Factors in the Design of Point-Contact Transistors

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FACTORS IN THE DESIGN OF POINT-CONTACT TRANSISTORS*

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Summary—Electrical characteristics of point-contact transistors depend essentially on four main factors: (1) the materials used for the point contacts, (2) the spacing of the point contacts, (3) the resistivity of the germanium, and (4) the electrical forming process. Control of these four factors during transistor fabrication makes possible the control of equivalent circuit resistances, current amplification factor, static characteristic curves, and frequeny response and, therefore, permits the design of different transistors each suitable for use in a specific type of circuit application. This paper discusses the design of point-contact transistors for use in radio-frequency amplifiers, oscillators, and switching or counter circuits, and the effects of electrical forming on the electrical characteristics.

Transistors for Radio-Frequency Amplifiers

Transistors designed for use as amplifiers at radio frequencies must be electrically stable when no appreciable external impedances are present in the emitter or collector circuits. This requirement, known as "short-circuit" stability, is particularly important in radio-frequency stages having parallel-tuned circuits in both the input and output of the transistor, because the impedance of the tuned circuits approaches zero in the off-resonance condition. For transistor stability under these short-circuit conditions, the following condition must exist:

$$\frac{r_e}{r_b} + \frac{r_e}{r_c} + 1 > \frac{r_m}{r_c}, \qquad (1)$$

where r_e is the emitter resistance, r_b is the base resistance, r_c is the collector resistance, r_m is the transfer resistance, and r_m/r_c is approximately equal to α_{ce}, the collector to emitter current amplification factor.[1,2]

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* Decimal Classification: R282.12.

[1] B. N. Slade, "Control of Frequency Response and Stability of Point Contact Transistors," *Proc. I.R.E.*, Vol. 40, p. 1382, November, 1952.

[2] R. M. Ryder and R. J. Kircher, "Some Circuit Aspects of the Transistor," *Bell Sys. Tech. Jour.*, Vol. 28, pp. 317-401, July, 1949.

The effect of various equivalent-circuit resistances on transistor stability may be analyzed by the substitution of typical values in this expression. For example, typical equivalent circuit resistances for a transistor having germanium resistivity of 5 ohm-centimeters and a point spacing of 0.002 inch might be

$$r_e = 180 \text{ ohms},$$

$$r_b = 200 \text{ ohms},$$

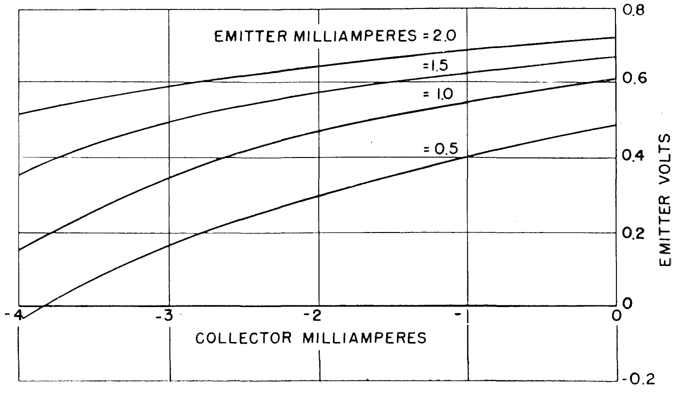
$$r_c = 20000 \text{ ohms},$$

$$\alpha_{ce} = 2.0.$$

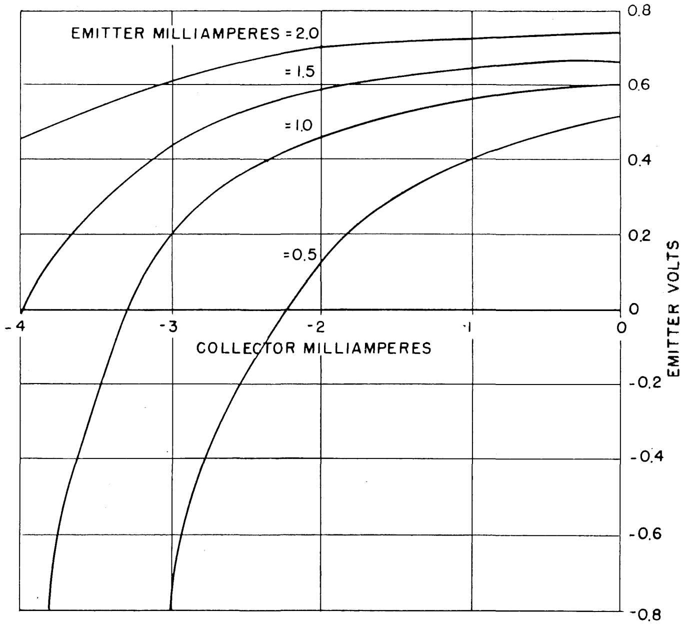
If these values are substituted in Expression (1), it is seen that the specified condition is not met, and, therefore, the transistor would not be stable under "short-circuit" conditions. Although either the germanium resistivity or the point spacing may be varied to achieve the resistance values required for stability, variation of the point spacing has a decided effect upon the frequency response of the transistor. From available design data for point-contact transistors,[1] it is possible to select a combination of germanium resistivity and point spacing which provides stability at a desired frequency of operation.

Before the resistivity and point-spacing values are selected, the value of equivalent base resistance required for stability must be determined from the expression given above. The term r_e/r_c can be neglected in these approximations because it is very small compared to the other terms of the expression. Since forming techniques allow control of α_{ce}, as will be shown later, a typical value of 2.0 may be assumed for this term. A value of r_b greater than that of r_e, therefore, causes instability, and a value less than that of r_e results in stability.

The value of r_b used in these expressions refers to only one direct-current operating point. Figures 1a and 1b show the feed-back characteristics of two developmental point-contact transistors. The slope of this curve at any point indicates the value of the equivalent base resistance. Since the slope increases as the collector current increases, the transistor may be stable at one value of collector current, but unstable at another. If the value of r_b in the above example should be less than that of r_e at 2.0 milliamperes, for instance, but greater than that of r_e at 2.5 milliamperes, it would be necessary to limit the operation of the transistor to 2.0 milliamperes or less to avoid unstable operation. Because of the nonlinearity of the feed-back characteristic, it is desirable to provide a value of r_b low enough to assure stability regardless of the direct-current operating conditions of the point-contact transistor. With few exceptions, a value less than 120 ohms for r_b assures short-circuit stability in a common-base amplifier circuit.



(a)



(b)

Fig. 1—Feedback characteristics of two developmental point-contact transistors.

If stability is extremely important, an additional safety factor of approximately 20 ohms is desirable. Within the range of resistivities discussed here, the value of r_e is usually sufficiently large to assure stability if the value of α_{ce} is approximately 2.0. As the value of α_{ce} increases, however, the transistor tends to become unstable, and the value of r_b must be decreased even further.

When transistors are designed for operation at specific frequencies, the curves given in Figure 2 may be used to determine values of point-spacing and resistivity which will provide the equivalent base resistance necessary for stability at the desired frequency. These curves represent a composite of design curves given in a previous paper.[1] The dashed line shows the variation of cutoff frequency (3 decibels down in current amplification factor) with point spacing for transistors

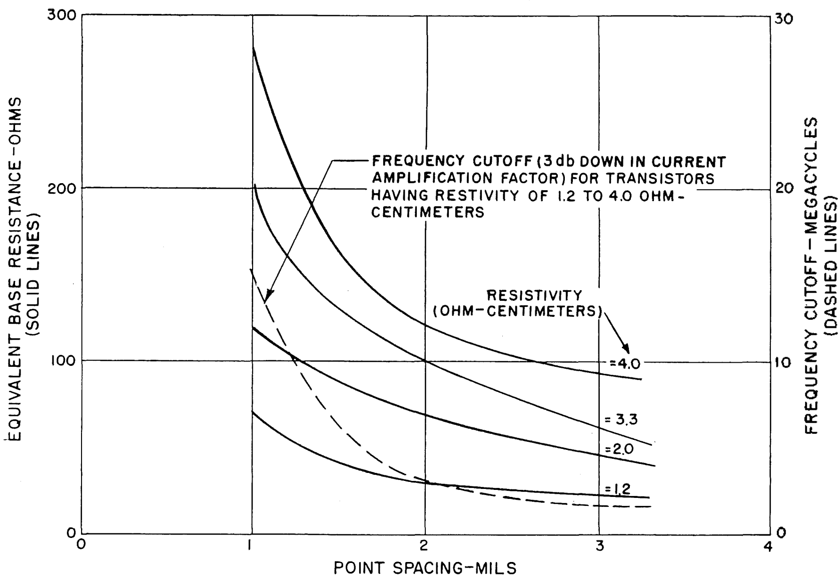


Fig. 2—Effect of variation of point spacing and germanium resistivity on frequency cutoff and equivalent base resistance.

having a resistivity ranging from 1.2 to 4.0 ohm-centimeters. In a transistor having a resistivity of 1.2 ohm-centimeters, a spacing of 1.0 mil, and an equivalent base resistance of 70 ohms, for example, a frequency cutoff of 15 megacycles can be obtained. If, for reasons to be discussed later, it is desirable to utilize a higher value of germanium resistivity, such as 3.3 ohm-centimeters, stability can be achieved at a spacing of 2.0 mils with a 100-ohm value of r_b, but the frequency cutoff would be only about 3.0 megacycles.

Although the curves included in this paper cannot be used as exact design data, their general shape serves as a guide to transistor design.

The curves were obtained by careful measurement of the resistivity of individual germanium specimens, and by variation of the spacing on each specimen to attain the separate resistivity curves. It is quite difficult, however, to maintain accurate point spacings, and measurement of the germanium resistivity is subject to some error. Because the transistors had to be formed electrically for each point on the curves, some error also arises due to the difficulty in reproducing the same forming conditions for each point.

For most amplifier applications, it is necessary to consider power gain and current amplification as well as frequency response and stability. A point-contact transistor usually should have a low-frequency power gain of at least 17 decibels and a current amplification factor of at least 2.0. It is possible to achieve a 17-decibel power gain using practically any value of resistivity within the range from one to 15 ohm-centimeters provided appropriate point spacings are used. If germanium having a resistivity of 10 ohm-centimeters is used, power gains greater than 17 decibels can be obtained at spacings greater than 10 mils.[3] When smaller resistivities are used, smaller spacings must be used to provide power-gain values of approximately 17 decibels or greater. When resistivities ranging from 1 to 5 ohm-centimeters and spacings of less than 3 mils are used, power-gain values greater than 17 decibels can usually be obtained for any combination of point spacing and resistivity. The small-signal power gain for radio-frequency applications, therefore, is not a serious consideration in the selection of a value of point spacing and resistivity.

Transistors for Switching Circuits

In the design of point-contact transistors for switching or counter circuits, the selection of point spacing and resistivity involves additional considerations. Figure 3 shows the output characteristics of several typical developmental point-contact transistors. Collector current is plotted as a function of collector to base voltage for varying values of emitter current. The current amplification factor may be computed from the curves of Figure 3 by dividing an increment of collector current along a line of constant collector voltage by the corresponding increment of emitter current. For most switching applications, I_{CO}, the collector current when there is no emitter current, should be as low as possible. In addition, the transistor should be capable of drawing a large amount of collector current at a low value of collector voltage when the emitter current is high. α_{ce} should be as constant

[3] B. N. Slade, "A High-Performance Transistor with Wide Spacing Between Contacts," *RCA Review*, Vol. XI, No. 4, p. 517, December, 1950.

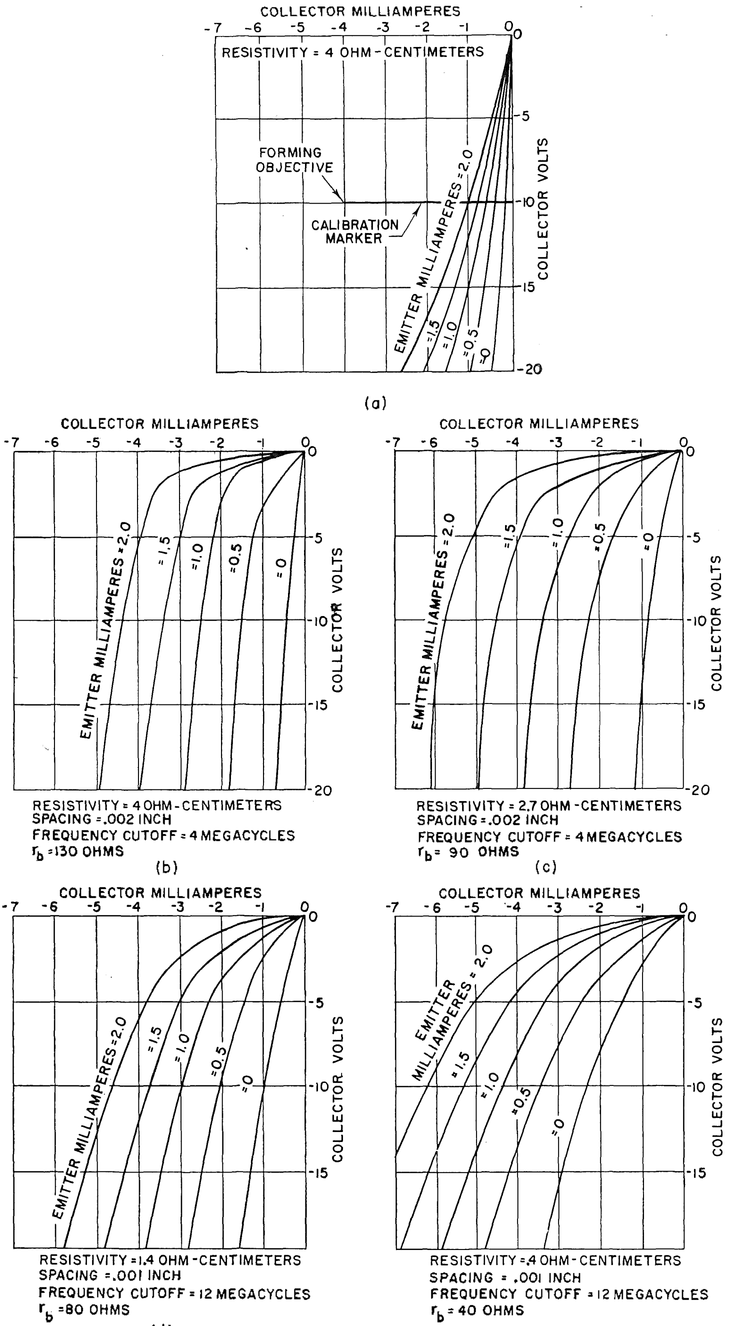


Fig. 3—Output characteristics of several developmental point-contact transistors: (a) before forming; (b), (c), (d), (e) after forming.

as possible over the entire range of collector voltages, and should generally be on the order of 2.0 or more. If the germanium resistivity is too low (on the order of 1 to 2 ohm-centimeters), it is difficult to obtain a high current amplification factor and still maintain a low value of collector current when there is no emitter current. This difficulty is due in part to the electrical forming treatment, which will be discussed later. Values of germanium resistivity greater than 3 ohm-centimeters permit higher current amplification factors with fairly low values of I_{CO}.

For switching circuits, it is not essential that the transistor be short-circuit stable. Relatively small point spacings, therefore, may be used with germanium having higher resistivities. Even in switching circuits, however, the value of the equivalent base resistance is subject to some limitations. If extremely narrow spacings are used with very high resistivities, the value of r_b may increase rapidly with increasing collector current because of the nonlinearity of the feed-back characteristic. In some cases, r_b of a transistor may vary from a few hundred ohms to a few thousand ohms over a collector-current range of three milliamperes, as evidenced by the shape of the curves in Figure 1b. The nonlinearity of the feed-back characteristic is much less pronounced when wider spacings or lower resistivities are used. If the speed of the switching circuits is not too high, therefore, wider point spacings and germanium having a higher resistivity may be used to achieve a low value of equivalent base resistance together with a high current amplification factor, and a low value of I_{CO}. As shown in Figure 3, a transistor using germanium having a resistivity of 4.0 ohm-centimeters and a point spacing of 2 mils would have an equivalent base resistance of approximately 120 ohms and a frequency cutoff of 3 megacycles. A higher value of resistivity could also be used at the same spacing without the equivalent base resistance becoming excessive for this type of application.

TRANSISTOR OSCILLATORS

Transistors normally will oscillate at frequencies much higher than the so-called "cutoff" frequency. For instance, a transistor having a frequency cutoff of 4 megacycles may oscillate at frequencies as high as 10 megacycles or more because the current amplification and the power gain at these higher frequencies is still sufficient to enable oscillations to occur. By utilizing point spacings of less than 0.001 inch, it is possible to achieve cutoff frequencies of 30 megacycles or more, and thus make possible oscillations at even higher frequencies. With spacings of approximately 0.0005 inch, transistors can be made which will oscillate at frequencies well above 100 megacycles.[4] Germanium resistivities less than 2 ohm-centimeters can be used at these narrow spacings if low equivalent base resistance is desired.

ELECTRICAL FORMING[5]

The material used for the point contacts greatly affects the transistor characteristics. The use of phosphor bronze for the collector contact is desirable because this material responds well to the electrical forming process. In the transistors discussed in this paper, phosphor bronze was also used for the emitter contacts. Because the emitter is not electrically formed, however, other point materials such as tungsten, steel, or berryllium copper can be used for the emitter without appreciably affecting major transistor characteristics.

The electrical forming treatment is very important in the fabrication of point-contact transistors. In a typical circuit used in the forming of transistors, as shown in Figure 4, a capacitor is charged to a

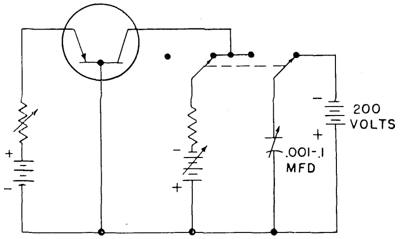


Fig. 4—Forming circuit for point-contact transistors.

voltage of approximately 200 volts and then discharged between the collector and base. The resulting surge of current causes a reduction in the collector resistance and an increase in the current amplification factor. Output characteristic curves for an unformed transistor are shown in Figure 3a and the output characteristic for the same transistor after it has been formed, is given in Figure 3b. The value of I_{CO} *increases slightly after forming, and the current amplification* factor increases considerably. The shape of the curves also changes, and α_{ce} becomes fairly uniform over the entire range from low voltages to the higher voltages. When the emitter current is zero, the collector draws only a few tenths of a milliampere; when the emitter current

[4] G. M. Rose and B. N. Slade, "Transistors Oscillate at 300 Mc," *Electronics*, Vol. 25, p. 116, November, 1952.

[5] J. Bardeen and W. G. Pfann, "Effects of Electrical Forming on the Rectifying Barriers of n- and p-Germanium Transistors," *Phys. Rev.*, Vol. 77, pp. 401-402, February, 1950.

is 2 milliamperes, however, the collector draws approximately 5 milliamperes at a voltage of only 10 volts.

This type of characteristic may be achieved by the repeated pulsing of the transistor by the capacitor-discharge method until the desired transistor characteristics are obtained, as observed on the oscilloscope of a curve tracer. The curve tracer may be switched in and out of the transistor circuit between discharges of the capacitor. The transistor can be pulsed to a desired operating point on the output characteristic. A calibration mark on the oscilloscope of a curve tracer can be set to this operating point. If, for example, a transistor is to be formed to the following operating point: emitter current = 2 milliamperes, collector voltage = —10 volts, collector current = —4.0 milliamperes, the calibration marker on the oscilloscope is set to this operating point, as shown in Figure 3a. The output characteristic is then plotted as the collector is swept with an alternating-current voltage while the emitter current is varied in steps from zero to 2 milliamperes. As the capacitor in Figure 4 is charged and discharged, the zero-emitter-current curve rises slightly while the constant-emitter-current curves begin to spread out. The value of the capacitor or charging voltage may be increased as additional pulses are applied until the 2-milliampere emitter-current curve passes through the —10-volt and —4.0-milliampere point marked by the calibrating marker.

The shape of the output characteristic obtained during the pulsing operation depends to some extent upon the germanium resistivity. If resistivities of about 2 ohm-centimeters or more are used, the shape of the characteristic curve approaches that of the plate characteristic curve of a pentode-type vacuum tube. When larger values of resistivities are used, I_{CO} may be decreased. When resistivities much smaller than 2 ohm-centimeters are used, it is often difficult to achieve values of α_{ce} much greater than 2 and maintain low values of I_{CO}. A "short-circuit-stable" transistor having a cutoff frequency of approximately 15 megacycles would have the output characteristic shown in Figure 3d, because germanium having fairly low resistivity would be used. Figures 3b through 3e indicate types of output characteristics that can be obtained with different germanium resistivities. Typical values of frequency cutoff and equivalent base resistance are given for each curve family.

Effect of Ambient Temperature

An important consideration in the design of point-contact transistors is the dependence of transistor characteristics upon variations in ambient temperatures. As ambient temperatures are increased, the equivalent circuit resistances decrease, in some cases to an intolerable degree. The amount of change that may be tolerated depends upon the application. As the ambient temperature increases from room temperature (25°C) to 60°C, r_e, r_b, and r_c tend to decrease while α_{ce} tends to increase. r_c changes most rapidly, and becomes very low at temperatures greater than 60°C. At elevated temperatures, however, the increase in α_{ce} tends to compensate for the decrease in r_c, and the power gain is kept fairly constant. For small-signal applications, therefore, changes in ambient temperatures may not be too serious up to temperatures of 50 or 60°C. For large-signal applications, however, large changes in I_{CO} are very serious, particularly in switching circuits.

The temperature problem in small-signal circuits is alleviated some-

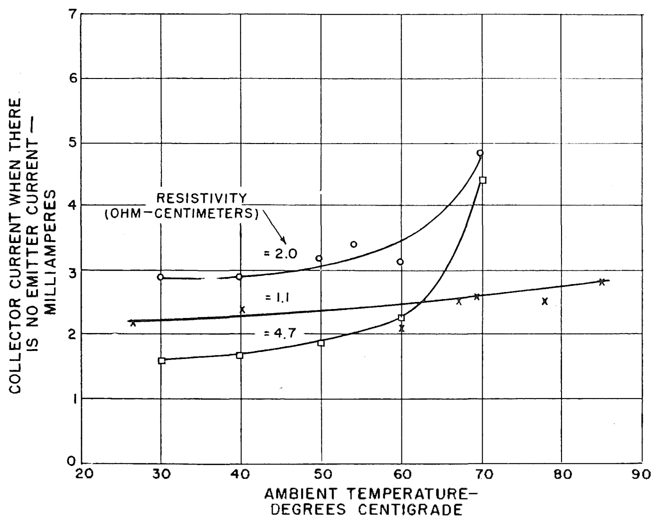


Fig. 5—Effect of variation of ambient temperature on collector current when there is no emitter current.

what because the temperature dependence of point-contact transistors decreases as the germanium resistivity decreases. Figure 5 shows a curve of I_{CO} versus ambient temperature for three different values of resistivities. When germanium having low resistivity is used, I_{CO} is less dependent upon temperature changes and the temperature at which the transistor may satisfactorily operate is extended beyond 60°C. The curves of Figure 6 show the variation of gain, r_e, and r_b with ambient temperature for developmental transistors having varying values of germanium resistivity. The dependence of the low-resistivity transistors on temperature is considerably less than that

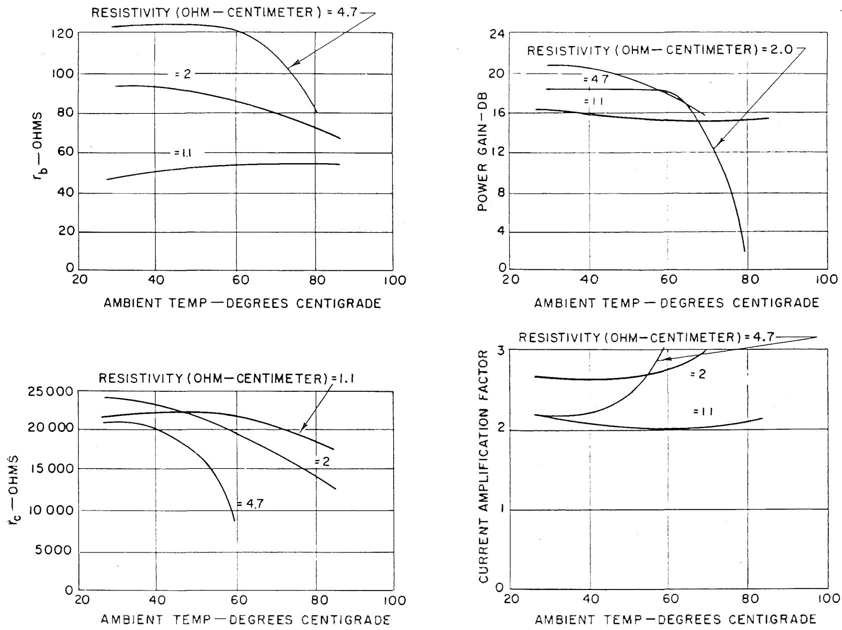


Fig. 6—Effect of variation of ambient temperature on current amplification factor, power gain, r_b, and r_c of developmental point-contact transistors.

of high-resistivity units. Thus, the temperature characteristics of the device may also be controlled to some extent by the proper choice of germanium resistivity.