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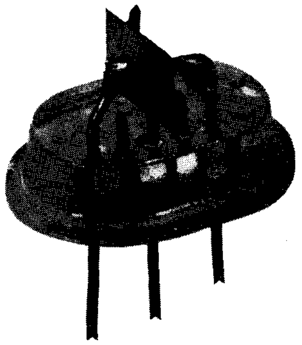


Some Properties of Experimental 1000-Mc Transistors

Abstract: Experimental transistors designed to operate above 1000 Mc are described and measurements of their electrical parameters discussed. The design is a diffused-base drift transistor structure with minimized bulk resistances and junction capacitances. Measurements of the short-circuit current gain ($-h_{21p}$) with both emitter and collector reverse-biased, indicated that the passive circuit comprising extrinsic parameters only could produce a gain greater than unity. Interpretation of measurements using a simplified equivalent circuit shows that reduction of bulk resistances leads to an appreciable passive or feed-through current. An oscillator is described in which the transistors operated up to 1550 Mc.

Introduction

Recent papers on high-frequency transistors have indicated that operation with useful gain above 1000 Mc is possible.[1] Little information has been available, however, concerning the actual measurement and analysis of the electrical parameters for transistors in this frequency range.

This paper describes the fabrication and measurement of some experimental drift transistors which were made explicitly to operate at frequencies above 1000 Mc. The role played by the extrinsic parameters was studied and found to have a great influence on transistor operation at these high frequencies.

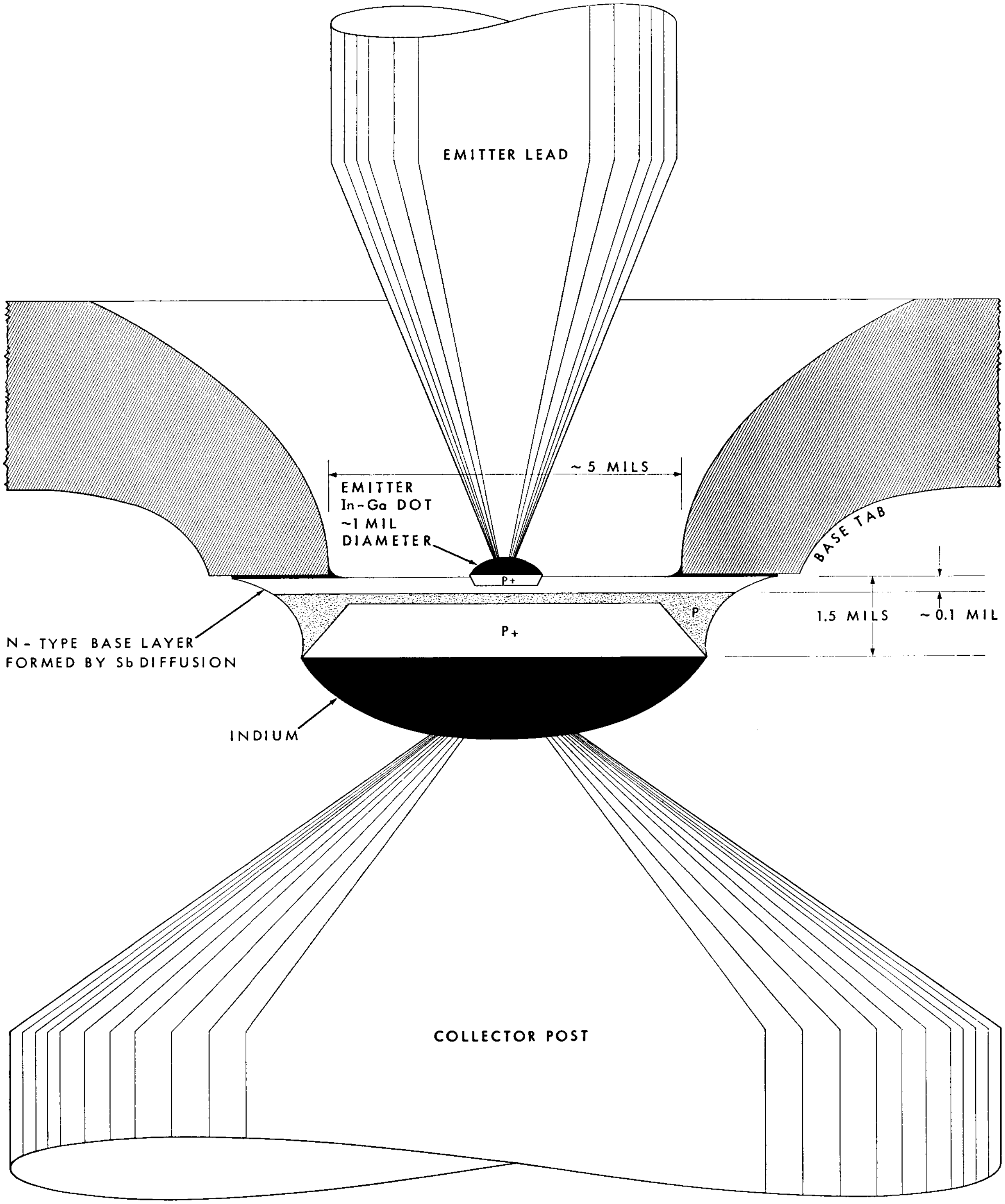
The first requisite for design of such transistors is a very narrow base width. Very small emitter and collector sizes are necessary to reduce junction transition capacitances to the lowest possible values, since the RC time constants reduce the gain at high frequencies.[2] It is evident, of course, that all internal bulk resistances must likewise be as low as possible except in the immediate vicinity of the collector junction, where a compromise is necessary in order to achieve an acceptable breakdown voltage.

Fabrication and testing

The structure chosen to meet these requirements is that of a diffused-base drift transistor. A cross-section is shown in Fig. 1. The transistor utilizes a circular base tab, since this geometry presumably would give the lowest possible base resistance. The base region is formed by diffusing antimony to a depth of $\sim 10^{-4}$ inch into a wafer of p-type germanium of approximately one ohm-cm resistivity. The method of diffusion is that developed by J. Marinace[3] of this laboratory. The wafer is coated with a thin amorphous film of Sb_2O_5 and then heat treated in air at 600°C for a time appropriate for the depth of diffusion needed. The diffusion process provides the very low surface-resistivity desired in drift transistor design[4] and helps provide the very low base resistance required. The emitter is alloyed from a one-mil sphere of an In-Ga alloy and the wetted diameter is slightly larger than one mil. The depth of penetration is not easily measured and is not accurately known nor, consequently, is the resulting base width, although the latter is estimated to be in the vicinity of 0.05 mils. The collector connection is made through an alloyed 5-mil indium dot. The depth of penetration of the low-resistivity recrystallized region is made such that it approaches the junction in the wafer formed by the diffusion process in order to reduce the collector bulk resistance to as low a value as possible without appreciably increasing the collector capacitance. The other pertinent dimensions are indicated in Fig. 1. The whole assembly is mounted on a standard subminiature 5-pin glass tube base, primarily for the ease of assembly of the delicate structure and for low capacitance between leads. Only the center and two outer leads are used. The header capacitance between the emitter and base and the collector and base leads is approximately 0.5 $\mu\mu$fd. The lead lengths were also kept as short as possible consistent with ease of assembly, in order to minimize lead inductance which, as will be described shortly, plays a major role at frequencies above 1000 Mc. The experimental transistors were assembled by E. W. Harden at the Research Laboratory.

Since the two primary variables (the depth of emitter and collector-alloy penetration) could not be easily con-

Figure 1 **Experimental high-speed transistor.** *Photo inset (page opposite) is approximately twice actual size.*

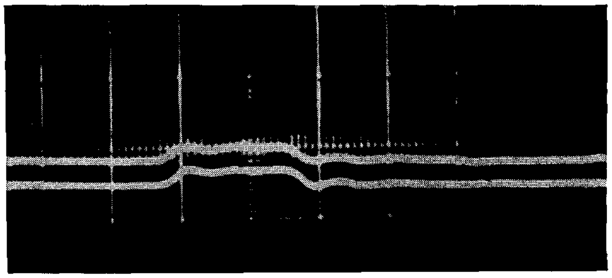


trolled to the accuracy desired, the transistors to be considered for high-frequency analysis were selected after assembly on the basis of two measurements: pulse rise and delay time, and maximum frequency of oscillation above 1100 Mc. Also, no transistors were considered which did not have a collector-to-emitter breakdown of 10 volts or greater and a low-frequency α_{cb} of 20 or greater.

The measurements for pulse response were made on the 517 Tektronix oscilloscope, the signal being fed directly to the vertical-deflection plates. A typical response for a grounded-base amplifier circuit using a 100-ohm collector resistor and a 1000-ohm series-emitter resistor connected to a terminated transmission line fed by a SKL Fast Rise Pulse Generator is shown in Fig. 2. The vertical sensitivity of the tube is 17 v/cm and the sweep speed is 5 mμsec/cm. The top trace shows the pulse generated on the collector load resistor when the transistor is replaced by a direct emitter-to-collector short circuit. The rise time of approximately 1 mμsec represents the limit of resolution of this particular oscilloscope tube. The bottom trace is the pulse at the collector load resistor with a 7.5-volt collector supply when a high-frequency transistor is in the circuit. A delay of a few tenths of a mμsec is the only apparent change in the display and indicates that the transistor has a frequency response equal to or greater than that of the oscilloscope tube. All transistors considered had comparable responses. It will be noted that this is a large-signal test and the output collector current is 30 ma; the test thus indicates that the transistor is useful as an uhf pulse-amplifier circuit element.

The oscillator used for preliminary testing of the transistors is a coaxial circuit shown in cross-section in Fig. 3. The transistor is inserted in the end of the coaxial line, as shown, with the collector contacting the center conductor and the base, a segment of an end plate which is soldered to the outer conductor. A movable tuning plunger whose length is chosen to be approximately $\lambda/4$ of the wavelength of the oscillation, and which acts as a rf choke, rides on the center conductor and is insulated from the outer conductor by small teflon feet. The end of the plunger acts as a short circuit to high frequencies and thus the left end of the coaxial line acts as a tuned circuit between the collector and base. At reasonably low frequencies, say 500 Mc, the measured length of the shorted coaxial line is shorter than $\lambda/4$ and indicates an equivalent inductance which is very close to that necessary to resonate with the collector capacitance for this frequency. At ultra high frequencies, however, the plunger is extremely close to the transistor and the boundary conditions are such that a lumped-parameter equivalent for the line cannot be easily calculated.

Figure 2 **Grounded-base pulse response for typical experimental high-speed transistor.**



A high-frequency IRC 5K resistor is soldered to the end of the emitter lead and connected to a positive bias supply. In this design, and for these transistors, sufficient energy from the tuned circuit between the collector and base was picked up by the emitter to be amplified and to sustain oscillations over a wide range of frequencies. It was found that plunger length was not critical and that a plunger corresponding to $\lambda/4$ for 1000 Mc would, in fact, tune the oscillator over a range of from 500 to above 1500 Mc. Only those transistors which sustained oscillation in this circuit at frequencies above 1100 Mc were considered for the detailed high-frequency, small-signal analysis. It is evident from the lack of an optimizing feedback control, that the highest frequency at which oscillation is observed is not necessarily the highest frequency at which the transistor has a power gain greater than unity.

Analysis of passive circuit

In attempts to measure the short-circuit current gain h_{21}, the transistors showed a tendency to oscillate at certain collector voltages and emitter bias currents. At other bias points where no oscillation was observed, the current gain (h_{21}) at certain frequencies was greater than unity.[5] This condition suggested the possibility of a resonant circuit. Consequently, measurements were made in an attempt to ascertain the high-frequency extrinsic parameters — namely, lead inductances, transition capacitances, and bulk resistances. For these measurements, the emitter and collector junctions were both reverse-biased, and the signal level was set sufficiently low to prevent any injection or rectification at the junctions.

Consider the simplified uhf equivalent circuit of the transistor given in Fig. 4. The current i_c consists of two components: the direct feed-through current, i_{ft}, and the current component due to the intrinsic transistor i_i. The latter is the current due to the transistor action as a result of minority carrier flow and does not appear explicitly in any loop of the equivalent circuit. With both junctions reverse-biased, the collector current is feed-through current only (i_{ft}). Values L_b and L_c are base and collector lead inductances respectively, r_b is a portion of the base resistance, which can be considered as common in both forward and reverse direction, while r_c is the effective bulk resistance in the collector.

The solution for i_{ft} as a function of i_e is then:

$$i_{ft}=\frac{i_e Z_b}{Z_b+Z_c+(1/sC_c)}, \tag{1}$$

where $s=j\omega$,

or the passive short-circuit gain

$$-h_{21p}=\frac{i_{ft}}{i_e}=\frac{r_b+sL_b}{(r_b+r_c)+s(L_b+L_c)+(1/sC_c)}. \tag{2}$$

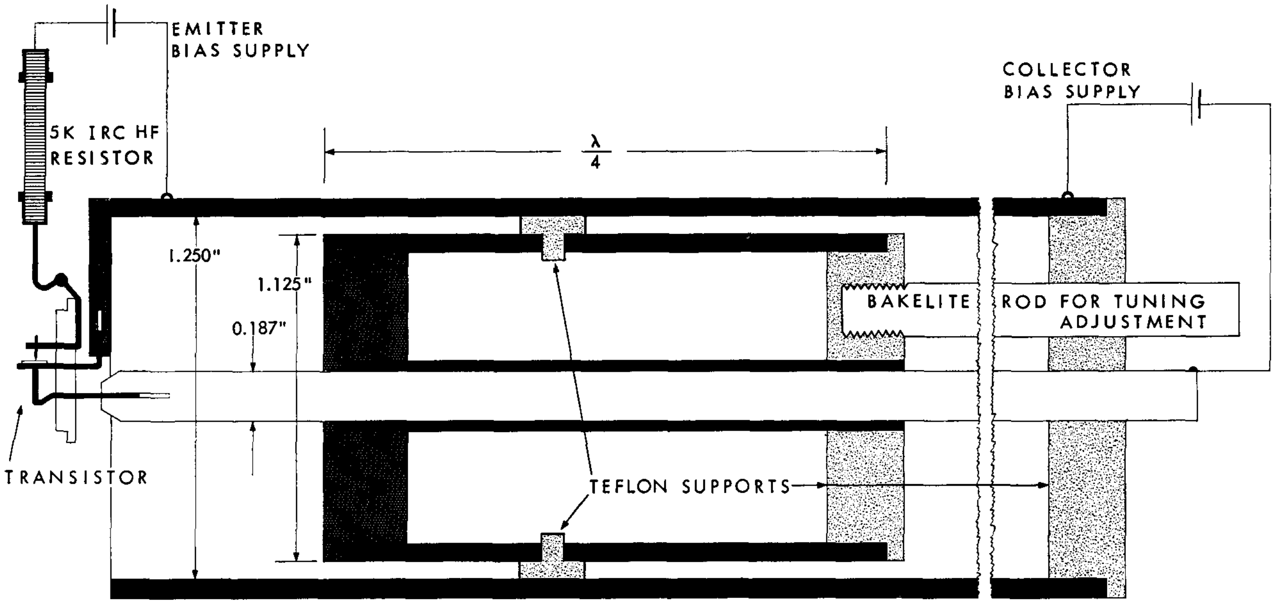


Figure 3 **Cross section of coaxial test oscillator.**

The effective base resistance r_b, which is determined primarily by the highly doped surface of the base region, remained essentially constant as the collector voltage was varied, while C_c showed the well-known variation with voltage due to depletion layer widening. Thus a change in collector voltage serves only to change C_c. Considering C_c a variable, the locus of Eq. (1) is a circle passing through the origin, with the center of the circle occurring at

$$\frac{r_b+sL_b}{2(r_b+r_c)} \qquad (3)$$

and with

$$\rho=\frac{\sqrt{r_b^2+(\omega L_b)^2}}{2(r_b+r_c)}, \qquad (3a)$$

where ρ is the radius of the circle.

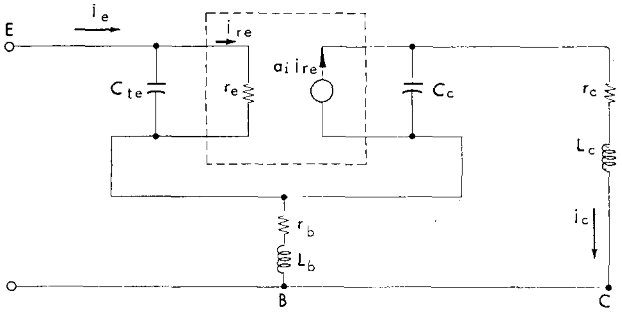
Thus, a plot of the $-h_{21p}$ as a function of collector voltage with both emitter and collector reverse-biased and the frequency held constant should produce a circle, since only feed-through current will be involved. Figure 5 shows measured values of $-h_{21p}$ as the collector voltage is varied within the permissible range of V_c less than breakdown. In all cases, maximum V_c was sufficiently less than breakdown to assure negligible avalanche multiplication at the collector junction. Measurements were made on different IBM units (all of which have the same structural symmetry) using the General Radio Transfer Function meter.

The standard IBM drift transistor[6] has an approximate $f_{\alpha co}$ of 150 Mc, while the alloy transistor[7] with its larger dimension and uniform base has a $f_{\alpha co}$ of 10 Mc. Direct comparison between the units cannot be made, since the frequency at which the values were obtained is different in each case. This was necessary to produce sufficient spread of the points to allow an accurate circle to be drawn. Since each unit is limited to a specific total change in capacitance, the measured values would tend to converge at the origin for both high and low frequencies. In general, as the frequency is raised, the points move clockwise on the circle, the radius increases, and the center of the circle shifts upward. It is interesting to note that the circle drawn for the alloy unit has a center occurring at approximately $0.5+j0$. This implies that L_b is negligible at this frequency compared to r_b and that $r_c << r_b$. If the frequency of measurement were increased to 500 Mc, for example, we would expect the range of points to move clockwise but with only slight change in radius or center. This condition was that actually observed.

Table 1 shows the values of the radii for the h_{21p} circle with the measurements taken at 1100 Mc for seven experimental units. The spread in values reflects the degree of uniformity of the transistors selected on the basis of ability to oscillate above 1100 Mc. The smaller radii were for those units having smaller base-lead inductances.

Figure 4 **Transistor uhf equivalent circuit with base and collector shown shorted for h_{21} measurements.**

Dotted area is intrinsic region.



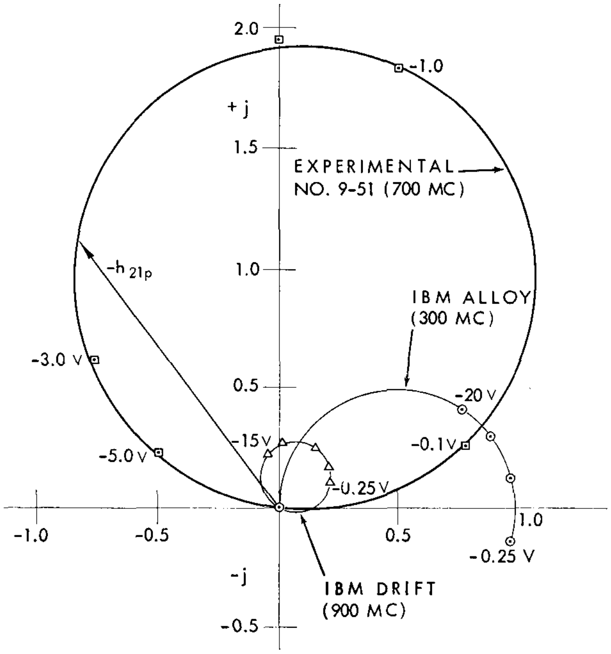


Figure 5 **Passive short-circuit current gain ($-h_{21}$) for different types of triode transistors.** *The numbers in parentheses are the measurement frequencies.*

Sufficient measurements were made on a number of experimental units to determine the extrinsic parameters r_b, r_c, L_b and L_c and thus to compare the measured circle with that obtained from Eqs. (3) and (3a). In all cases, the agreement was excellent. Unit 9-50, which had an α_{cb} of 200 and oscillated at 1550 Mc, will be discussed here in detail.

Measurements of Z_{21} as a function of frequency were made to determine the common base impedance Z_b. The passive Z_{21} was the same as Z_{12}, which is consistent with the proposed equivalent circuit. A plot of the reactance X_{21} versus frequency yielded a straight line intersecting the origin, with a slope corresponding to base lead inductances of approximately 4 mμhenry for a majority of the experimental units. This is in good agreement with the calculated value from lead dimensions. For Transistor 9-50, the determined values of the component Z_b were

$r_b = 2.5$ ohms ,

$L_b = 2.75$ mμhenry .

This unusually small value of L_b (which could account for the very high frequency of oscillation) was due to a shorter base-lead length caused by excessive flow of solder during fabrication.

Since Z_{21} is an open-circuit measurement, while h_{21}, on the other hand, is a short-circuit measurement, the measured Z_{21} does not necessarily give the common impedance Z_b. This was observed in the units having higher base resistance and can be explained by considering an additional base current path which includes a portion of the collector region. With low values of base resistance and collector capacitance, this collector component is negligible, and the total current in the base lead is independent of the impedance seen by the collector. The plot of X_{21} versus frequency, which intersects at the origin, is a good indication of the validity of the Z_{21} measurements in determining Z_b, since if the collector component is appreciable, Z_{21} will appear capacitive at low frequency.

Table 1 **Radii for seven experimental units.**

Unit Number	*Radius of h_{21p} Circle*
9-50	1.1
9-51	1.28
9-52	1.76
9-53	1.97
9-54	1.87
9-55	1.75
9-56	1.45

The real part of Z_{22} yields the sum of r_c and r_b, while the reactive part determines the sum of L_c and L_b as well as the collector transition capacitance. Since L_b and r_b are already determined by the Z_{21} measurement, L_c and r_c can be easily obtained. The capacitances measured in this way give values very close to those determined by low frequency (1 Mc) capacitance bridge measurements. For Transistor 9-50, the particular values obtained for r_c and L_c were

$r_c = 6.5$ ohms ,

$L_c = 4.6$ mμhenries .

The values did not vary with collector voltage over the measurement range of from -0.1 to -3 volts. Substituting the above values into Eqs. (3) and (3a) and with $\omega = 2\pi(1100\text{ Mc})$ shows that as V_c is varied, a circle is generated, the center of which is at $0.14 + j1.06$. This circle is compared with the observed circle for $-h_{21p}$ measurements in Fig. 6. In the Figure, the values of capacitance corresponding to the collector voltages at which the real part of $-h_{21p}$ is zero are indicated. The measured low-frequency capacitance for the collector voltage producing this condition was 2.66 μμf. The calculated value, using extrinsic values previously obtained, is 2.78 μμf. The reasonably close agreement of the two circles is interpreted to mean that the simplified equivalent circuit is a good first-order approximation at frequencies in the order of 1000 Mc.

Active $-h_{21}$ measurements

Measurements were made at a frequency where the unit did not oscillate in the transfer function meter with the emitter forward-biased in a similar fashion as those of the passive circuit. The frequency and bias current were thus constant, while V_c was varied. A series of circles resulted, as shown in Fig. 7. This can be explained if the equivalent circuit of Fig. 1 is re-analyzed to include the active (intrinsic) portion of the output current. The intrinsic current is affected by the shunting action of the emitter transition capacitance. Thus, the equivalent current generator

$$\alpha_i i_{re} = \frac{\alpha_i i_e}{1+sr_eC_{te}}, \tag{4}$$

where α_i is the complex intrinsic current gain, and

$r_e \cong kT/qI_e$.

The component of this current existing in the shorted output is then

$$i_i = \frac{\alpha_i i_{re}}{1+sC_c(Z_b+Z_c)}$$

$$= \frac{\alpha_i i_e}{(1+sr_eC_{te})[1+sC_c(Z_b+Z_c)]}. \tag{5}$$

Equation (5) can be simplified if the emitter time constant r_eC_{te} is included in the intrinsic current gain.

Thus, let $$\alpha'_i = \frac{\alpha_i}{1+sC_{te}r_e} = \frac{\alpha_i}{1+s\tau_e}, \tag{6}$$

where

$\tau_e = r_eC_{te}$.

Then

$$i_c = i_{ft} + i_i = \frac{i_e sC_cZ_b}{1+sC_c(Z_b+Z_c)} + \frac{i_e\alpha'_i}{1+sC_c(Z_b+Z_c)}. \tag{7}$$

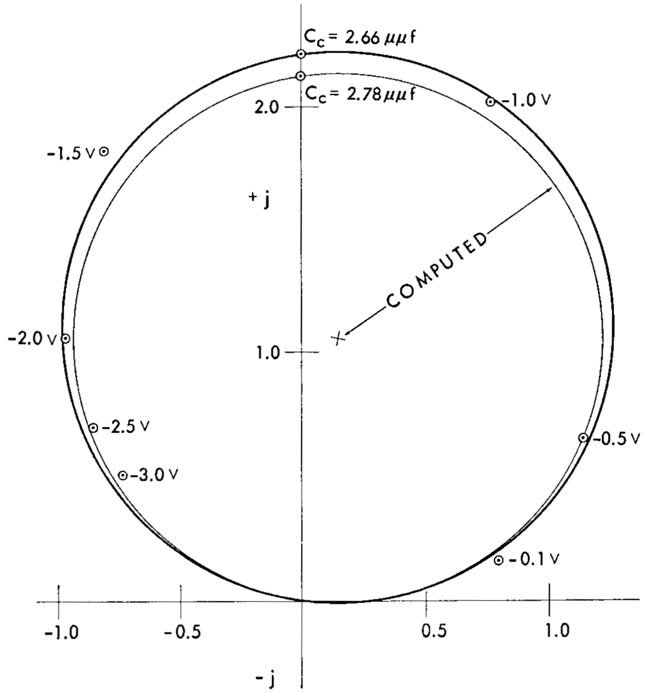
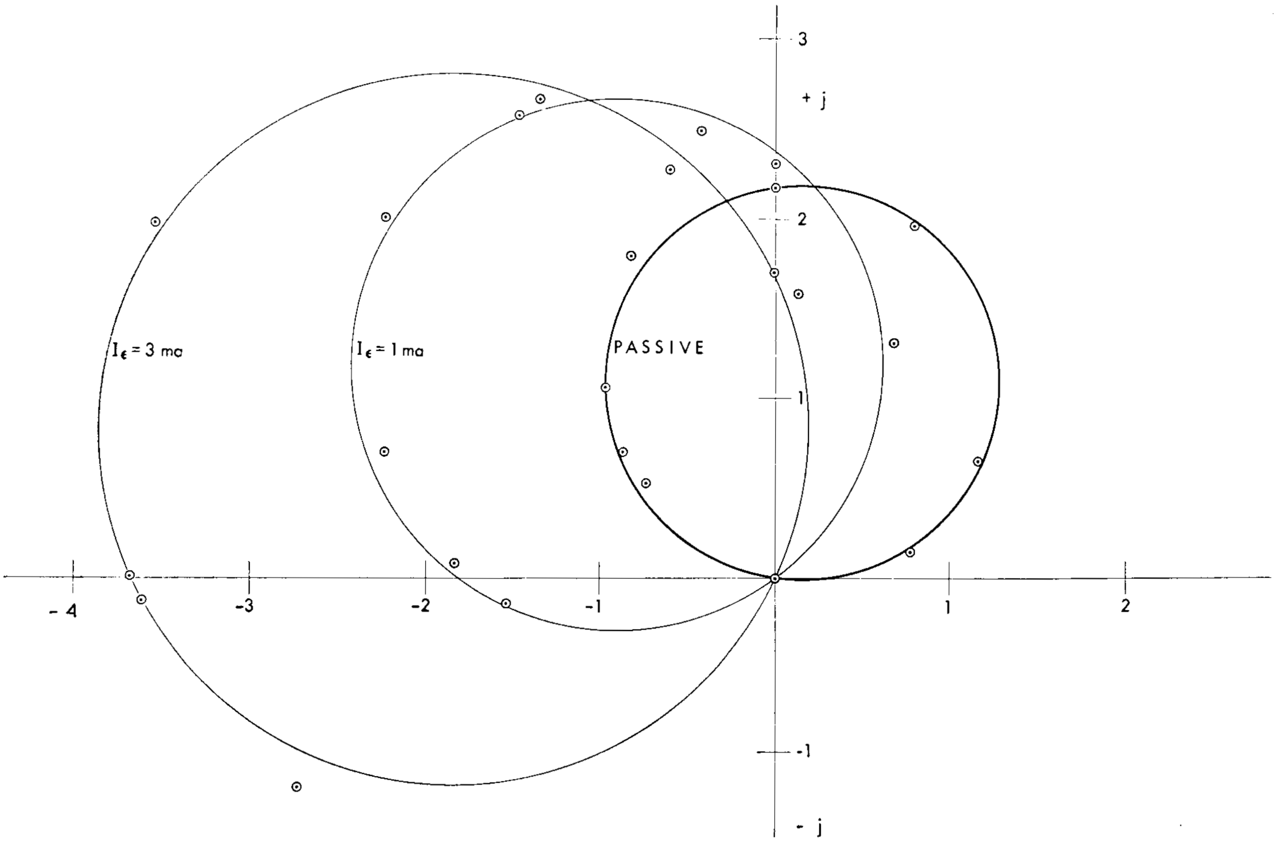


Figure 6 **Passive $-h_{21p}$ as a function of collector voltage for f=1100 Mc.**

Figure 7 **Passive and active $-h_{21}$ as a function of collector voltage for f=1100 Mc.**



Then for the direction of i_c as shown,

$$\frac{i_c}{i_e}=-h_{21}=\frac{\alpha'+sC_cZ_b}{1+sC_c(Z_b+Z_c)}. \tag{8}$$

Now with I_e constant and assuming the Early effect is negligible,[7] a change in collector voltage results only in a change in C_c. (It was previously indicated that V_c had negligible effect on r_b and r_c.)

As C_c is varied, Eq. 8 generates a circle passing through the origin, with the center determined by the expression

$$\frac{r_b+sL_b}{2R}+\frac{\alpha_i'(R-sL)}{2R},$$

where

$$R=r_b+r_c, \qquad L=L_b+L_c.$$

Thus, for different values of emitter current, distinctive circles are produced. The departure of the center of the active circle from the center of the passive circle and the change in radius is dependent on R, L, α_i and the emitter time constant τ_e. The quantities R, L, and α_i can be considered to vary only slightly with current while τ_e decreases as current increases.

Conclusions

Transistors made with very low bulk resistances and junction capacitances showed power gains greater than unity at frequencies as high as 1550 Mc. However, analysis of $-h_{21}$ measurements in the 1000 Mc range showed that a large portion of the collector current is due to the passive circuit comprised of the extrinsic parameters of the transistor. In fact, it was found that short-circuit current gains greater than unity can occur at ultra high frequencies because of a resonating condition of this passive circuit. This condition apparently can be realized only in transistors in which the bulk resistances have been reduced to a few ohms in value. Measurements on other lower-frequency transistors which had considerably higher base and collector resistances showed passive feed-through current gains much lower than unity.

The amount of feed-through or passive current is determined largely by the effective base resistance r_b, base-lead inductance L_b, and the collector resistance r_c. The effective base resistance is the component of the total base resistance which contributes to a voltage at the collector.

A detailed analysis of the measurements of the transistor including the active portion is not attempted, although some measurements of the total $-h_{21}$ are presented and shown to be consistent with a simplified theory and equivalent circuit.

The very low bulk resistances which are necessary in addition to low junction capacitances for uhf transistors causes an appreciable feed-through current unless lead inductances are negligible. Since fabrication requirements make extremely low lead inductance difficult to achieve, their effects will have to be included in the design of uhf circuits.

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