LB-963

COMPARATIVE HIGH-FREQUENCY OPERATION OF JUNCTION TRANSISTORS MADE OF DIFFERENT SEMICONDUCTOR MATERIALS

RADIO CORPORATION OF AMERICA

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Approved

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Introduction

Charge carriers in semiconductors are of two types, minority carriers and majority carriers. In an n-type semiconductor, the electrons are the majority carriers and are normally present; the holes are the minority carriers, often injected from one of the boundaries. The reverse is true for p-type semiconductors.

Because, in the conventional junction transistor, it is the minority carriers which flow out of the emitter, through the base, and into the collector, the role of the *majority* carriers is often neglected. This leads to an incorrect concept of the factors which enter into high-frequency behavior. It is true that the high-frequency performance of a junction transistor is affected by the time required for the minority carriers to traverse the base region and that large minority carrier mobility contributes to the reduction of this transit time. But this is only part of the story. Since charge neutrality must exist, minority carriers flowing into, and out of, the base region are accompanied by flow of *majority* carriers also into, and out of, the base region. This produces an h-f voltage drop in the base-lead resistance which is determined in part by the *majority* carrier mobility. *Majority* carrier mobility also affects the very important collector-to-base junction capacitance.

An important result of the analysis of high-frequency operation carried out in this bulletin is that both majority and minority carrier mobilities are of nearly equal importance. It follows that p-n-p type transistors should be generally not very different from n-p-n type transistors in high-frequency performance. Furthermore, for evaluation of new semiconductors, a knowledge of the values of both majority and minority carrier mobilities is required. A figure of merit for semiconductors is proposed which is formed by the product of the two *drift* mobilities, divided by the square root of the dielectric constant. With the aid of this figure of merit, semiconductor materials that have been considered advantageous because of their large electron Hall mobility may be properly evaluated for use in transistor devices.

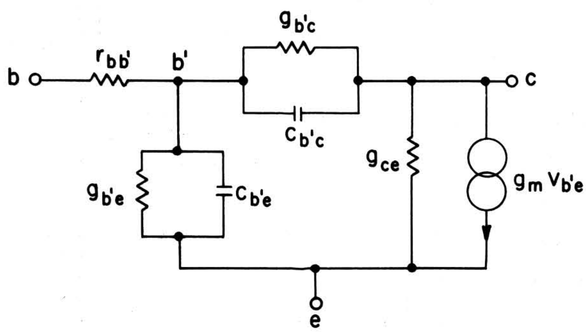
In this bulletin, after a discussion of the general equation for high-frequency performance, a comparison is drawn first, between transistors of *different polarity* (n-p-n and p-n-p) but made with the same semiconductor material and second, between transistors of the same polarity but made with *different semiconductor materials*. This report covers only the analysis, but the conclusions drawn are in accord with extensive small-signal experimental data on germanium and silicon junction transistors.

I. High-Frequency Operation

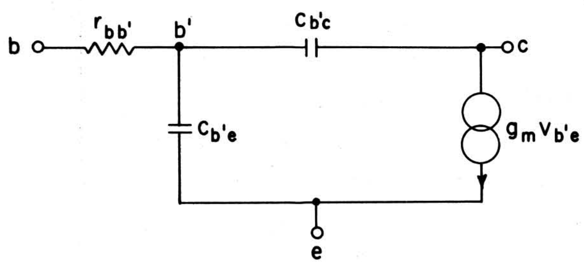
The hybrid-π common-emitter equivalent circuit as shown in Fig. 1a will be employed as the basis for the study of high-frequency operation.[1]

At higher operating frequencies the conductances shown in Fig. 1a are negligible in comparison with the capacitive susceptances, and the equivalent circuit which is applicable is that shown in Fig. 1b. An approximate analysis of this circuit indicates that the maximum power amplification is given by

$$P.A. \approx \frac{g_m}{4\omega^2 r_{bb'} C_{b'e} C_{b'c}} \qquad (1)$$



(a) Complete circuit.



(b) Circuit applicable at high frequencies.

Fig. 1 - Hybrid-π common-emitter equivalent circuit.

With the aid of equations for the transistor parameters and some approximations, this equation can be written in terms of the semiconductor constants and the operating point. Expressions will be written of general validity, but, for clarity, the subscript notation will be that for an n-p-n transistor. In order to obtain the expressions for a p-n-p transistor it is only necessary to interchange n and p subscripts and d and a (donor and acceptor) subscripts wherever they occur. The development throughout this report is for abrupt impurity transitions as found in alloy type junction transistors. In grown type junction transistors the impurity transition is generally gradual. Although the detailed results differ, the basic conclusions are the same for both alloy and grown type junction transistors.

For a reasonably good transistor, emitter and collector currents are approximately equal so that $g_m \approx \Lambda I_E$ where Λ is 39 volts^{-1} at room temperature* and I_E is the emitter current. The base-lead resistance, $r_{bb'}$, is a function of transistor geometry. From measurements, $r_{bb'}$ is known to be inversely proportional to the conductivity of the base-region semiconductor, σ_b, so that $r_{bb'} = 1/(G\sigma_b)$ where G is the constant of proportionality involving the transistor geometry. The expression for the diffusion capacitance, $C_{b'e}$ is

$$C_{b'e} = \Lambda^2 I_E \frac{W_b^2}{2\mu_n}$$

where μ_n is the electron mobility in the p-type base semiconductor and W_b is the base thickness between points of zero electrostatic voltage gradient. Throughout this report, W_b will be considered constant.[2] The collector-to-base capacitance, $C_{b'c}$, generally consists of two factors. In high-frequency transistors where W_b is small and σ_b is large, the collector junction barrier capacitance will predominate so that

$$C_{b'c} \approx A_c \left[\frac{K_e \varepsilon_o \sigma_b}{2\mu_p V_{CE}}\right]^{\frac{1}{2}}$$

where A_c is the collector area, K_e is the dielectric constant of the base semiconductor, ε_o is the permittivity of free space, μ_p is the

[1] L. J. Giacoletto, "The Study and Design of Alloyed-Junction Transistors", 1954 National Convention Record of the I.R.E., Part 3-Electron Devices and Component Parts, pp. 99-103. The same circuit is also shown in *LB-915, A P-N-P Triode Alloy Junction Transistor for Radio-Frequency Amplification.*

*For other temperatures, $\Lambda = \frac{e}{kT}$ where e is the electronic charge and k is Boltzmann's constant. Hence Λ = 11600/T where T is in degrees K.

[2] When W_b is very small or the collector voltage very large, the dependence of W_b upon the collector voltage may have to be considered.

hole mobility in the p-type base semiconductor, and V_{CE} is the collector voltage. With the further aid of $\sigma_b \approx eN_a\mu_p$ (where e is the electron charge and N_a is the density of the base impurity acceptor atoms), Eq. (1) can be written

$$P.A. \approx \frac{G\mu_p \mu_n}{\omega^2 A_c \Lambda \left[\frac{2K_e \varepsilon_o}{eN_a V_{CE}}\right]^{\frac{1}{2}} W_b^2} \qquad (2)$$

As mentioned above, this expression is applicable to alloy type junction transistors where the collector junction barrier occurs in the base semiconductor.

Examination of Eq. (2), at first glance, makes it seem advisable to choose a high collector bias, V_{CE}, and a high base impurity density, N_a. However, the "breakdown" phenomenon of the collector, considered in the next section, is such that, when N_a rises, the maximum V_{CE} falls. Furthermore, when N_a rises sufficiently, the mobilities μ_p and μ_n begin to decrease noticeably. The next two sections of the bulletin discuss these inter-relationships.

II. Effect of Collector Voltage

In so far as the operating point is concerned, Eq. (2) indicates that the high-frequency power amplification is independent of emitter current but directly proportional to the square-root of the collector voltage. For improved high-frequency performance V_{CE} should be made as large as possible. There are two possible limits to the magnitude of V_{CE}. First, the collector voltage may be so large that the collector junction barrier thickness is comparable to W_b. This is not likely to occur in high-frequency transistors where σ_b is relatively large. As mentioned before,[2] the variation of W_b with V_{CE} must be considered in this region of operation; other factors which are considered in Section VI may also be significant. Second, the collector voltage may be so large that collector breakdown occurs. This is the more likely limitation on the magnitude of V_{CE}. The practical maximum collector voltage will generally be some fraction of the collector breakdown voltage. Two mechanisms, Zener breakdown[3] and avalanche breakdown[4], have generally been used to account for collector breakdown. Zener breakdown is due to internal field emission and should in theory occur when the collector-to-emitter voltage is

$$V_Z = \frac{K_e \varepsilon_o}{2eN_a} E_Z^2 \qquad (3)$$

The critical Zener field, E_Z, is proportional to the "band gap" and the lattice spacing of the material. Avalanche breakdown is due to electron-hole pair formation by ionization similar to Townsend discharges in gases. It is now generally believed that the avalanche mechanism plays the predominant role in collector breakdown. The complete theory of avalanche breakdown has not as yet been published, but preliminary measurements indicate that the breakdown voltage is proportional to N_a^{-k} where k is approximately 0.7. The semiconductor surface also contributes to the breakdown characteristics, but its contribution is largely to obscure the actual breakdown. For purposes of this report, the differences between Zener and avalanche breakdown dependence on N_a are minor so, for simplicity, it will be assumed that collector breakdown voltage is proportional to $1/N_a$.

There has been considered above the improvement in high-frequency performance with operating point, namely the collector voltage. There will now be considered the improvement in high-frequency performance that can be obtained by altering the transistor design.

III. Optimum Transistor Design

In accordance with Eq. (2), improved performance can be obtained by designing for a large geometrical factor, G, (small $r_{bb'}$), small collector area, A_c, (small $C_{b'c}$), and small base thickness, W_b, (small $C_{b'e}$). In addition, the semiconductor material can be

[3] C. Zener, "A Theory of the Electrical Breakdown of Solid Dielectrics", *Proc. Roy. Soc.* (London), Vol. 145A, pp. 523–529; July, 1934.

[4] K. G. McKay, "Avalanche Breakdown in Silicon", *Phys. Rev.*, Vol. 94, pp. 877–884; May 15, 1954.

"doped" more heavily to increase N_a. However, this will cause μ_p and μ_n to decrease and will necessitate a reduction in V_{CE}. If V_{CE} is always adjusted to some fixed fraction of the breakdown voltage, then $N_a V_{CE}$ will be constant independent of N_a. In this event, relatively pure (say σ_b<1 mho/cm) semiconductor material should be used since $\mu_p\mu_n$ will then be maximum. This may be better understood by considering that the change in $r_{bb'}$, for different semiconductor conductivities, is exactly counterbalanced by a change in $C_{b'c}$ when V_{CE} is readjusted in proportion to the breakdown voltage.

The situation may be considerably different if, in the operation of the transistor, the collector voltage is to be held constant independent of the semiconductor conductivity. In this event σ_b should be chosen so that $(eN_a)^{\frac{1}{2}}\mu_p\mu_n = (\sigma_b\mu_p)^{\frac{1}{2}}\mu_n$ has its maximum value, keeping in mind that the μ's are functions of N_a and σ_b. For the latter, the optimum value of σ_b can be determined by plotting $(\sigma_b\mu_p)^{\frac{1}{2}}\mu_n$ or by satisfying the relation

$$\frac{1}{\sigma_b} + \frac{1}{\mu_p}\frac{\partial\mu_p}{\partial\sigma_b} + \frac{2}{\mu_n}\frac{\partial\mu_n}{\partial\sigma_b} = 0 \qquad (4)$$

Similar expressions with n and p subscripts interchanged are applicable for a p-n-p transistor. Eq. (4) states that the optimum value of σ_b is such that the sum of the fractional change in base conductivity plus the fractional change in majority carrier mobility plus twice the fractional change in minority carrier mobility is zero. The optimum value of σ_b can be determined if the functional relationship between μ_n and μ_p and σ_b is known or if measured data are available. Thus, in the case of germanium,[5] the optimum σ_b is approximately 8 mhos/cm for a n-p-n transistor and 22 mhos/cm for a p-n-p transistor.

The design implications of optimum σ_b, when the collector voltage is fixed, can be summarized as follows. The σ_b to be employed is the smallest of the two values determined from (a) the optimum σ_b as given by Eq. (4) and (b) the σ_b corresponding with a collector breakdown voltage somewhat larger than the operating collector voltage.

[5] M. B. Prince, "Drift Mobilities in Semiconductors I. Ge", *Phys. Rev.*, Vol. 93, pp. 681-687; Nov. 1, 1953.

IV. Comparison of n-p-n with p-n-p Transistors Made with the Same Semiconductor Material

If an n-p-n and a p-n-p transistor are made with the same semiconductor material containing equal densities of impurity atoms, with identical geometries including the same W_b, and the two are operated at the same collector voltage and frequency, then from Eq. (2)

$$\frac{P.A._{n-p-n}}{P.A._{p-n-p}} = \frac{\mu_p\mu_n]_{p-material}}{\mu_n\mu_p]_{n-material}} \approx 1 \qquad (5)$$

That is, the high-frequency power amplification of the two transistors would be approximately equal. The approximation comes about only because of the relationship between mobility and impurity density but is quite valid for germanium even with relatively large impurity densities (with conductivities of around 1 mho/cm, the accuracy is within 2 per cent).

If, instead of comparing the two transistors with equal impurity densities, they are compared with equal conductivities of the base material, then

$$\frac{P.A._{n-p-n}}{P.A._{p-n-p}} = \frac{(\mu_p)^{\frac{1}{2}}\mu_n]_{p-material}}{(\mu_n)^{\frac{1}{2}}\mu_p]_{n-material}} \approx b^{\frac{1}{2}} \qquad (6)$$

where b is the ratio of electron to hole mobility in intrinsic material. The $b^{\frac{1}{2}}$ result ($2.05^{\frac{1}{2}} = 1.43$ for germanium and $2.4^{\frac{1}{2}} = 1.55$ for silicon), although exact only for small conductivities approaching that of intrinsic material, is still approximately correct for relatively large conductivities. Thus, for 1 mho/cm germanium the more exact evaluation is 1.34.

The optimum value of σ_b forms a somewhat better basis for comparing n-p-n and p-n-p transistors. This comparison can be carried out when data of minority and majority carrier mobilities as a function of σ_b are available. For germanium when σ_b is optimum, the $\frac{P.A._{n-p-n}}{P.A._{p-n-p}}$ ratio is approximately unity (0.95).

The comparisons above are for equal collector voltages. If the collector voltages are adjusted in proportion to the breakdown voltages, then in all cases the ratio is that given by Eq. (5) so that the two transistors have approximately equal high-frequency power amplifications.

V. Comparison of Transistors Made with Different Semiconductor Materials

According to Eq. (2), the power amplification of an n-p-n transistor is proportional to $[\frac{N_a V_{CE}^{\frac{1}{2}}}{K_e}]\mu_p\mu_n$. Consider two n-p-n transistors made of two different semiconductor materials with the same impurity densities, identical geometries including the same W_b, and operating at the same d-c collector voltage and frequency. In order for the first semiconductor to be superior to the second, it is necessary for the $\frac{\mu_p\mu_n}{K_e^{\frac{1}{2}}}$ factor of the former to be larger than that of the latter. Similarly, if instead of the same impurity densities, the same base conductivities are used, the appropriate factor is $[\frac{\mu_p}{K_e}]^{\frac{1}{2}}\mu_n$.

If the collector voltages are adjusted in proportion to the collector breakdown voltages, the appropriate comparison factor is $\mu_p\mu_n M$ independent of the base conductivities. M is a factor, dependent upon the material, which would be equal to E_Z if the collector breakdown were due to a Zener mechanism.

In order to compare p-n-p transistors it is only necessary to interchange the p and n subscripts in the above factors. It is important to remember that although interchanging subscripts does not alter the form of some of the factors, the numbers substituted will generally be different when considering "doped" semiconductors. The numbers should be those of the majority and minority mobilities in the base material used.

It is noted that the comparison factor changes, depending upon the basis of comparison. Generally, detailed theoretical or measured data concerning minority and majority carrier mobilities in a semiconductor are needed before transistors with different semiconductor materials can be compared analytically. As a convenient basis of comparison, a factor of $\frac{\mu_p\mu_n}{K_e^{\frac{1}{2}}}$ for the intrinsic material can be used as a figure of merit. A few values of this factor are tabulated in Table I. It is important to note here that the mobilities to be used are drift mobilities. When drift mobility data are not available, rough comparisons can be made using mobility data obtained by other methods. However, it should be understood that these comparisons may not be highly significant in so far as transistor operation is concerned.

VI. Further Discussion

It was mentioned that W_b is a function of the collector voltage and that this must be considered when W_b is small. W_b decreases with larger collector voltages so that the improvement in power amplification should be somewhat greater than that predicted by Eq. (2). In so far as this equation is concerned, the power amplification should vary inversely as W_b^2. In the derivation of (1), the output self-conductance term, g_{ce}, (see Fig. 1a) was neglected. This term is inversely proportional to W_b and may no longer be negligible when W_b is very

[6] M. B. Prince, "Drift Mobilities in Semiconductors II Si", *Phys. Rev.*, Vol. 93, pp. 1204-1206; March 15, 1954.

[7] *LB-949, Some Properties of Germanium-Silicon Alloy Semiconductors.* The mobility data shown in the table are preliminary values based on a drift measurement for μ_n and an estimated value for μ_p from a Hall measurement.

Table I

Semiconductor Figure of Merit

Material	μ_p	μ_n	K_e	$\frac{\mu_p\mu_n}{K_e^{\frac{1}{2}}}$
Germanium[5]	1900	3900	16	1.85×10^6
Silicon[6]	500	1200	12	0.17×10^6
90% Ge-10% Si[7] Alloy	570 est.	1300	15.6 est.	0.19×10^6

small. The modified expression for the power amplification including g_{ce} is

$$\text{P.A.} \approx \frac{g_m}{4\omega^2 r_{bb'} C_{b'e}^2 \left[\frac{C_{b'c}}{C_{b'e}} + \frac{g_{ce}}{g_m}\right]} \qquad (6)$$

Therefore, when g_{ce} dominates the effect of $C_{b'c}$, the power amplification should vary at an even faster rate than formerly, namely inversely proportional to W_b^3.

If constructional techniques should be developed such that $r_{bb'} \to 0$, then both $C_{b'e}$ and $C_{b'c}$ could be "tuned out" with suitable circuits. In this event, the maximum high-frequency performance of the transistor would be limited by the transit time of the minority carriers through the base, and the drift mobility of the minority carriers would be of primary importance.

Modified methods of junction transistor construction[8,9] will alter some of the results, but generally drift mobilities of both carriers will still be important. In all cases it is desirable to make the base width as small as possible, to use a most favorable geometry including small junction areas, to use a base material whose conductivity is optimum, and to operate at a large collector-to-emitter voltage.

[8] H. Krömer, "The Drift Transistor", *Die Naturwissenschaften*, Vol. 40, No. 22, pp. 578–579; 1953.

[9] J. M. Early, "P-N-I-P and N-P-I-N Junction Transistor Triodes", *B.S.T.J.*, Vol. 33, pp. 517–533; May, 1954.

L. J. Giacoletto