LB - 804

A HIGH-PERFORMANCE TRANSISTOR WITH WIDE SPACING BETWEEN CONTACTS

RADIO CORPORATION OF AMERICA
RCA LABORATORIES DIVISION
INDUSTRY SERVICE LABORATORY

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

INDUSTRY SERVICE LABORATORY

LB-804

A High-Performance Transistor With Wide Spacing Between Contacts

Approved

Stuart Wm Seeley

Summary

A number of transistors having contact spacings ranging between 0.010 inch and 0.020 inch have been made which give power gains of 20 to 30 db and current gains as high as 25. These values are as good as or better than those previously reported for narrow-spaced units. An improvement in operational stability may result from the use of wide-spaced contacts through a reduction in the average value of the equivalent base resistance. Current gain falls off more rapidly with frequency in wide-spaced than in narrow-spaced transistors because of transit-time effects. These effects limit the usefulness of wide-spaced transistors to low-frequency applications. However, the technique of activating at wide spacing with an auxiliary contact, then operating with a close-spaced contact makes high current gains and reduced values of equivalent base resistance obtainable at frequencies of 1 to 5 Mc per second.

A High-Performance Transistor With Wide Spacing Between Contacts

Introduction

The importance of maintaining close and accurate spacing between the emitter and collector contacts of the transistor has been emphasized in various published papers[1] discussing transistor characteristics. These papers stress that 0.002 inch is the maximum spacing for good transistor action, and any greater values would result in lower power gains and current gains. Curves in these papers show an almost exponential decrease in current gain and power gain as the spacing is increased. However, recent work reported here has indicated that transistors of considerably wider spacings may be made with no appreciable sacrifice in power gain. The use of wide contact spacings not only can simplify the assembly of transistors, but also may result in two improvements in electrical characteristics. These improvements are (1) a decrease in internal feedback which may result in better operational stability, and (2) higher current gain. These improvements are offset to some degree by a reduction in the frequency response, thus limiting wide-spaced transistors to low-frequency applications.

Equivalent Base Resistance as a Function of Contact Spacing

In order to study the phenomena involved in wide-spaced transistors, both the equivalent base resistance[2] and gain were measured as a function of contact spacing.

The equivalent base resistance, the mutual element of the T-network equivalent circuit of the transistor[3], represents the internal impedances which are common to both input and output circuits. It will be shown that wide spacing of the transistor contacts will result in a decrease of this resistance, thus resulting in a decrease of internal feedback.

It is believed that the equivalent base resistance is composed of the bulk resistance of the germanium crystal, leakage between emitter and collector contacts, and electronic effects, the nature of which are not completely understood. High values of equivalent base resistance due to leakage and these electronic effects are illustrated in Fig. 1 by the family of curves of emitter voltage vs. collector

[1] J. Bardeen and W. H. Brattain, "Physical Principles Involved in Transistor Action", *Physical Review*, 75:1208-25, April 15, 1949.

W. C. Dunlap Jr., "Germanium, Important New Semi-conductor", *G. E. Review*, 52:15-17, February 1949.

C. E. Atkins, "Crystal That Amplifies", *Radio and Television News*, 40:39, October 1948.

__________, "Transistor, A Crystal Triode", *Electronics* 21:68-71, Sept. 1948.

[2] A committee of the IRE is presently considering the use of the term "equivalent block resistance"to replace the term "equivalent base resistance".

[3] R. N. Ryder, R. J. Kircher, "Some Circuit Aspects of the Transistor", *Bell System Technical Journal*, Page 374, July 1949.

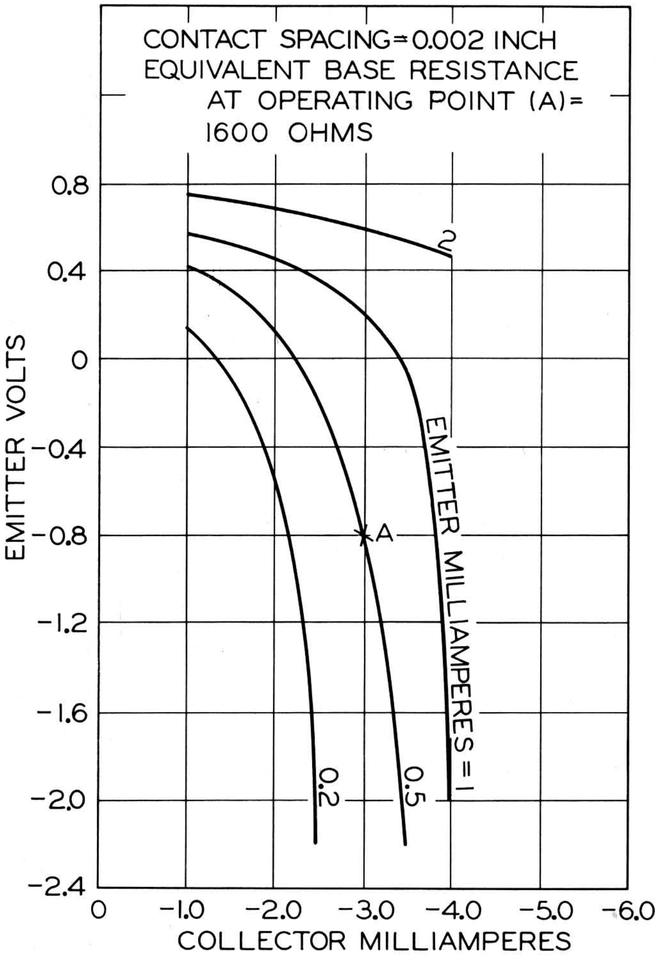

Fig. 1 - Static characteristic of narrow-spaced transistor having equivalent base resistance of 1600 ohms.

current at constant emitter current for a narrow-spaced transistor. The equivalent base resistance, which is equal to the slope of these curves, is not only high at the operating point A, but is also greatly dependent upon emitter and collector currents. Transistors with these characteristics have appreciable feedback since the equivalent base resistance at the operating point (A) is approximately 1600 ohms. Shelf life tests on more than two hundred units have indicated that transistors having high and variable values of equivalent base resistance are quite unstable and have poor life.

Fig. 2 shows a similar set of curves for a narrow-spaced transistor having an equivalent base resistance varying from 100 to 200 ohms throughout the operating range. Leakage between contacts has been reduced, but the electronic

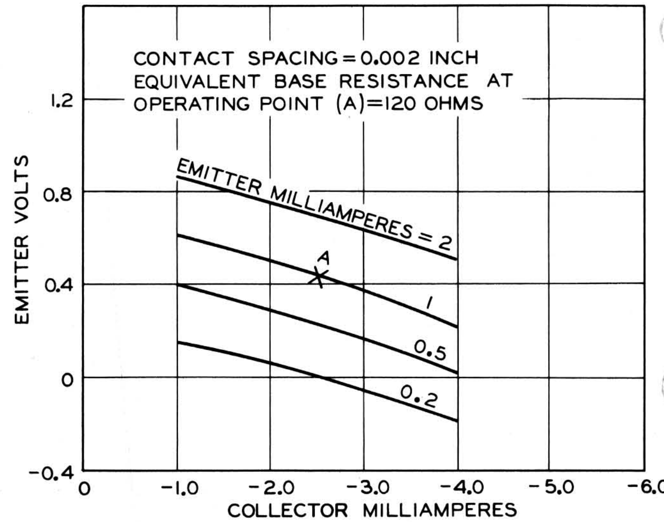

Fig. 2 - Static characteristic of narrow-spaced transistor having equivalent base resistance of 120 ohms.

effects which cause the equivalent base resistance to vary with bias currents are still present to a small degree. Equivalent base resistance at the operating point A equals 120 ohms, and there is appreciable feedback in this transistor, though not as great as in the unit described in Fig. 1. These curves are probably typical of many, if not most narrow-spaced transistors, although occasional narrow-spaced units have equivalent base resistance values as low as 30 ohms.

Fig. 3 shows a family of curves for a wide-spaced transistor. It can be seen from

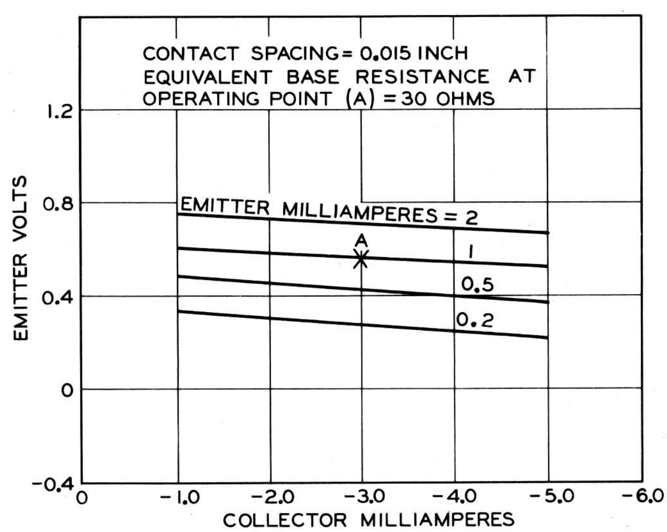

Fig. 3 - Static characteristic of wide-spaced transistor having equivalent base resistance of 30 ohms.

These curves that the equivalent base resistance is not only small, approximately 30 ohms at the operating point A, but also practically independent of changes in emitter or collector currents. These curves are typical of almost all wide-spaced transistors. The extent to which the value of the equivalent base resistance decreases with increasing point spacing

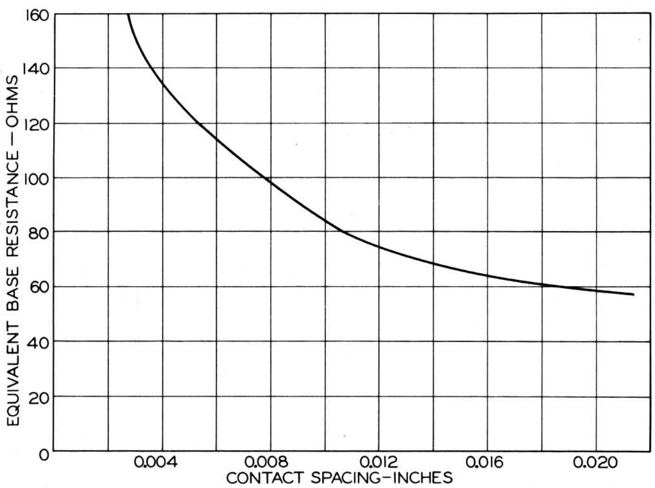

Fig. 4 – Effect of varying contact spacing on equivalent base resistance.

is shown in Fig. 4[4]. In this curve, the equivalent base resistance decreases exponentially and approaches a value which is approximately equal to the bulk resistance of the crystal. Surface leakage and other effects appear to have been minimized at these wide spacings.

Power Gain and Current Gain as a Function of Contact Spacing

The effect of increased contact spacing on power gain is illustrated in Fig. 5 which shows curves of power gain vs. contact spacing for three crystals. Each unit was formed at a contact spacing of 0.016 inch. The collector remained fixed while the emitter was moved for each reading. All data were read at constant emitter and collector current conditions. It appears from these three curves that power gain is relatively independent of spacing up to approximately 0.015 inch.

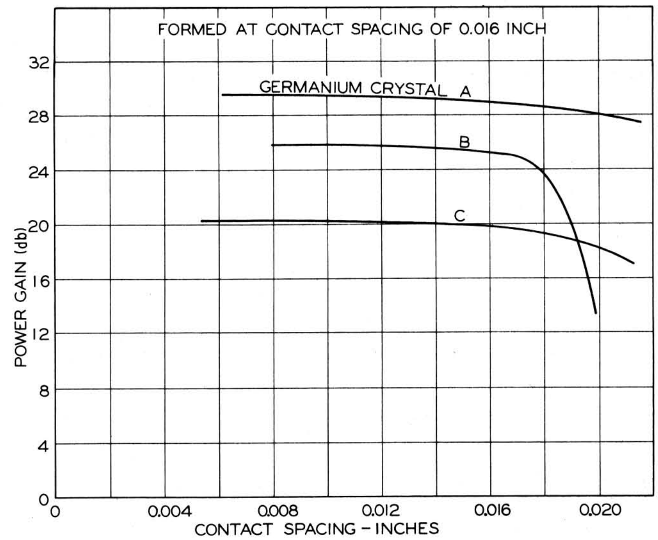

Fig. 5 – Effect of varying contact spacing on power gain.

If, however, a transistor is formed at 0.003 inch, as illustrated in Fig. 6, current gain decreases fairly rapidly with increased spacing. A second curve in Fig. 6 shows that if the same crystal is formed at 0.016 inch, the current gain remains fairly independent of the spacing. Significantly, the current gain of the unit formed at 0.016 inch is more than three times as great as the current gain for the same crystal formed at 0.003 inch. The third curve in Fig. 6 shows a plot of current gain vs. contact spacing published by Bardeen

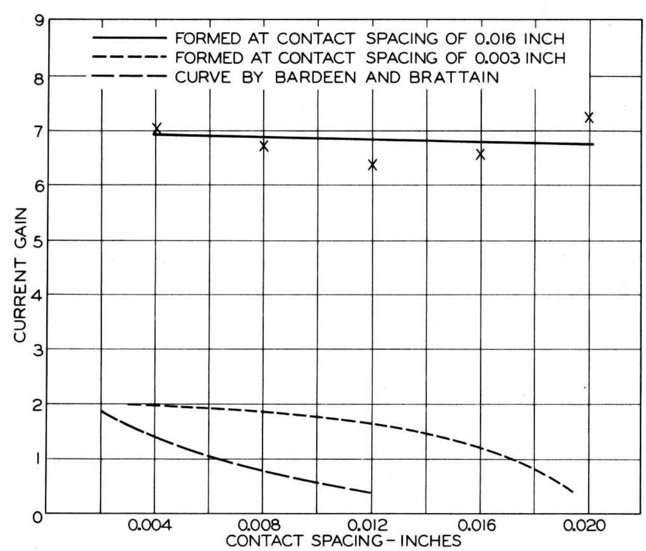

Fig. 6 – Effect of varying contact spacing on current gain.

---

[4] Data provided by J. I. Pantchechnikoff, RCA Laboratories Division.

and Brattain. This curve, like the curve of the unit formed at a spacing of 0.003 inch, decreases in gain with increased contact spacing.

Relation of Crystal Resistivity to Wide-Spaced Operation

In addition to the forming of the transistors, the crystal resistivity appears to be an important factor in the operation of wide-spaced transistors. The effect of crystal resistivity on the gain vs. spacing characteristic is illustrated in Fig. 7 which shows curves of power gain vs. contact spacing for two high-resistivity crystals and one low-resistivity crystal. All three transistors were

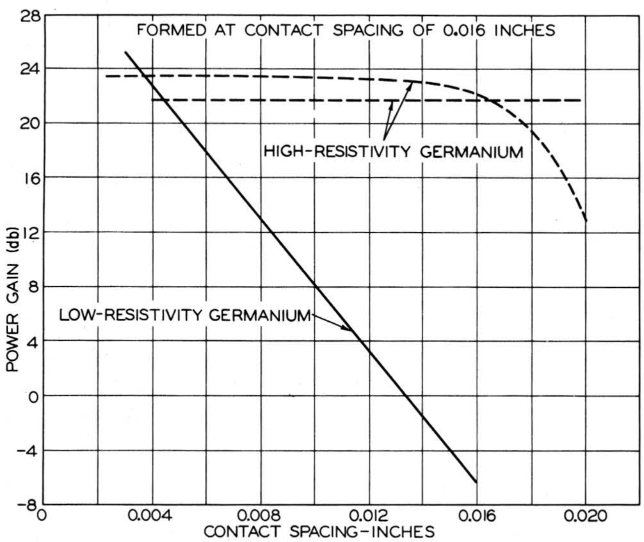

Fig. 7 - Effect of varying contact spacing on power gain of high- and low-resistivity germanium crystals.

formed at a contact spacing of 0.016 inch. RCA germanium usually ranges from ½ to 15 ohm-centimeter in resistivity. Exact measurements of the resistivity of the germanium crystals which are best suited for wide spacing have not yet been made. However, high-resistivity germanium as discussed in this bulletin generally will include the upper portion of the ½ to 15 ohm-centimeter range while low-resistivity germanium will usually cover the lower part of this range. The transistor using the low-resistivity crystal shows a rapid decrease in gain with increasing point spacing. The gains of the two transistors having high-resistivity crystals are relatively independent of contact spacing up to 0.016 inch.

It appears that two requirements are necessary, therefore, in order that gain be relatively independent of contact spacing. First, the germanium must have relatively high resistivity, and secondly, the transistor should be formed with emitter and collector spaced far apart.

Electrical Characteristics of Wide-Spaced Transistors

The gain and impedance characteristics of completed wide-spaced transistors are shown in Table I. Here four wide-spaced transistors are compared with four narrow-spaced units.

Table I

TRANSISTOR No.	CONTACT SPACING inches	RESISTANCES Input Load ohms	Transfer ohms	Output Load ohms	EQUIV. BASE RESISTANCE ohms	CURRENT GAIN	POWER GAIN Meas. db	Calc. db
1	0.015	740	42000	5000	30	6.2	20.8	18.3
2	0.015	160	12000	2500	20	6.0	22.6	21.5
3	0.015	260	26000	5000	20	5.0	21.9	20.8
4	0.015	800	50000	9000	20	5.4	19.0	19.1
AVERAGE	-	490	32500	5375	22.5	5.65	21.1	19.9
1	0.002	320	42000	14000	80	2.8	22.8	19.3
2	0.002	440	60000	22000	180	2.8	27.8	19.9
3	0.002	320	44000	23000	100	1.8	18.8	17.6
4	0.002	360	45000	14000	60	3.2	23.5	19.9
AVERAGE	-	360	47750	18250	105	2.65	23.2	19.2

The average value of equivalent base resistance for the wide-spaced transistors listed in the table is 30 ohms as compared to 105 ohms for the narrow-spaced transistors. The significance of the equivalent base resistance in causing feedback may be appreciated by noting the difference between measured gain and calculated gain. Power gain, exclusive of feedback, is calculated from the expression

$$\text{Power Gain (db)} = 10 \log \left[(\text{current gain})^2 \times \frac{\text{output load resistance}}{4 \times \text{input load resistance}}\right]$$

where the input and output load resistances are adjusted for maximum output of the transistor. Table I shows that in the case of the narrow-spaced units the measured gain is approximately 4 db greater than the calculated value. This difference between the measured and calculated gain is approximately equal to the gain due to feedback. The gain due to feedback of the wide-spaced units is approximately 1.4 db.

Table I shows that the output load resistance of the wide-spaced transistor is smaller, on the average, than that of the narrow-spaced transistors. Table I also shows that the current gain of the wide-spaced transistors is higher, on the average, than that of the narrow-spaced transistor. These higher values of current gain account for the high values of power gains.

Table II shows impedance and gain characteristics for three crystals. Each crystal

Table II

CRYSTAL No.	CONTACT SPACING inches	RESISTANCES Input Load ohms	Transfer ohms	Output Load ohms	EQUIV. BASE RESISTANCE ohms	CURRENT GAIN	POWER GAIN Meas. db	Calc. db
1	0.002	440	125000	45000	200	2.5	28.8	22.0
	0.015	140	42000	4000	10	10.0	27.8	28.5
2	0.002	520	45000	20000	320	2.5	24.0	17.8
	0.015	560	38000	2500	10	14.0	23.8	23.4
3	0.002	320	60000	25000	160	2.5	26.9	20.9
	0.015	500	42000	1000	10	26.0	25.2	25.3

was mounted as a transistor and formed at a spacing of 0.002 inch. After measurements were recorded, each crystal was remounted and formed at a contact spacing of 0.015 inch. The use of one crystal for tests at both 0.002 inch and 0.015 inch permits a comparison of wide and narrow spacings and minimizes the variables encountered when different pieces of germanium are used. Here, as in Table I, the output load resistance is considerably smaller in the case of the wide-spaced transistor. The current gains at 0.002 inch were 2.5 for all three samples, but at 0.015-inch spacing, current gains were 10, 14, and 26. In the case of the wide-spaced transistors, because the calculated gains were practically equal to the measured gains, very little feedback was indicated. The calculated gains of the narrow-spaced transistors, however, averaged 6 db less than the measured gain. This large amount of feedback in the case of the narrow-spaced units may be attributed to the high values of equivalent base resistance which ranged from 160 to 320 ohms.

Limitations of Wide Spacing of Contacts

The principal limitations of the wide-spaced transistors are apparent from Fig. 8

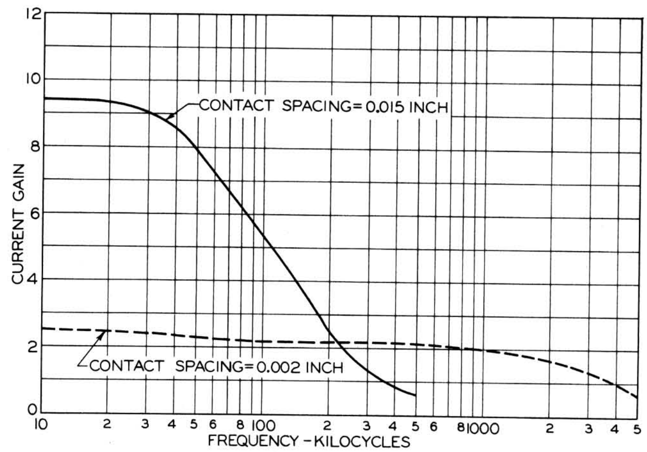

Fig. 8 - Frequency response of a wide-spaced and a narrow-spaced transistor.

which shows curves of current gain vs. frequency for both a wide- and a narrow-spaced transistor.[5] Due to the effects of transit time, the frequency response of the wide-spaced transistors is poor at frequencies much greater than 100 kc per second. Consequently, these transistors are limited to low-frequency applications.

Transistors Formed at Wide Spacing but Operated at Narrow Spacing

It has been found that a crystal of low resistivity may be formed at wide spacings, and even though its gain may be very small at these spacings, a high current gain and power gain will be obtained if the emitter is then moved to approximately 0.002 inch from the collector. Fig. 9 shows a curve of current gain vs. contact spacing for a low-resistivity crystal formed at 0.016 inch spacing. As the emitter is moved toward the collector, the current gain increases. At 0.003-inch spacing a current gain of 10 is obtained. Due to the limitations of the equipment used for taking these measurements, current gain at spacings smaller than 0.003 inch were not measured. If a crystal of high resistivity is used, excessive feedback usually occurs if the emitter is moved close to the collector after forming at wide spacings; consequently it is necessary to use fairly low-resistivity germanium for this transistor.

[5] Data for transistor having contact spacing of 0.002 inch provided by G. Olive, RCA Laboratories Division.

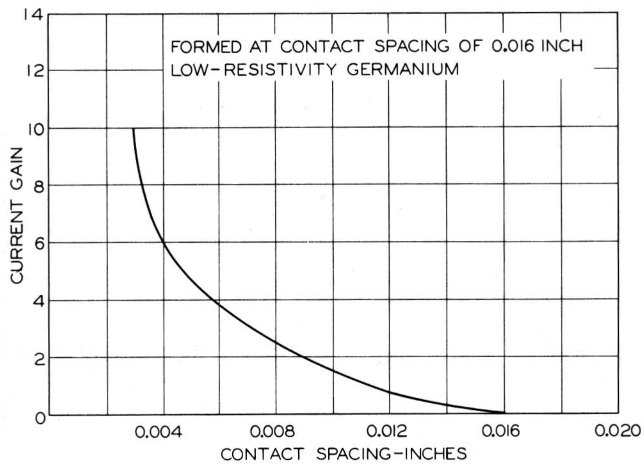

Fig. 9 – Effect of varying contact spacing on current gain for a low-resistivity germanium crystal.

A transistor which is formed at wide spacing and operated at narrow spacing may be assembled with three contacts as illustrated in Fig. 10.

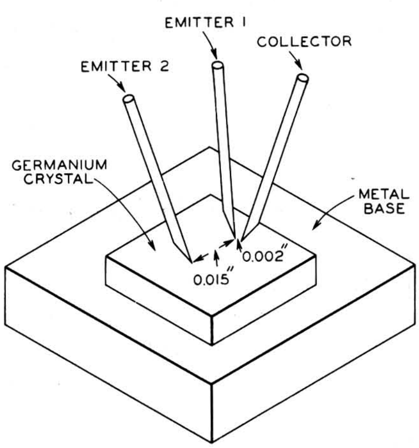

Fig. 10– Contact arrangement of transistor formed at wide spacing and operated at narrow spacing.

Emitter 2, which is spaced 0.015 inch from the collector, draws approximately three milliamperes of current during forming. Emitter 1 is out of the circuit. After forming, the unit is operated as a narrow-spaced transistor with emitter 1. Emitter 2 is no longer used and may be removed. Values of current gain for these units have ranged from 4 to 20. Power gain ranges from 20 to 30 db. Because only low-resistivity germanium is used, the equivalent base resistance averages about 75 ohms as compared to over 100 ohms for conventional transistors.

Fig. 11 shows two typical frequency-

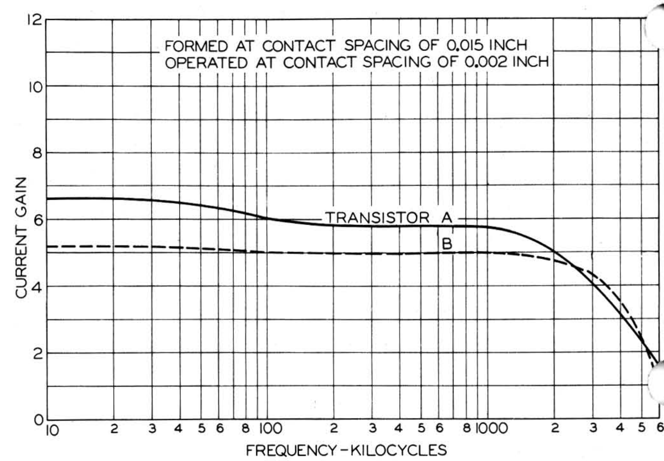

Fig. 11– Frequency response of a transistor formed at wide spacing and operated at narrow spacing.

response curves of transistors formed at 0.015 inch and operated at 0.002 inch. These curves are only 3 db down at approximately 3 Mc per second. The frequency response of these transistors is, therefore, comparable to conventional narrow-spaced transistors; in addition, the current gains are comparable to the current gains of wide-spaced transistors.

Conclusions

It is possible to make transistors with contact spacings of 0.015 inch or greater. These transistors, compared with narrow-spaced transistors, have higher current gain, lower equivalent base resistance, and approximately the same power gain. These advantages, in addition to the obvious simplification in manufacture of transistors, are obtained at the expense of good frequency response. However, the process used in the forming of wide-spaced transistors may be used to obtain high current gains and good frequency response at narrow contact spacings if the germanium crystal material is properly selected. Transistors which are processed in this manner have higher values of equivalent base resistance than ar obtained with the use of wide-contact spacings.

Bernard N. Slade
Bernard N. Slade
RCA Tube Dept., Harrison, N. J.