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FACTORS IN THE DESIGN OF POINT-CONTACT TRANSISTORS

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Approved

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Introduction

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 frequency response and, therefore, permits the design of different transistors each suitable for use in a specific type of circuit application. This bulletin discusses the design of point-contact transistors for use in r-f amplifier, oscillator, and switching or counter circuits, and the effects of electrical forming on the electrical characteristics.

Although this bulletin includes some information issued previously,[1] such material is closely related to the new information given here and is repeated for the sake of completeness.

Transistors for RF 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 r-f 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 value of the expression $(r_e/r_b+r_e/r_c+1)$ must be greater than that of r_m/r_c, where r_e is the emitter impedance, r_b is the base impedance, r_c is the collector impedance, r_m is the transfer impedance, and r_m/r_c is equal to the current amplification factor, α.[1,2]

[1] LB-867, *Control of Frequency Response and Stability of Point-Contact Transistors.*

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 could be

$$r_e = 180 \text{ ohms}$$
$$r_b = 200 \text{ ohms}$$
$$r_c = 20000 \text{ ohms}$$
$$\alpha = 2.0$$

If these values are substituted in the expression $(r_e/r_b+r_e/r_c+1)$, the result is $(0.9+0.009+1)$ or 1.909. Because this value is less than that of α, the transistor would not be stable under "short-circuit" conditions. Al-

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

though 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 remainder of the expression in parentheses. Because forming techniques allow control of α, 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 (because r_e/r_b+1 should be greater than 2.0), 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 d-c operating point. Figs.1a and 1b show the feedback characteristics of two developmental point-contact transistors. The slope of this curve at any point indicates the value of the equivalent base resistance. Because 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 non-linearity of the feedback characteristic, it is desirable to provide a value of r_b low enough to assure stability regardless of the d-c 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 grounded-base amplifier circuit. 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 is approximately 2.0. As the value of α increases, however, the transistor tends to become unstable, and the value of r_b must be decreased even further.

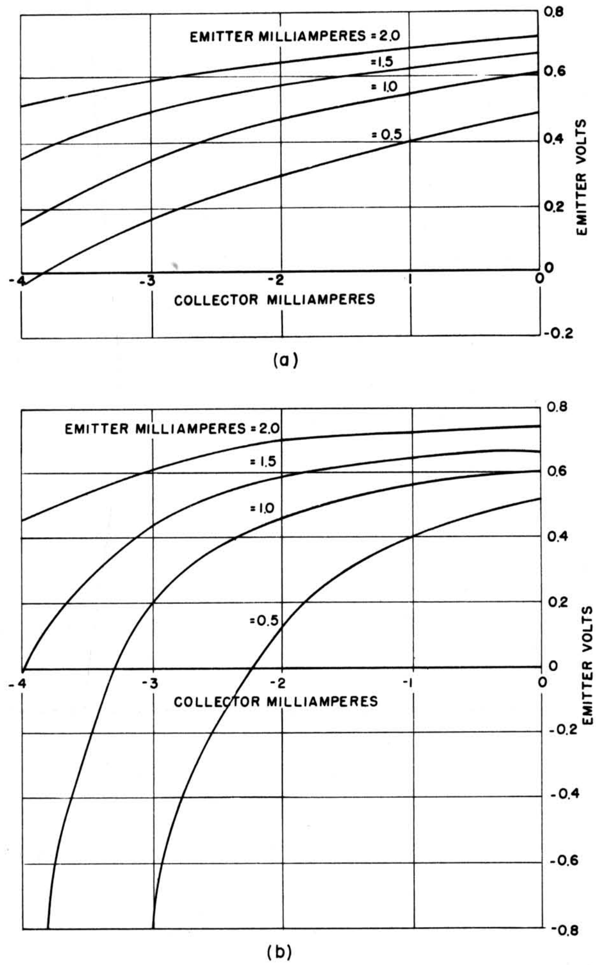

Fig. 1 - Feedback characteristics of two developmental point-contact transistors.

When transistors are designed for operation at specific frequencies, the curves given in Fig. 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 LB-867[1]. The dashed line shows the variation of cutoff frequency (3 db down in α or current amplification factor) with point spacing for transistors 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 Mc 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 Mc.

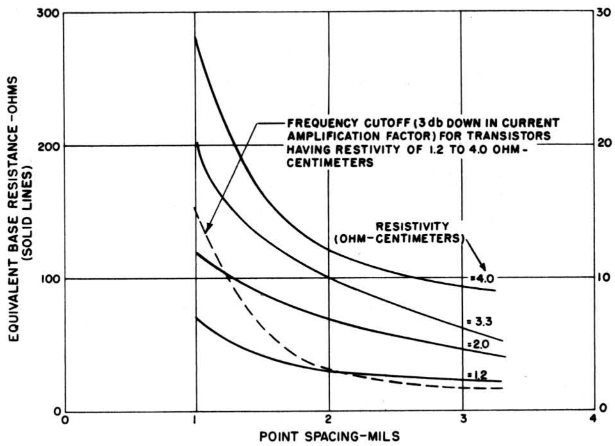

Fig. 2 - Effect of variation of point spacing and germanium resistivity on frequency cutoff and equivalent base resistance.

Although the curves included in this bulletin cannot be used as exact design data, their general shape serves as a guide to transistor design. The data 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 db and a current amplification factor of at least 2.0. It is possible to achieve a 17-db power gain using practically any value of resistivity within the range from 1 to 15 ohm-centimeters if appropriate point spacings are used. If germanium having a resistivity of 10 ohm-centimeters is used, power gains greater than 17 db 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 db 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 db can usually be obtained for any combination of point spacing and resistivity. The small-signal power gain for r-f 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. Fig. 3 shows the output characteristics of several typical developmental point-contact transistors. Collector current, I_c, is plotted as a function of collector voltage, E_c, for varying values of emitter current, I_e. The current amplification factor, α, may be computed from the curves of Fig. 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 should be as constant as possible over the entire range of collector voltages, and should generally be in the order of 2.0 or more. If the germanium resistivity is too low (in the order of 1 to 2 ohm-centimeters), it is difficult to obtain a high value of current amplification and still maintain a low value of collector current when there is no emitter current, or I_{co}. This difficulty is due in part to the electrical forming treatment, which will be discussed later. Values of ger-

[3] LB-804, *A High Performance Transistor with Wide Spacing Between Contacts.*

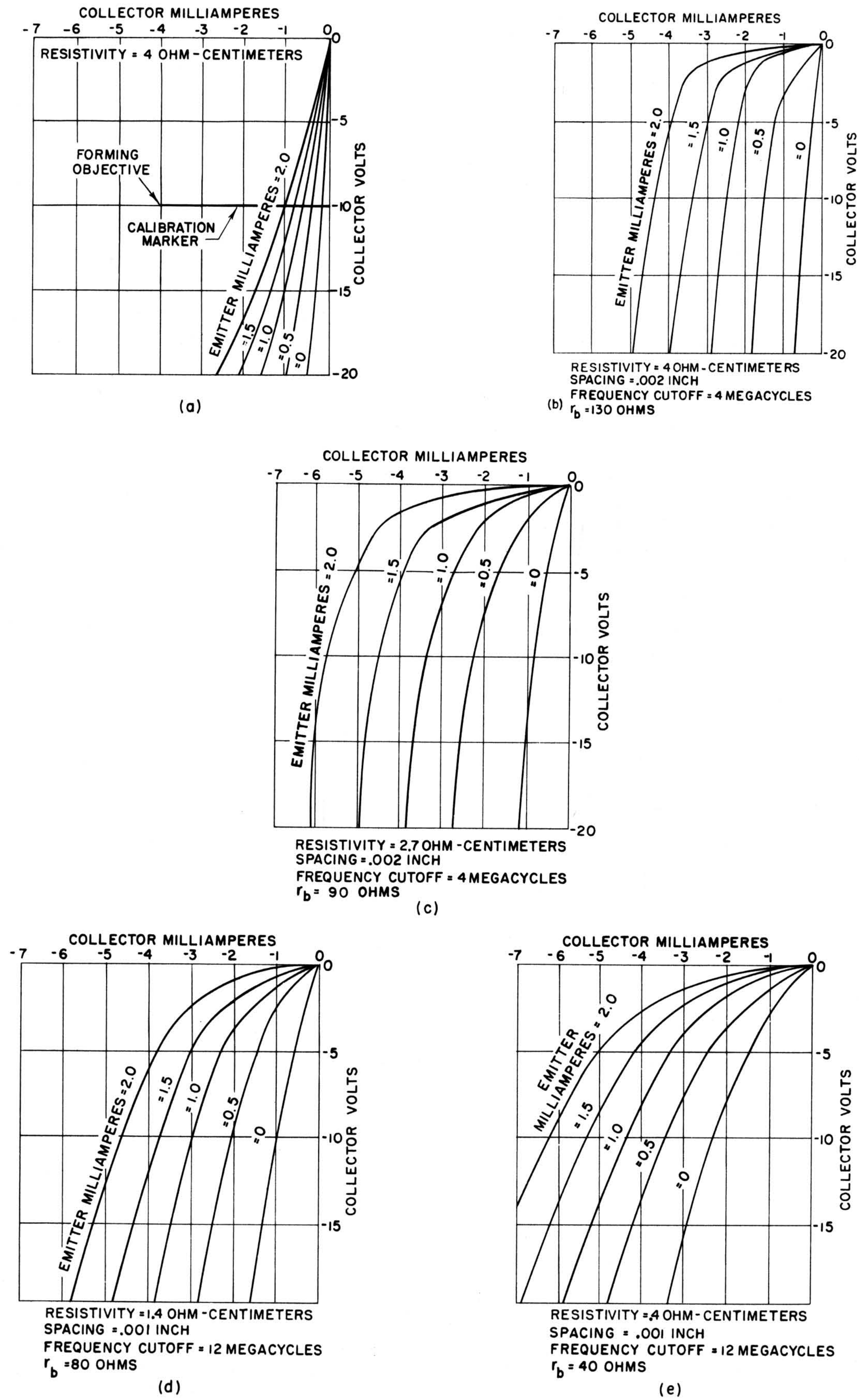

Fig. 3 - Output characteristics of several developmental point-contact transistors: (a) before forming; (b), (c), (d), (e) after forming.

manium resistivity greater than 3 ohm-centimeters allow for higher current gains 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 values of r_b may increase rapidly with increasing collector current because of the nonlinearity of the feedback characteristic. In some cases, the 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 Fig. 1b. The nonlinearity of the feedback 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 value of current amplification and a low value of I_{co}. As shown in Fig. 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 Mc. 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 Mc may oscillate at frequencies as high as 10 Mc 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 Mc 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 Mc.[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 bulletin, 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 beryllium 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 Fig. 4, a capacitor is charged to a 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, α. Output characteristic curves for an unformed transistor are shown in Fig. 3a and the output characteristic for the same transistor after it has been formed, is given in Fig. 3b. The value of I_{co}, the collector current when there is no emitter current, increases slightly after forming, and the current amplification factor increases considerably. The shape of the curves also changes, and α 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

[4] G. M. Rose and B. N. Slade, "Transistors Oscillate at 300 Mc", *Electronics*, 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, 1950.

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

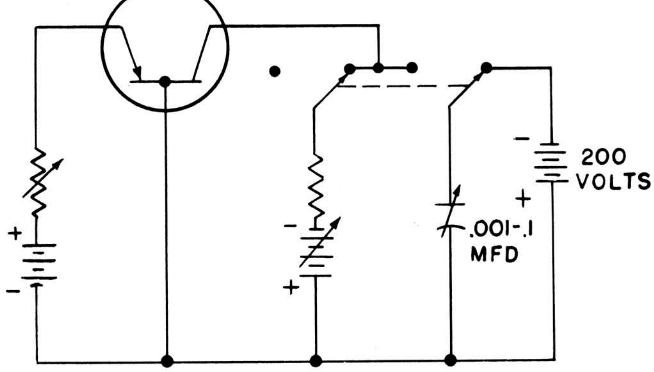

Fig. 4 - Forming circuit for point-contact transistors.

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 Fig. 3a. The output characteristic is then plotted as the collector is swept with an a-c voltage while the emitter current is varied in steps from zero to 2 milliamperes. As the capacitor in Fig. 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, the collector current when there is no emitter current, or I_{co}, may be decreased. When resistivities much smaller than 2 ohm-centimeters are used, it is often difficult to achieve values of α much greater than 2 and maintain low values of I_{co}. A "short-circuit-stable" transistor having a cutoff frequency of approximately 15 Mc would have the output characteristic shown in Fig. 3d, because germanium having fairly low resistivity would be used. Figs. 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 tem-

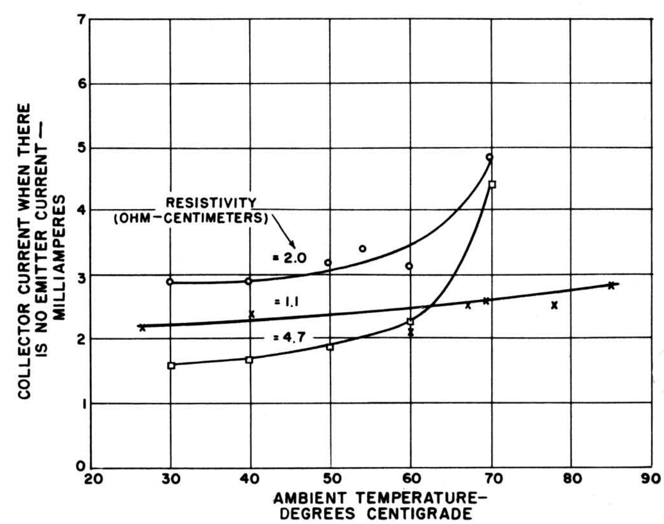

Fig. 5 - Effect of variation of ambient temperature on collector current when there is no emitter current

perature (25°C) to 60 degrees C, r_e, r_b, and r_c tends to decrease while α tends to increase; r_c changes most rapidly, and becomes very low at temperatures greater than 60 degrees C. At elevated temperatures, however, the increase in α 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 degrees 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 somewhat because the temperature dependence of point-contact transistors decreases as the germanium resistivity decreases. Fig. 5 shows a curve of I_{co} vs ambient temperature for three different values of resistivities. When germanium having low resistivity is used, the I_{co} is less dependent upon temperature changes and the temperature at which the transistor may satisfactorily operate is extended beyond 60 degrees C. The curves of Fig. 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 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.

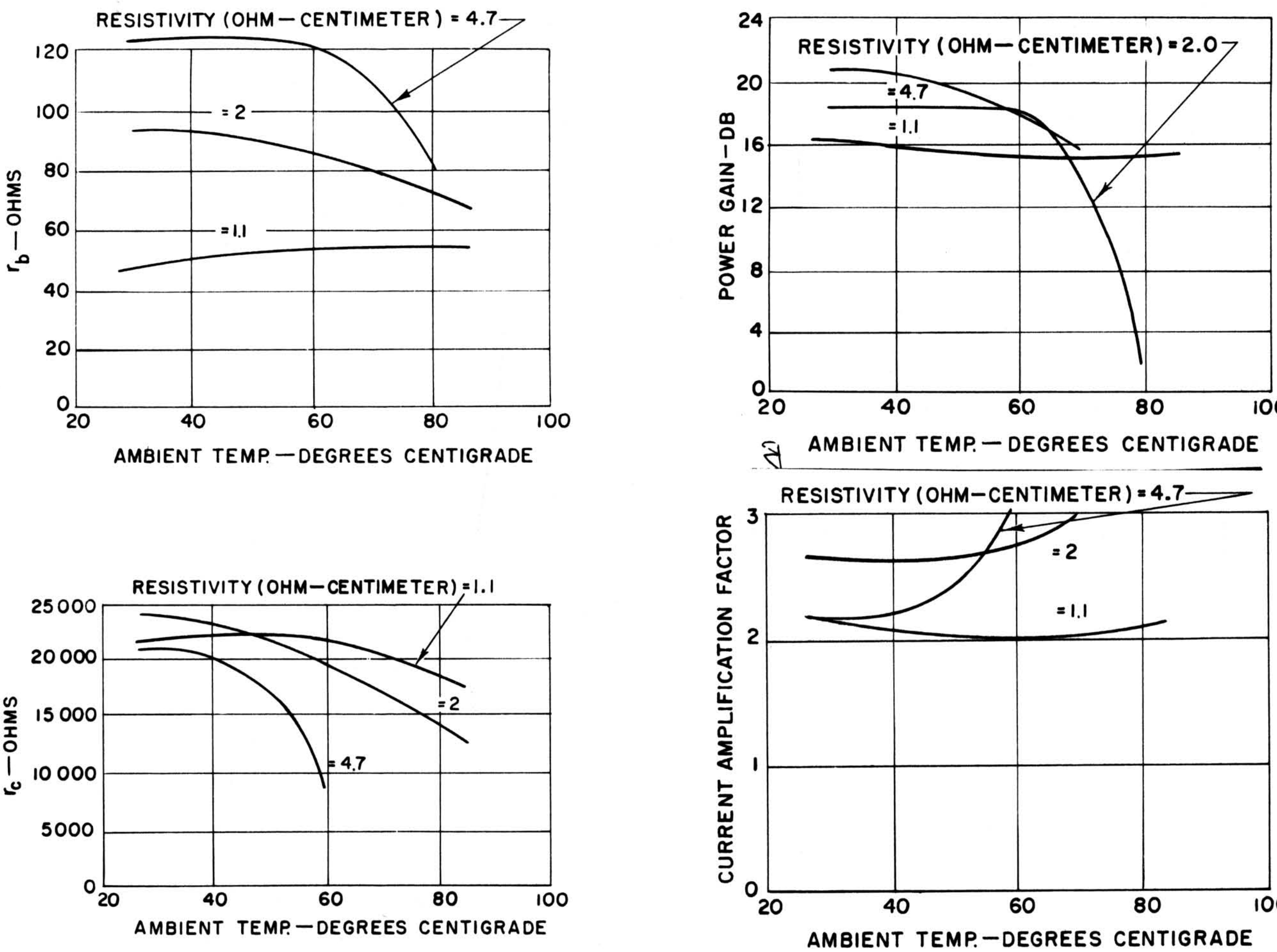

Fig. 6 - Effect of variation of ambient temperature on current amplification factor, power gain, r_b, and r_c of developmental point-contact transistors.

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