circuit

	To ↓ / From →	Hybrid-π (Low freq.)	T Circuit and $r_{bb'}$	h (Common Emitter)
Hybrid-π	$r_{b'e}$	$r_{b'e}$	$r_b + (1 + \alpha_{fe})r_e - r_{bb'}$	$h_{ie} - r_{bb'}$
	$r_{b'c}$	$r_{b'c}$	$\dfrac{\{r_b + (1 + \alpha_{fe})r_e - r_{bb'}\}r_c}{r_e(1 + \alpha_{fe})}$	$\dfrac{h_{ie} - r_{bb'}}{h_{re}}$
	g_m	g_m	$\dfrac{\alpha_{fe}}{r_b + (1 + \alpha_{fe})r_e - r_{bb'}}$	$\dfrac{h_{fe}}{h_{ie} - r_{bb'}}$
	r_{ce}	r_{ce}	$\dfrac{r_{ce}}{1 + \alpha_{fe}} \cdot \dfrac{r_b + (1 + \alpha_{fe})r_e - r_{bb'}}{r_b - r_{bb'}}$	$\dfrac{1}{h_{oe} - \dfrac{(1 + h_{fe})h_{re}}{h_{ie} - r_{bb'}}}$
T Circuit	α_{fb}	$\dfrac{g_m r_{b'e}}{1 + g_m r_{b'e}}$	α_{fb}	$\dfrac{h_{fe}}{1 + h_{fe}}$
	α_{fe}	$g_m r_{b'e}$	α_{fe}	h_{ie}
	r_c	$\dfrac{r_{b'c}}{1 + \dfrac{r_{be}}{r_{ce}(1 + g_m r_{b'e})}}$	r_c	$\dfrac{h_{fe} + 1}{h_{oe}}$
	r_m	$\dfrac{g_m r_{b'c} r_{ce}}{\dfrac{r_{ce}}{r_{b'e}}(1+g_m r_{b'e})+1}$	r_m	$\dfrac{h_{fe}}{h_{oe}}$
	r_b	$r_{bb'} + \dfrac{r_{b'e}}{1 + \dfrac{r_{ce}}{r_{b'c}(1 + g_m r_{b'e})}}$	r_b	$h_{ie} - \dfrac{h_{re}(1 + h_{fe})}{h_{oe}}$
h (common emitter)	h_{ie}	$r_{bb'} + r_{b'e}$	$r_b + (1 + \alpha_{fe})r_e$	h_{ie}
	h_{re}	$\dfrac{r_{b'e}}{r_{b'c}}$	$\dfrac{r_e(1 + \alpha_{fe})}{r_c}$	h_{re}
	h_{fe}	$g_m r_{b'e}$	α_{fe} or $\dfrac{r_m}{r_c - r_m}$	h_{fe}
	h_{oe}	$\dfrac{1 + g_m r_{b'e}}{r_{b'c}} + \dfrac{1}{r_{ce}}$	$\dfrac{1 + \alpha_{fe}}{r_c}$	h_{oe}

TABLE 7

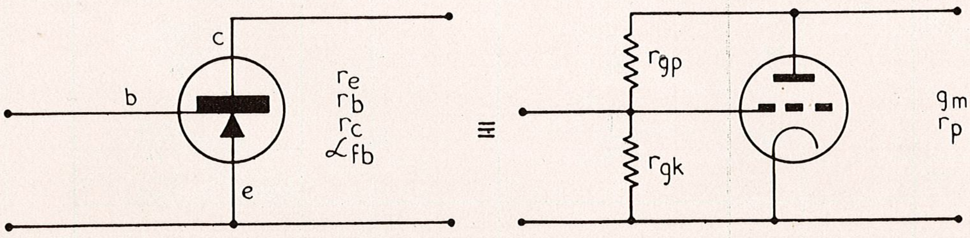
Conversion Formulæ—Low Freq. r, h and y Parameters

To ↓	From →	r (Low Freq. z)	h	y
(Low Freq .z)	r_i	r_i	$h_i - \frac{h_r h_f}{h_f}$	$\frac{1}{y_i - \frac{y_r y_f}{y_o}}$
	r_r	r_r	$\frac{h_r}{h_o}$	$-\frac{1}{\frac{y_i y_o}{y_r} - y_f}$
	r_f	r_f	$-\frac{h_f}{h_o}$	$-\frac{1}{\frac{y_i y_o}{y_f} - y_r}$
	r_o	r_o	$\frac{1}{h_o}$	$\frac{1}{y_o - \frac{y_r y_f}{y_i}}$
h	h_i	$r_i - \frac{r_r r_f}{r_o}$	h_i	$\frac{1}{y_i}$
	h_r	$\frac{r_r}{r_o}$	h_r	$-\frac{y_r}{y_i}$
	h_f	$-\frac{r_f}{r_o}$	h_f	$\frac{y_f}{y_i}$
	h_o	$\frac{1}{r_o}$	h_o	$y_o - \frac{y_r y_f}{y_i}$
y	y_i	$\frac{1}{r_i - \frac{r_r r_f}{r_o}}$	$\frac{1}{h_i}$	y_i
	y_r	$-\frac{1}{\frac{r_i r_o}{r_r} - r_f}$	$-\frac{h_r}{h_i}$	y_r
	y_f	$-\frac{1}{\frac{r_i r_o}{r_f} - r_r}$	$\frac{h_f}{h_i}$	y_f
	y_o	$\frac{1}{r_o - \frac{r_r r_o}{r_i}}$	$h_o - \frac{h_r h_f}{h_i}$	y_o

TABLE 8

Relations between the Parameters for the Low Frequency Transistor and Valve Equivalent Circuits

Thermionic Valve Parameter	CRYSTAL VALVE PARAMETER		
	h System		T Circuit
	Common Base	Common Emitter	
g_m	$-\dfrac{h_{fb}+h_{rb}}{h_{ib}}$	$\dfrac{h_{fe}}{h_{ie}}$	$\dfrac{\alpha_{fb}}{r_e+r_b(1-\alpha_{fb})}$
r_p	$\dfrac{h_{ib}}{h_{rb}}$	$\dfrac{h_{ie}}{h_{ie}h_{oe}-h_{re}(1+h_{fe})}$	$r_c\left\{\dfrac{r_e}{r_b}+(1-\alpha_{fb})\right\}$
r_{gk}	$\dfrac{h_{ib}}{1+h_{fb}}$	h_{ie}	$r_b+\dfrac{r_e}{1-\alpha_{fb}}$
r_{gp}	$\dfrac{h_{ib}}{h_{ob}h_{ib}-h_{rb}(1+h_{fb})}$	$\dfrac{h_{ie}}{h_{re}}$	$r_c\left\{1+\dfrac{r_b}{r_e}(1-\alpha_{fb})\right\}$
μ	$-\left(\dfrac{h_{fb}}{h_{rb}}+1\right)$	$\dfrac{h_{fe}}{h_{ie}h_{oe}-h_{re}(1+h_{fe})}$	$\dfrac{\alpha_{fb}r_c}{r_b}$



Crystal Valve

Thermionic Valve

5. THREE CIRCUIT CONFIGURATIONS

(a) *General:*

Each of the three ways of connecting a transistor, i.e., with both the input and output circuits returned to the base, emitter or collector leads has special and useful properties. For various reasons, as discussed later, the common emitter has become the more generally used of the three configurations.

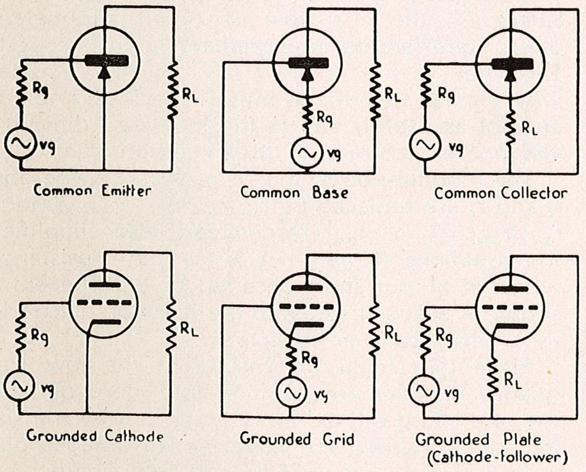
The three transistor amplifier circuits have their counterparts in thermionic valve amplifier circuits — the common emitter being analogous to the grounded cathode, the common base to the grounded grid and the common collector to the grounded plate or cathode follower circuit. If the common emitter circuit is taken as the standard it can be seen[10] that both the common base and common collector circuits are feedback versions of the standard. Figure 15 shows simplified circuits drawn to emphasise this feedback difference and to show the equivalent thermionic valve circuit.

The properties of each of these circuits for a junction transistor are set out in Sections b, c, d, e.

TABLE 9

Comparison of Amplifier Circuits

Characteristic	Common Emitter	Common Base	Common Collector
Equiv. Thermionic Valve Circuit	Grounded Cathode	Grounded Grid	Grounded plate (cathode follower)
Forward Current Gain (short circuit) α	High $\alpha_{fe} = \frac{-\alpha_{fb}}{1 + \alpha_{fb}}$ (+49)	<1 α_{fb} (−0·98)	High $\alpha_{fc} = \frac{-1}{1 + \alpha_{fb}}$ (−50)
Input Impedance	Medium	Low	High $\doteqdot \alpha_{fe} R_L$ ($49\ R_L$)
Output Impedance	Medium	High	Low $\doteqdot \frac{R_g}{1 + \alpha_{fe}}$ $\left(\frac{R_g}{50}\right)$
Max. Operating Frequency	< common base $\doteqdot (1 - \alpha_{fb})\, f_{\alpha b}$	Highest $f_{\alpha b}$	Varies with R_g $\doteqdot (1 - \alpha_{fb}) f_{\alpha b}$
Collector Cutoff Current I_{co}	Large $\doteqdot \alpha_{fe}\, I_{co}$	Small I_{co}	Large $\doteqdot \alpha_{fe}\, I_{co}$
Phase shift between input and output			
Voltage	180°	0°	0°
Current	0°	180°	180°



Common Emitter Common Base Common Collector

Grounded Cathode Grounded Grid Grounded Plate (Cathode-follower)

Fig. 15

(b) *Common Emitter:*

(i) Similar to the normal or grounded cathode thermionic valve circuit.

(ii) Most often used.

(iii) Available power gain higher than either common base or collector circuits.

(iv) High current gain, approx. equal that of common collector.

$$\left(\alpha_{fe} = \frac{\alpha_{fb}}{1 - \alpha_{fb}} = 20 \text{ to } 150\right).$$

(v) Voltage gain approximately equal that of common base.

(vi) Capable of both voltage and current amplification at same time.

(vii) Input and output voltages 180° out of phase.

(viii) Medium input and output impedances of more convenient values than other circuits.
(ix) Low input drive power required due to high power gain.
(x) Gives more accurate information about the transistor—the other two require the measurement of some parameter as the difference between two large values.
(xi) Alpha cut-off frequency much lower than that for common base.

$$\left(f_{\alpha e} \approx \frac{f_{\alpha b}}{1 + a_{fe}} \right)$$

(c) Common Base:

(i) Similar to grounded grid valve circuit.
(ii) Power gain $= \frac{1}{a_{fe}} \times$ power gain of common emitter.
(iii) Current gain less than unity.
(iv) Voltage gain approximately equal that of common emitter.
(v) Input and output voltages in phase.
(vi) Input impedance low.
(vii) Output impedance high.
(viii) Over normal range of load resistance, R_L, the input resistance is less affected by the value of R_L than in either common emitter or collector circuits.
(ix) Considerable isolation between output and input terminals.
(x) Low distortion when driven from current source due to linearity of common base collector characteristics.
(xi) Easy to stabilise.

(d) Common Collector:

(i) Similar to grounded plate or cathode-follower valve circuit.
(ii) Power gain smaller than either common emitter or base circuits.
(iii) Current gain similar to that of common emitter ($a_{fe} + 1 = 20\text{-}150$).
(iv) Voltage gain less than unity.
(v) Input and output voltages in phase.
(vi) Input impedance high.
(vii) Output impedance low — lowest of three circuits $\left(\approx \frac{\text{Source impedance}}{1 + a_{fe}}\right)$.
(viii) Input and output impedance very dependent on load and source impedances.
(ix) Input and output voltages in phase.
(x) Poor isolation between output and input circuits.
(xi) Large degree of negative feedback, and therefor low distortion.
(xii) Can be driven from a resistance-capacitance coupled driver because the driving current is small.

(e) Comparison of Properties of Three Circuits:

Table 9 lists the main properties of the three transistor circuits.

6. TRANSISTOR CIRCUIT DESIGN EQUATIONS

(a) General:

One of the most important considerations for anyone engaged on transistor work is the method of determining the performance of a particular transistor. This section will be devoted to notes on how this is achieved and will list the more important formulae.

It is possible to treat only a few of the aspects of transistor circuit performance in this article. Discussion will be restricted to low frequencies only, and the use of the various systems of parameters to determine major characteristics of an amplifier, e.g., input and output impedance, voltage, current and power gain, etc. A following article will outline the steps to be followed in the design of various types of amplifiers. For a more detailed treatment of the problems involved in the use of transistors, the reader is referred to the literature[7,8,10,11,12,13].

The design equations for circuits using transistors are complicated by the following facts:—

(a) current flows in each of the transistor's electrodes;
(b) feedback exists between input and output circuits;
(c) due to (a) and (b), the value of the load resistance R_L and the signal source or generator resistance R_g materially affects the value of the input resistance R_i and the output resistance R_o respectively.

These complications are particularly true if the T circuit parameters are used. As pointed out in Section 4, the h system of circuit parameters offers considerable improvement in this respect. The other systems "z" or "r", "y", etc., have somewhat similar advantages but, as previously noted, are not as useful, due to the increased difficulty and poorer accuracy of their measurement.

The modification to the "r" system[7,8], whereby r_f and r_r are replaced by r_{is} (r_{ies}, r_{ibs} or r_{ics}) and r_{os}, (r_{oes}, r_{obs} or r_{ocs}) respectively also simplifies the equations. (Note — r_{is} is the input resistance with the output short circuited to a.c. The extra subscript e, b or c refers to the common electrode — emitter, base or collector.)

Since the circuit parameters of the low frequency h system are coming into more general use, are being quoted more and more by transistor manufacturers and have the advantages discussed above, they will be the only circuit type treated in the following sections.

TABLE 10.

Circuit Performance Equations

Characteristic	Symbol and Definition (See Fig. 16)	h† Parameters	z or r † Parameters	Short Circuit† r Parameters	T Circuit Parameters §	
					Common Emitter	Common Base
Input Impedance	$Z_i = \frac{v_i}{i_i}$	$h_i - \frac{h_f h_r Z_L}{1 + h_o Z_L}$	$r_i - \frac{r_r r_f}{r_o + R_L}$	$\frac{r_i(R_L + r_{os})}{R_L + r_o}$	$r_b + \frac{r_e(r_c + R_L)}{r_c(1 - \alpha_{fb}) + R_L}$	$r_e + r_b \frac{r_c(1 - \alpha_{fb}) + R_L}{r_c - R_L}$
Output Impedance	$Z_o = \frac{v_o}{i_o}$	$\frac{1}{h_o - \frac{h_f h_r}{h_i + Z_g}}$	$r_o - \frac{r_r r_f}{r_i + R_g}$	$r_o \cdot \frac{R_g + r_{is}}{R_g + r_i}$	$r_c(1 - \alpha_{fb}) + \frac{r_e(r_m + R_g)}{r_e + r_b + R_g}$	$r_c \frac{r_e + r_b(1 - \alpha_{fb}) + R_g}{r_e + r_b + R_g}$
Current Gain	$A_i = \frac{i_o}{i_i}$	$\frac{h_f}{1 + h_o Z_L}$	$\frac{r_f}{r_o + R_L}$	$\frac{r_f}{r_o + R_L}$	$\frac{\alpha_{fb}}{1 - \alpha_{fb} + \frac{R_L}{r_c}}$	$-\frac{\alpha_{fb}}{1 + \frac{R_L}{r_c}}$
Voltage Gain	$A_V = \frac{v_o}{v_i}$	$\frac{1}{h_r - \frac{h_i}{Z_L}\left(\frac{1 + h_o Z_L}{h_f}\right)}$	$\frac{r_f R_L}{r_i(r_o + R_L) - r_r r_f}$	$\frac{r_f R_L}{r_i(r_{os} + R_L)}$	$\frac{-\alpha_{fb} r_c R_L}{r_c[r_e + r_b(1 - \alpha_{fb})] + R_L(r_e + r_b)}$	$\frac{\alpha_{fb} r_c R_L}{r_c[r_e + r_b(1 - \alpha_{fb})] + R_L(r_e + r_b)}$
Power Gain	$P.G. = A_v A_i$ $= \frac{v_o i_o}{v_i i_i}$	$\frac{\frac{h_f}{1 + h_o Z_L}}{h_r - \frac{h_i}{Z_L}\left(\frac{1 + h_o Z_L}{h_f}\right)}$	$\frac{r_f^2 R_L}{(r_i r_o - r_r r_f + r_i R_L)(r_o + R_L)}$	$\frac{r_f^2 R_L}{r_i(R_L + r_o)(R_L + r_{os})}$	$\frac{\alpha_{fb}^2 r_c^2 R_L}{\{r_c(1 - \alpha_{fb}) + R_L\}\{R_L(r_e + r_b) + r_c[r_e + r_b(1 - \alpha_{fb})]\}}$	$\frac{\alpha_{fb}^2 r_c^2 R_L}{(r_c + R_L)\{r_c[r_e + r_b(1 - \alpha_{fb})] + R_L(r_e + r_b)\}}$

§ The formulae quoted are approximate and are derived from the exact versions using the following assumptions :—$r_e << r_c - r_m$, $r_b << r_c$ and $\frac{r_m}{r_c} = \alpha_{fb}$.

† These equations apply to each of the circuit configurations provided the appropriate symbols are used.

The parameters of the T equivalent circuit however, still have a useful place in transistor circuit work, mainly because (a) they are the original series and therefore well known, and (b) they are of the device type and relate the transistor's circuit performance to its physical characteristics.

(*b*) *Calculation of Amplifier Characteristics:*

The main characteristics are defined as follows:—

Source impedance, Z_g — the impedance seen looking toward the generator from the line 1-1 of Fig. 16.

Input impedance, Z_i — the impedance seen looking toward the network from the line 1-1 of Fig. 16.

Output impedance, Z_o — the impedance seen looking toward the network from the line 2-2 of Fig. 16.

Load impedance, Z_L — the impedance seen looking toward the load from the line 2-2 of Fig. 16.

Current gain, A_i — the ratio of a.c. output current i_o to the a.c. input current i_i.

Voltage gain, A_v — the ratio of a.c. output voltage v_o to a.c. input voltage v_i.

Operating power gain, P.G. — the ratio of the a.c. power developed in the load to the a.c. power supplied to the input terminals of the network.

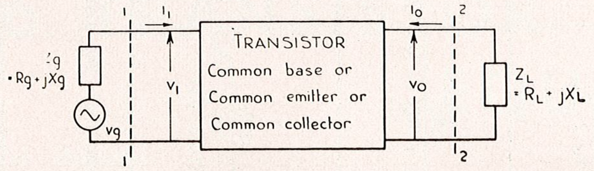


Fig. 16

For low frequencies where the reactive terms become negligible the Z terms can be replaced by their resistive counterparts, i.e., Z_g becomes R_g, etc.

Table 10 lists the five main characteristics of an amplifier expressed in terms of the h, z, short circuit r and T circuit parameters.

All the equations which follow are general, i.e., apply to each of the three configurations providing the appropriate value of the parameter is used.

A discussion of the rules to be followed in the determination of the operating conditions such as d.c. operating point, collector load resistance, collector dissipation efficiency, etc., will not be included here as the subject will be covered in a following article.

In section 4, d, (iii), it was stated that the use of the h instead of the T circuit parameters simplified considerably the work of calculating the characteristics of a transistor amplifier. A numerical example illustrating this simplification is given below:—

A series of measurements on a particular transistor 2N77 in a common emitter circuit give the following h parameters:—

Input resistance (output short circuit to a.c.) $h_{ie} = 2720\Omega$.

Forward current transfer ratio (output short circuit to a.c.) $h_{fe} = 55$.

Reverse voltage transfer ratio (input open circuit to a.c.) $h_{re} = 3.23 \times 10^{-4}$.

Output conductance (input open circuit to a.c.) $h_{oe} = 14\ \mu A/V$.

Find the voltage amplification A_v for a load $R_L = 20{,}000\Omega$.

Method (A) — Using T Circuit Parameters
To find r_e:

$$h_{re} = \frac{r_e}{r_e + r_c\,(1 - \alpha_{fb})} = 3.23 \times 10^{-4} \quad \ldots\ldots\ldots\ldots (1)$$

$$\text{and } h_{oe} = \frac{1}{r_e + r_c\,(1 - \alpha_{fb})} = 14 \times 10^{-6}\ \text{A/V} \quad \ldots\ldots\ldots\ldots (2)$$

where r_e, r_c are the parameters of the T equivalent circuit of Fig. 12.

α_{fb} is the forward current transfer ratio common base circuit (α of Fig. 12).
Then dividing equation (1) by (2) we have

$$\frac{h_{re}}{h_{oe}} = r_e = \frac{3.23 \times 10^{-4}}{14 \times 10^{-6}}$$

$$= 23.1 \text{ ohms.}$$

Substituting in equation (2)

$$\frac{1}{23.1 + r_c\,(1 - \alpha_{fb})} = 14 \times 10^{-6}$$

$$\therefore\ 14 \times 10^{-6}\,[23.1 + r_c\,(1 - \alpha_{fb})] = 1$$

$$r_c\,(1 - \alpha_{fb}) = \frac{1 - 14 \times 23.1 \times 10^{-6}}{14 \times 10^{-6}}$$

$$= 7.14 \times 10^4 \text{ ohms} \ \ldots. \quad (3)$$

$$\text{Now } h_{fe} = \frac{\alpha_{fb}}{1 - \alpha_{fb}} = 55$$

$$\therefore \quad \alpha_{fb} = \frac{55}{55 + 1}$$

$$= 0.982$$

Substituting in equation (3)

$$r_c = \frac{7.14 \times 10^4}{1 - \alpha_{fe}}$$

$$= \frac{7.14 \times 10^4}{1 - 0.982}$$

$$= 3.97 \times 10^6 \text{ ohms.}$$

Also $h_{ie} = r_b + \frac{r_e}{1 - a_{fb}}$

$$2720 = r_b + \frac{23.1}{0.018}$$

$$\therefore r_b = 2720 - 1285$$

$$= 1433 \text{ ohms}$$

From Table 10 the voltage gain is given by

$$A_v = \frac{-\alpha_{fb}\, r_c\, R_L}{r_c\,[r_e + r_b\,(1 - \alpha_{fb})] + R_L\,(r_e + r_b)}$$

Substituting the values for a_{fb}, r_e, r_b and r_c with $R_L = 20{,}000\Omega$.

$$\approx A_v \quad \frac{-0.982 \times 3.97 \times 2 \times 10^{10}}{19.4 \times 10^7 + 2.92 \times 10^7}$$

$$\approx \quad -348$$

Method (B) — Using the h Parameters

From Table 10

$$A_v = \frac{1}{h_{re} - \frac{h_{ie}\,(1 + h_{oe}\,R_L)}{R_L\,(\quad h_{fe}\quad)}}$$

$$= \frac{1}{3.23 \times 10^{-4} - \frac{2720 \quad (1 + 14 \times 2 \times 10^{-2})}{2 \times 10^4\,(\quad 55 \quad)}}$$

$$= \frac{1}{3.23 \times 10^{-4} - 3165}$$

$$= -352$$

The great saving in labour using method B is obvious. This, of course, illustrates the worst case, i.e., where the T circuit parameters are not given and must be calculated from the h parameters.

For the other case, where both sets of parameters are quoted, the second method still represents a saving in time and effort and is more accurate.

---

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(4) W. T. Cocking "Transistor Equivalent Circuits", Wireless World, August, '55, Page 392.

(5) See "Principles of Transistor Circuits", R. F. Shea. pp33, 34.

(6) Proceedings of the I.R.E., July, 1956. pp935-37.

(7) R. F. Shea: "Principles of Transistor Circuits" p494.

(8) L. B. Johnson: "An Improved Method for Calculating the A.F. Performance of Junction Transistors". Mullard Tech. Communication, July '54. p187.

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(11) R. F. Shea: "Principles of Transistor Circuits", p333.

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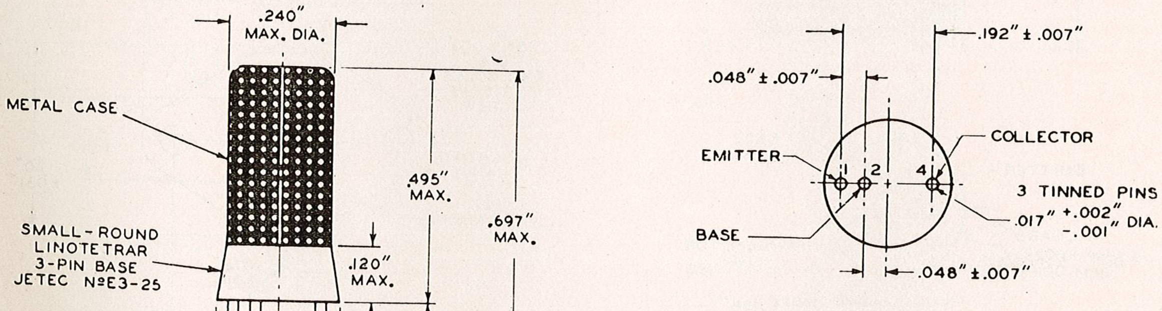
DIMENSIONAL OUTLINES

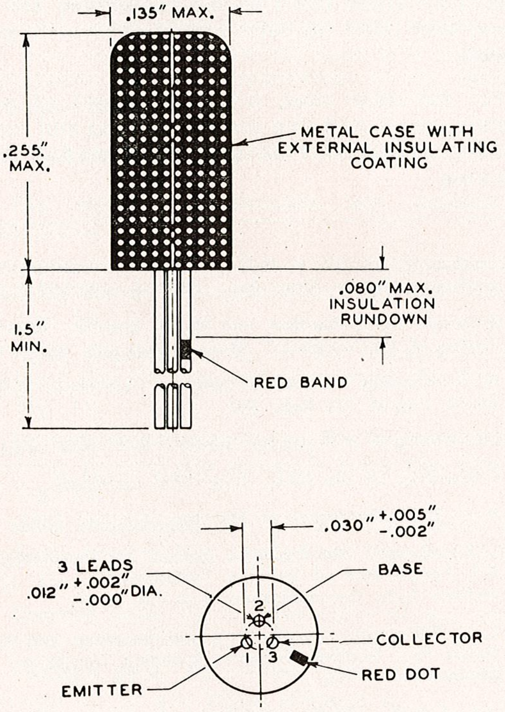
A



PIN-SPACING TOLERANCES ARE NOT CUMULATIVE

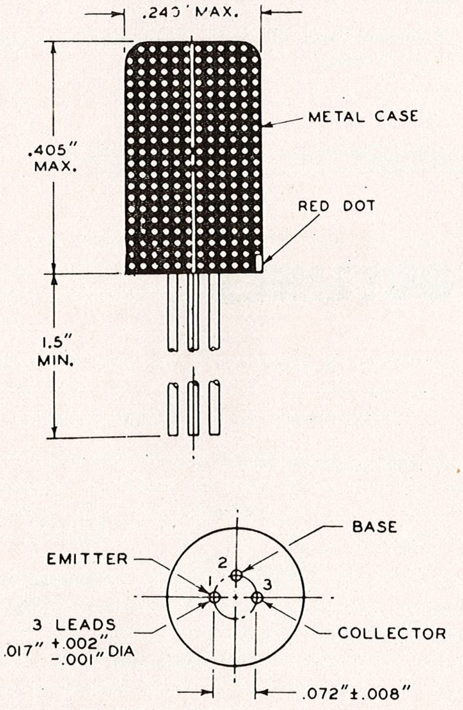
2N104
2N109
2N139
2N140
2N175
2N405
2N407
2N409
2N411

B



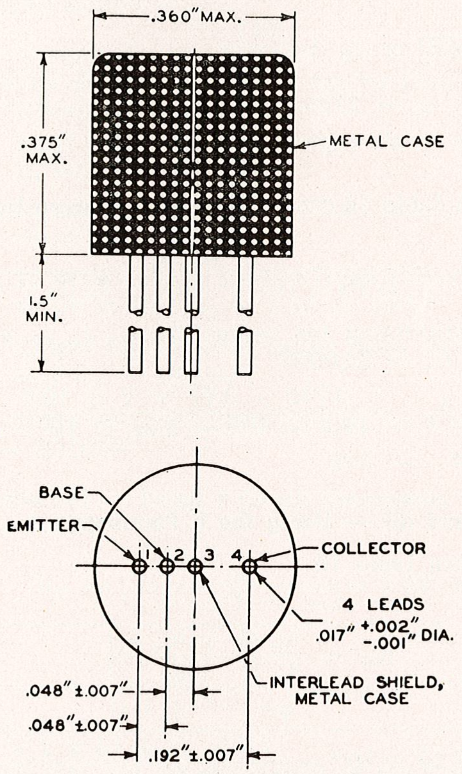
2N105

C



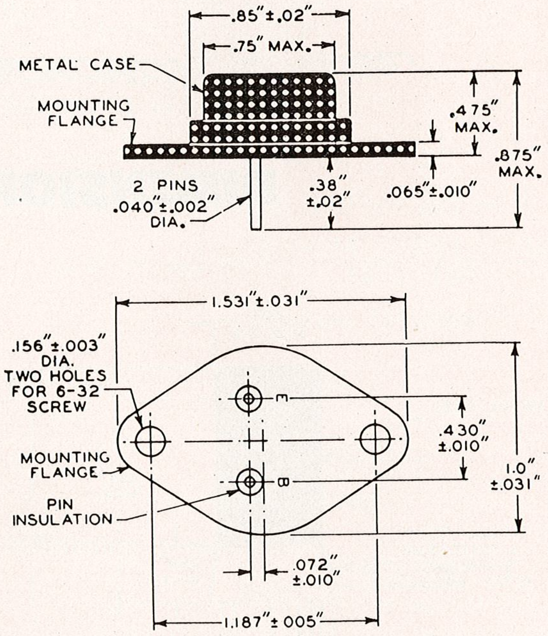
2N215	**2N219**	**2N408**
2N217	**2N220**	**2N410**
2N218	**2N269**	**2N412**
	2N406	

D



2N247 **2N370** **2N371** **2N372**

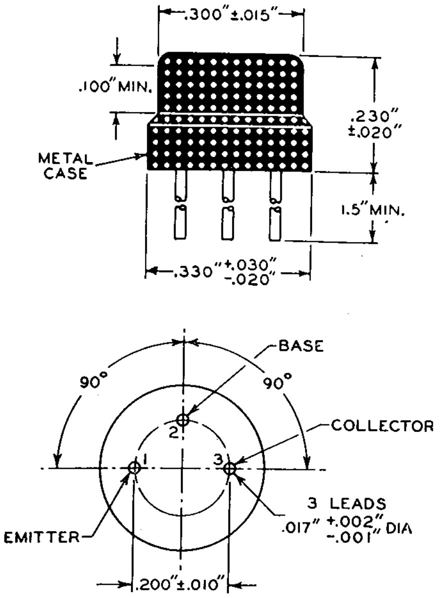
E



E=EMITTER
B=BASE
MOUNTING FLANGE=COLLECTOR

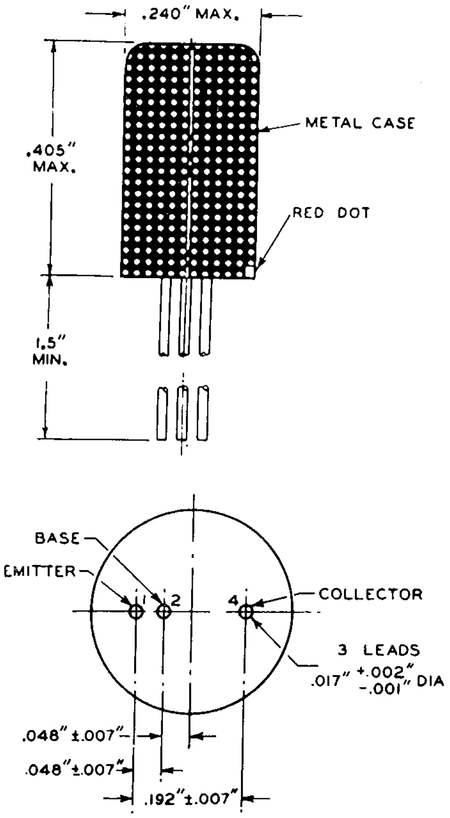
2N301 **2N301A**

F



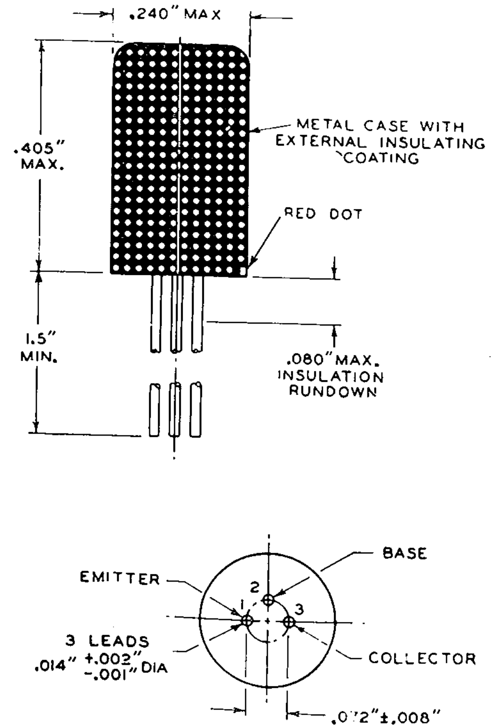
2N331 **2N398** **2N404**

H



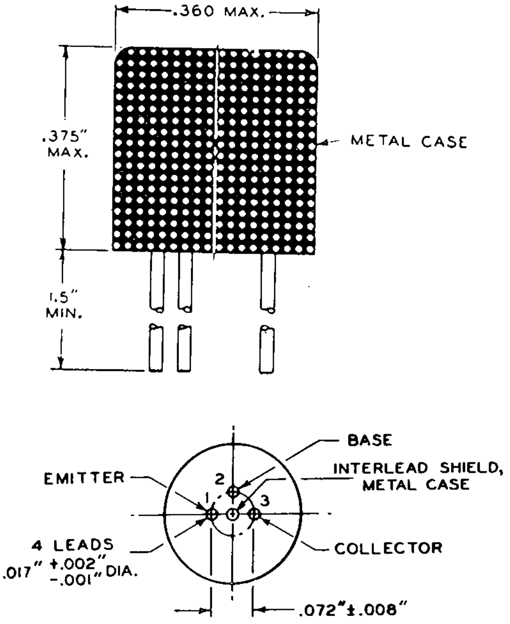
2N274 **2N384**

G



■ Lead Diameter is .017" + .002" or — .001"

I



2N270


AWV