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JUNCTION TRANSISTOR EQUIVALENT CIRCUITS AND VACUUM TUBE ANALOGY

RADIO CORPORATION OF AMERICA

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Junction Transistor Equivalent Circuits and Vacuum Tube Analogy

Approved

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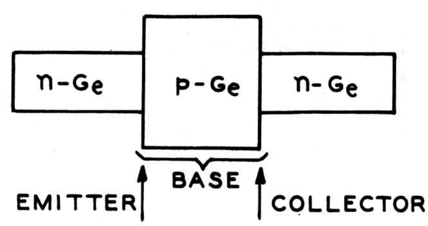
Introduction

The junction transistor possesses operating characteristics that are closely comparable to a modified triode vacuum tube. A direct comparison between the two devices is particularly interesting if a π equivalent circuit is used for the transistor. The vacuum tube analogy and transistor equivalent circuits are considered in some detail in this bulletin. For purposes of comparison, a side-by-side tabulation of operating characteristics of a transistor and a vacuum tube has been prepared.

Vacuum Tube Analogy

In recent publications,[1,2] the point contact transistor has been considered as a device that is a dual of a vacuum tube. The junction transistor,[3] on the other hand, can be related directly to the vacuum tube.[4] This direct relationship is emphasized by comparison with a slightly unusual vacuum tube.

Consider an n-p-n junction transistor in Fig. 1a consisting of an emitter plane, base, and collector plane. The comparable vacuum tube is shown immediately below in Fig. 1b. The cathode is directly analogous to the emitter, and the anode to the collector. In the transistor the active region is the p-type germanium base. The corresponding active region in the vacuum tube is the space included between the cathode and anode. In order that the vacuum tube active space be field free, as is approximately the case in the transistor, the vacuum tube active space is enclosed between two grids connected together to form a grid structure which is now comparable with the transistor base element.



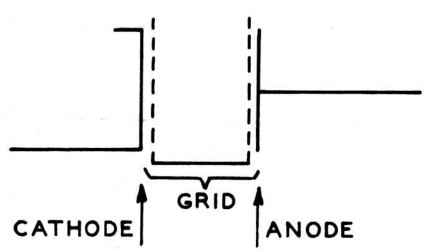


Fig. 1 - n-p-n transistor and corresponding vacuum tube.

[1] R. L. Wallace, Jr. and G. Raisbeck, "Duality as a Guide in Transistor Circuit Design", *B.S.T.J.*, Vol. 30, pp. 381-417; April, 1951.

[2] R. L. Wallace, Jr., "Duality, A New Approach to Transistor Circuit Design", *Proc. I.R.E.*, Vol. 39, p. 702; June, 1951.

[3] R. L. Wallace, Jr. and W. J. Pietenpol, "Some Circuit Properties and Applications of n-p-n Transistors", *Proc. I.R.E.*, Vol. 39, pp. 753-767; July, 1951.

[4] A direct relationship between the junction transistor and vacuum tube was indicated by W. Shockley, U.S. Patent 2,569,347.

See also W. Shockley, "The Theory of p-n Junctions in Semiconductors and p-n Junction Transistors", *B.S.T.J.*, Vol. 28, pp. 435-489; July, 1949 and W. Shockley, M. Sparks, and G. K. Teal, "P-N Junction Transistors", *Phys. Review*, Vol. 83, pp. 151-162; July, 1951.

The junction transistor collector characteristics are of a pentode character, i.e., the collector current saturates as a function of the collector voltage. This is equivalent to saying that the collector current is independent of the collector voltage, or, more accurately, that the emitter is not influenced to any appreciable degree by the collector voltage. The same operation is characteristic of the structure of Fig. 1b since the cathode field will be essentially independent of the anode voltage. For the structure of Fig. 1b the cathode will have to be biased negatively with respect to the grid in order to get any significant anode current. This again is entirely analogous to similar bias arrangements in a transistor. The ensuing grid current is comparable to the base current. A current amplification factor, $\alpha = -I_a/I_k$ can be defined for the vacuum tube similar to that defined for a transistor. Here, I_a is the short-circuited a-c anode current, and I_k is the a-c cathode current.

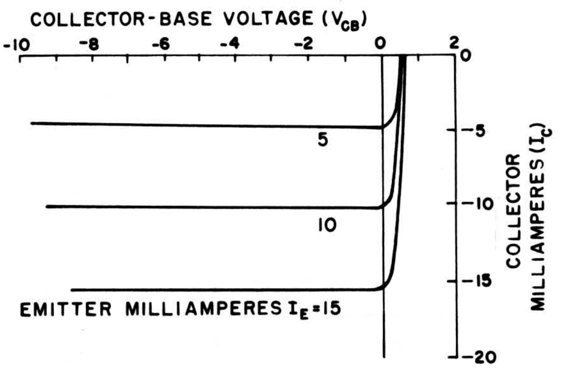


Fig. 2a - Collector characteristics of p-n-p junction transistor.

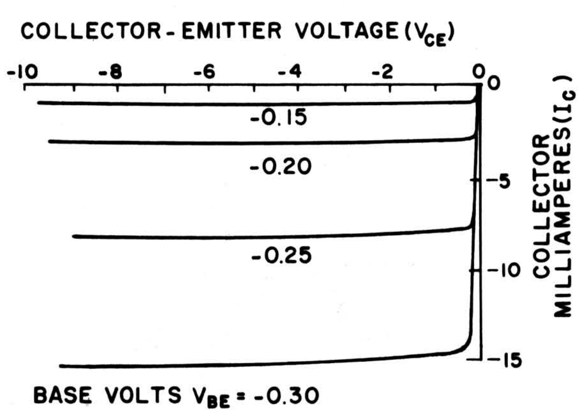


Fig. 2b - Collector characteristics of p-n-p junction transistor.

Consider the grid-to-anode region. The electrons leaving the grid structure are drawn to the anode because of the positive voltage thereupon. If the grid-to-anode voltage is small, the electron flow will be of a space-charge character. For a somewhat larger grid-to-anode voltage the anode current will remain the same for any larger grid-to-anode voltage, i.e., the anode current has saturated at a value corresponding approximately with the current entering the grid structure. Now, if the cathode is made more negative with respect to the grid, more electrons are injected into the grid structure so that the anode current saturation value is correspondingly increased. A closely analogous operation takes place in the n-p-n transistor. The base-to-emitter voltage determines the number of electrons entering the base wafer. These electrons flow to the collector and become the corresponding saturation collector current. The correspondence between collector characteristics and anode characteristics is immediately apparent.

The discussion above has centered about an n-p-n junction transistor. A p-n-p junction transistor might be considered analogous to a vacuum tube of the type shown in Fig. 1b in which the cathode emits positrons. The charge carrier for either device is now positive so that all voltage polarities must be reversed after which the statements made above can be applied.

In the past, the collector characteristics have usually been plotted with the emitter current as the running parameter. This method of presentation using data of an early experimental RCA p-n-p transistor is shown in Fig. 2a. In order to emphasize the tube analogy it is desirable to use the base-to-emitter voltage as the running parameter as shown in Fig. 2b. In accordance with vacuum tube practice, the voltages in Fig. 2b are measured with the emitter as the reference point so that V_{CE} will differ slightly from V_{CB}.[5]

Fig. 3a shows the input characteristics of the transistor to complement the output characteristics of Fig. 2b. The associated transfer characteristics are shown in Fig. 3b and are similar to transfer characteristics for the vacuum tube of Fig. 1b if due allowance is made

[5] Throughout this bulletin upper-case letter subscripts will be used to denote d-c values and lower-case letter subscripts will be used to denote a-c values.

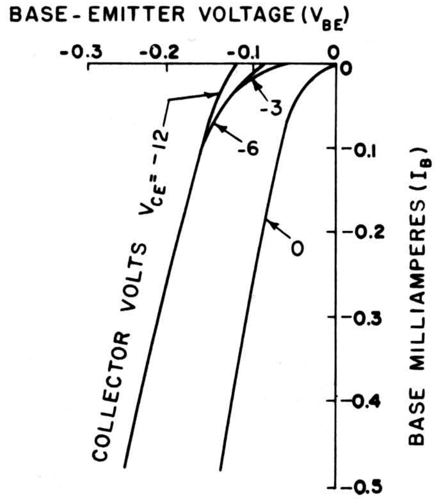


Fig. 3a - Base characteristics of p-n-p junction transistor.

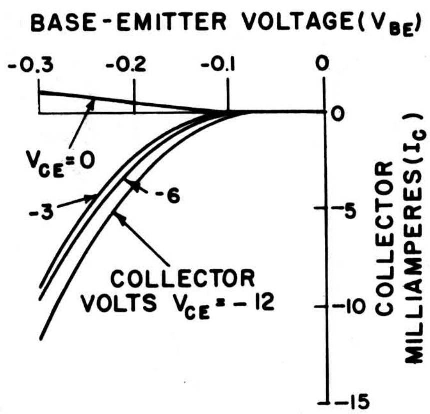


Fig. 3b - Transfer characteristics of p-n-p junction transistor.

for the difference in carrier polarity. It is apparent that the transistor exhibits non-linear transfer characteristics. The linear operation of a transistor is therefore not appreciably different from a vacuum tube with degeneration being required for either device if linear operation is desired.

Transistor Transconductance

The transistor transconductance is shown in Fig. 4. The g_m curve is roughly exponential and somewhat similar to vacuum tube g_m curves except for magnitude. The nature of the transistor g_m curve can be understood in an approximate way from the transistor operation described above. Since the collector current is approximately the same as the emitter current, the transconductance is about equal to the emitter conductance, $1/r_e$ which W. Shockley[4] has shown to be eI_e/kT. Consequently, the transconductance to emitter current ratio, $g_m/I_E = e/kT = 38.6$. Here, e is the absolute charge of an electron; k is Boltzmann's constant; and T is the absolute operating temperature of the transistor. This is a theoretical value but does not differ appreciably from measured values when the emitter current is small. For vacuum tubes the same transconductance-to-current ratio has a theoretical value of 11.6 although measured values are hardly ever larger than 2. Thus the transistor has at least a 20:1 higher value than vacuum tubes for this important constant.

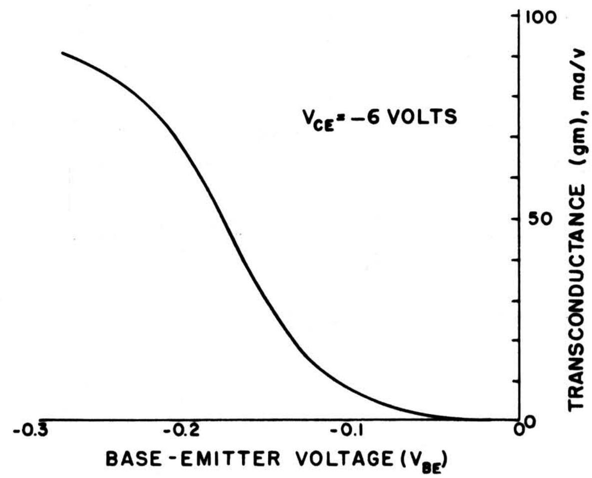


Fig. 4 - Transconductance characteristics of p-n-p junction transistor.

π Equivalent Circuits

The T equivalent circuit has been used most frequently in connection with transistors.[6,7,8] In contrast, the π equivalent circuit has usually been used in connection with grounded-cathode vacuum tubes. In Fig. 5a there is shown the common-emitter T equivalent circuit for the p-n-p transistor being studied.

[6] W. M. Webster, E. Eberhard, and L. E. Barton, "Some Novel Circuits for the Three-Terminal Semiconductor Amplifier", *RCA REVIEW*, Vol. 10, pp. 5-16; March, 1949.

[7] R. M. Ryder and R. J. Kircher, "Some Circuit Aspects of the Transistor", *B.S.T.J.*, Vol. 28, pp. 367-400; July, 1949.

The major difference[8] between this equivalent circuit and the more familiar common-base circuit is that the resistor in series with the collector terminal for the latter is $r_c - r_m$ = 0.514 megohm. Fig. 5b shows the equivalent π circuit of the same p-n-p junction transistor shown in Fig. 5a. The T equivalent circuit is transformed to a π circuit in accordance with the theory developed by L.C. Peterson.[9]

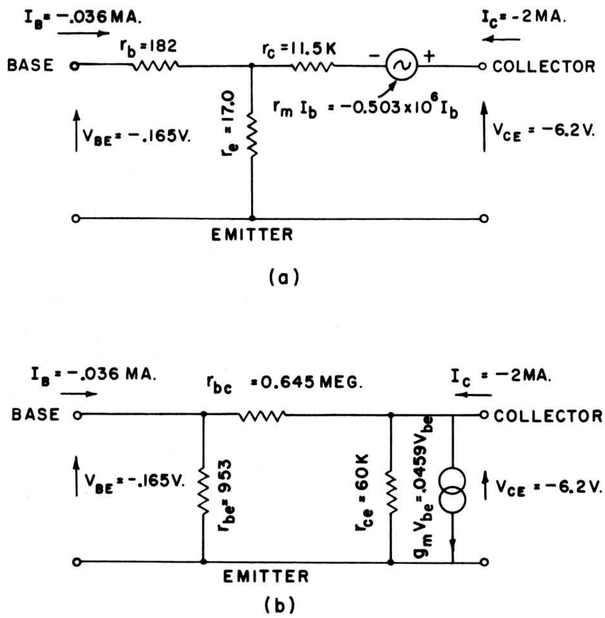


Fig. 5 – T and π equivalent circuits of p-n-p junction transistor.

From the component values given in Fig. 5b it is seen that although the resistance between the input and output is not infinite as is the case for a vacuum tube, it is large so that, to an approximation, it is permissible to consider the input and output circuits independently. For comparison purposes, the π equivalent circuits for the common-base and the common-collector circuits are shown in Figs. 6a and 6b respectively.

It is, of course, immaterial whether a direct or a dual comparison is drawn between a vacuum tube and a transistor or whether a T or π equivalent circuit is employed. It is believed that, for many engineers who have developed a background of vacuum tube experience, the direct comparison and the π equivalent circuit will be easier to use. The comparison is sufficiently complete that most of the vacuum tube technology may be transferred directly to the transistor. An important difference between the two devices is the presence in the transistor of a finite resistance between base and collector.

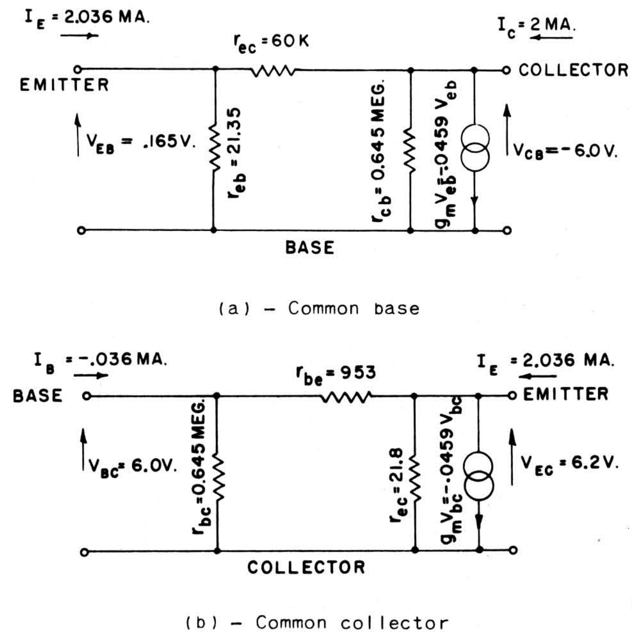


Fig. 6 – π equivalent circuits of p-n-p junction transistor.

Comparative Operating Data

Since a direct comparison has been drawn between the vacuum tube and the transistor, it is interesting to prepare a side-by-side comparison between the two. For this comparison, shown in Table I, a 6AG5 pentode and the previously described RCA p-n-p junction transistor have been selected. A few comments concerning this tabulation are appropriate. There is no special reason for comparing the 6AG5 with the junction transistor other than that the 6AG5 is a well known vacuum tube. It would be more appropriate to compare the transistor with the unconventional vacuum tube of the type shown in Fig. 1b. The large g_m and g_m/I_e ratio of the transistor have already been mentioned. The input impedance of a negative grid vacuum tube is very large as compared with 438 ohms for the

[8] Marcel J. E. Golay, "The Equivalent Circuit of the Transistor", *Proc. I.R.E.*, Vol. 40, p. 360; March, 1952.

[9] L. C. Peterson, "Equivalent Circuits of Linear Active Four-Terminal Networks", *B.S.T.J.*, Vol. 27, pp. 593–622; October, 1948.

transistor. The large input impedance is an important advantage for the vacuum tube and accounts in part for the large power gain. In order to facilitate comparison, a finite grid resistor of 10 megohms has been associated as an integral part of the vacuum tube. Large grid resistors of this magnitude are sometimes employed in low-frequency, low-level vacuum tube circuits. The current and noise associated with the grid resistor are charged to the vacuum tube and account for the grid current, the finite current amplification factor and the 3-db noise factor.

In studying the data of Table I, it is important to remember that the transistor selected was an early developmental unit and that transistors are in their early stages of development as compared with vacuum tubes.

Table I

Comparison between Vacuum Tube and Transistor Characteristics and Performance

6AG5 PENTODE	P-N-P JUNCTION TRANSISTOR
Heater Power = 1.9 watts	Heater Power = 0 watts
Grid-Cathode Voltage = V_{GK} = -0.9 volt	Base-Emitter Voltage = V_{BE} = -0.165 volt
Grid Current = I_G = 0.09 μa	Base Current = I_B = -0.036 ma
Screen-Cathode Voltage = V_{SK} = 125 volts	Collector-Emitter Voltage = V_{CE} = -6.2 volts
Anode-Cathode Voltage = V_{AK} = 125 volts	
Screen Current = I_S = 2.1 ma	Collector Current = I_C = -2.0 ma
Anode Current = I_A = 7.2 ma	
Current Amplification Factor (grounded grid) = $-I_a/I_k \approx 0.775$	Current Amplification Factor (common base) = $-I_c/I_e$ = 0.977
Current Amplification Factor (grounded cathode) = $-I_a/I_g \approx -80 \times 10^3$	Current Amplification Factor (common emitter) = $-I_c/I_b$ = -43.6
r_{gk} = 10 Megohms	r_{be} = 953 ohms
r_{ga} = ∞	r_{bc} = 0.645 Megohm
r_{ak} = 0.5 Megohm	r_{ce} = 60 K ohms
g_m = 5.1 ma/v	g_m = 45.9 ma/v
g_m/I_K = 0.55	g_m/I_E = 22.6
$R_{input\ match.}$ = 10 Megohms	$R_{input\ match.}$ = 438 ohms
$R_{output\ match.}$ = 0.5 Megohm	$R_{output\ match.}$ = 25.3 K ohms
Maximum Power Gain = 75 db	Maximum Power Gain = 40 db
Noise Factor at 1 kc/s = 3 db	Noise Factor at 1 kc/s = 22 db

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