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LB-940

HIGH-FREQUENCY OPERATION OF P-TYPE POINT-CONTACT TRANSISTORS

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High-Frequency Operation of P-Type Point-Contact Transistors

Approved

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Introduction

This bulletin discusses the characteristics of developmental p-type transistors in radio-frequency amplifier or oscillator applications. Higher frequencies can be obtained from transistors using p-type germanium rather than n-type germanium because of the greater mobility of the minority carriers (electrons) in the former as compared to the mobility of the minority carriers (holes) in the latter. Short-circuit-stable p-type amplifier transistors have been developed having a current-amplification-factor cutoff frequency of 50 to 60 Mc. P-type oscillator transistors have been operated at frequencies up to 425 Mc. Experimental tests have shown that both p-type and n-type oscillator transistors perform satisfactorily at temperatures up to approximately 75 degrees Centigrade.

General Discussion

Early in the development of point-contact transistors, it was discovered that transistor action could be obtained from p-type as well as n-type germanium.[1] In general, p-type transistors had higher frequency-response characteristics but lower current amplification factors than n-type units.[1,2] Because a high current amplification factor is important to point-contact transistor action, n-type germanium has been used predominantly in these devices. P-type transistors can be made, however, having current amplification factors which are satisfactory for r-f applications. This bulletin discusses the development of the high-frequency possibilities of p-type point-contact transistors.

Electrical "Forming" of P-Type Transistors

Semiconductor theory[3] ascribes transistor action to the presence of an inversion layer, or a change of conductivity type in the barrier layer, of the emitter contact. This layer, believed to be present on the surface of n-type germanium, enables the emitter to inject minority carriers in n-type germanium when the transistor is biased in the forward direction. The injection of minority carriers into p-type germanium by a forward-biased emitter is normally very small because of the poor rectification qualities of p-type germanium. It has been found, however, that electrical "forming" of the emitter of a p-type transistor makes it possible to increase the forward emitter current and thus enhance transistor action.[4]

Stable RF Amplifier Transistors

It can be predicted from theoretical considerations that the frequency response of p-type transistors will be higher than that of n-type units. Shockley[5] has expressed the

[1] W. G. Pfann and J. H. Scaff, "The P-Germanium Transistor", *Phys. Rev.*, Vol. 76, p. 459; August, 1949.

[2] W. G. Pfann and J. H. Scaff, "The P-Germanium Transistor", *Proc. IRE*, Vol. 38, No. 10, pp. 1151-1154; October, 1950.

[3] W. Schottky and E. Spenke, WISS. VEROFFENTL. SIEMENS-WERKEN, Vol. 18, p. 225, 1939.

[4] 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; December, 1950.

[5] W. Shockley, ELECTRONS AND HOLES IN SEMICONDUCTORS, D. Van Nostrand Co., Inc., New York, N.Y., 1950.

transit time of electron or hole carriers traveling from the emitter through germanium to the collector as $\tau = \frac{S^3\sigma}{\mu I_e}$, where τ is the transit time in seconds, S is the spacing in centimeters between the emitter and collector contacts, σ is the conductivity of the germanium in reciprocal ohm-centimeters, μ is the mobility of the electrons or holes in centimeters squared per volt-second, and I_e is the emitter current in amperes. Because the transit time has an approximately inverse relationship to frequency response, the frequency response would be expected to vary directly with the mobility of the minority carrier, other factors remaining constant. The following values for the mobility of electrons and holes were obtained from drift-mobility measurements on single-crystal filaments of n- and p-type germanium.[5]

Hole mobility in n-type germanium,
μ_p = 1700 cm^2/volt sec.

Electron mobility in p-type germanium,
μ_n = 3600 cm^2/volt sec.

The ratio of the mobility of electron minority carriers in p-type germanium to that of hole minority carriers in n-type germanium is approximately 2 to 1. Provided all other factors of the transit time equation remain constant, therefore, a change from n-type germanium to p-type germanium should increase the frequency response of a transistor by a factor of approximately 2.

Fig. 1 shows the variation of frequency cutoff (3 db down in current amplification factor) with point-spacing for p-type and n-type transistors.[6] Although these curves are average curves representing a number of transistors, identical point-spacing intervals and germanium-resistivity values were used. A comparison of these curves shows that higher frequency-cutoff values were achieved by the substitution of p-type germanium for n-type germanium. Variation of the resistivity of the germanium within a range of 1 to 5 ohm-centimeters had little effect on the frequency response. The electrical forming treatment, however, affected the frequency response considerably, and extreme care was taken during the forming operation to assure uniform treatment of the transistors. Values of frequency cutoff as high as 25 Mc at a spacing of 0.002 inch and 50 Mc at a spacing of 0.001 inch were attained for p-type transistors, depending on the electrical forming.

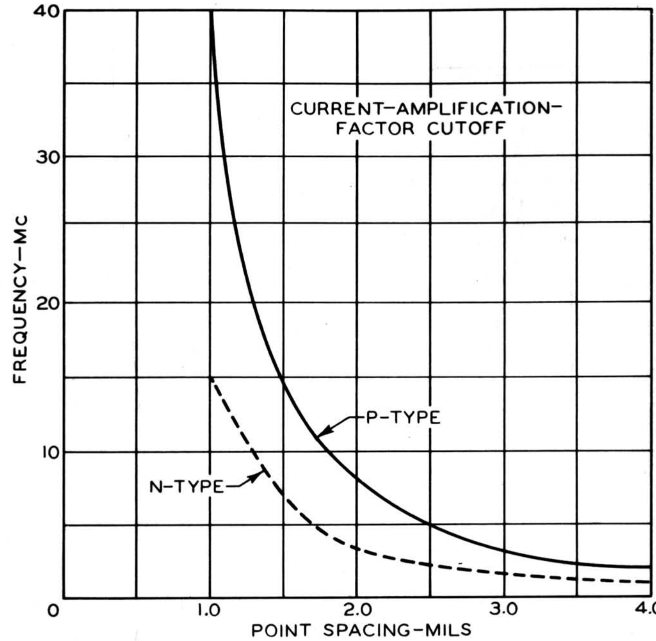

Fig. 1 - Effect of variations in point spacing on frequency response of p-type and n-type point-contact transistors.

One of the factors affecting the stability of point-contact transistors is their equivalent base resistance.[7] Generally, values of equivalent base resistance of approximately 100 ohms or less will assure transistor stability. Fig. 2 shows the equivalent base resistance of p-type point-contact transistors as a function of point spacing for various values of germanium resistivity. The curves of Fig. 2 resemble similar curves taken on n-type transistors[7] except that the equivalent base resistances are somewhat lower for the p-type transistors for any given resistivity and point spacing. Although the curves in Figs. 1 and 2 cannot be used as exact design data, their general shape serves as a guide to transistor design.

By the use of proper control of germanium resistivity and point spacing, a stable point-contact transistor can be designed to operate at high frequencies. Short-circuit-stable transistors using n-type germanium and designed

[6] B. N. Slade, "Factors in the Design of Point-Contact Transistors", *RCA REVIEW*, Vol. 14, No. 1, pp. 17-27; March, 1953.

[7] B. N. Slade, "The Control of Frequency Response and Stability of Point-Contact Transistors", *Proc. IRE*, Vol. 40, No. 11, pp. 1382-1384; November, 1952.

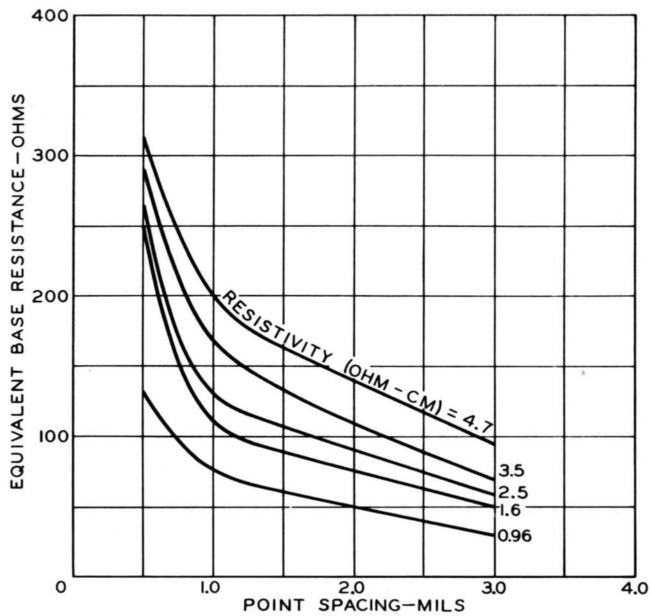

Fig. 2 – Effect of variations in point spacing and resistivity on equivalent base resistance of p-type transistors.

for radio-frequency amplification have been reported previously to have frequency responses up to 30 Mc.[7] Analogous p-type transistors have been made having frequency responses up to 60 Mc. Fig. 3 shows the current amplification factor, α_{ce}, as a function of frequency for two typical short-circuit-stable radio-frequency-amplifier transistors using p-type germanium.

Oscillator Transistors

A number of p-type point-contact oscillator transistors have also been made having the same point-contact spacings and germanium resistivities as the n-type point-contact oscillator transistors described in a previous paper[8] but differing in the type of impurities predominant in the germanium. Fig. 4 shows the output characteristics of both the p-type and the n-type oscillator transistors. The curves of collector voltage vs collector current at constant emitter currents are flatter for the n-type transistors than for the p-type units over the normal

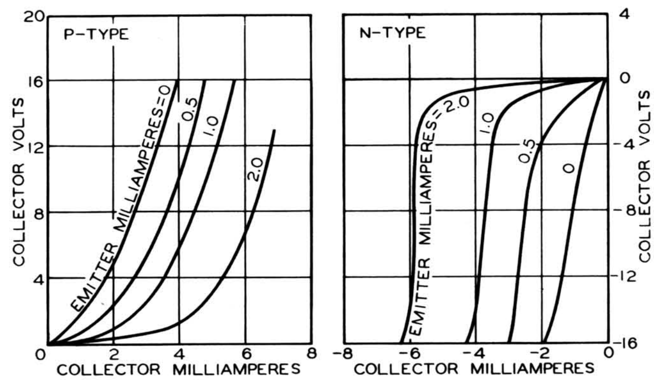

Fig. 4 – Output characteristics of point-contact oscillator transistors.

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

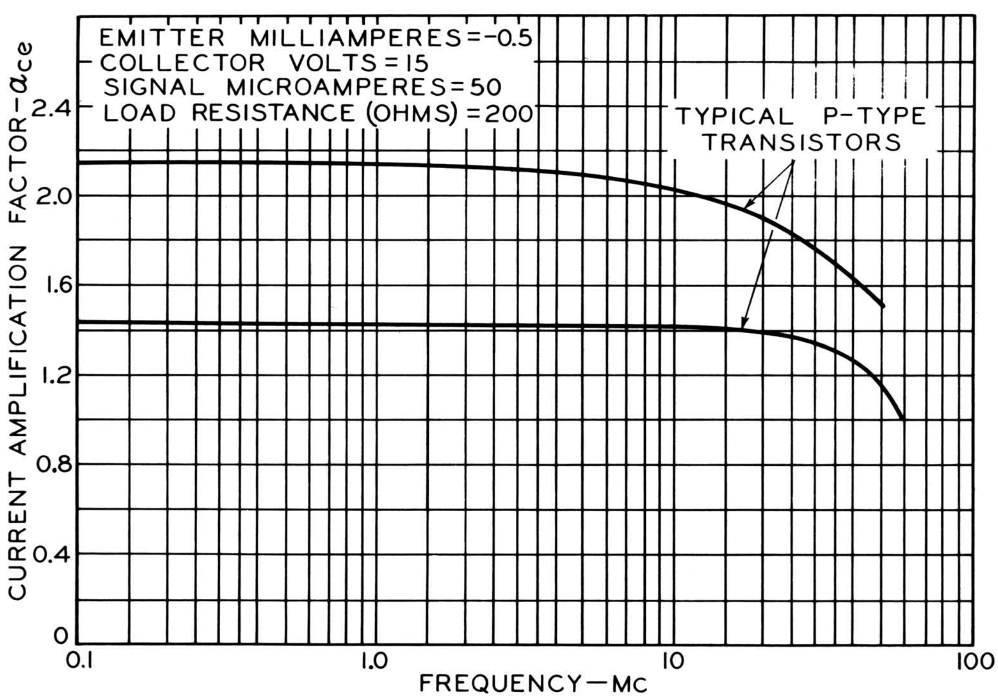

Fig. 3 – Frequency-response curves of two typical short-circuit-stable r-f amplifier p-type transistors.

operating range of the transistors, illustrating the better rectification qualities of n-type germanium. The collector resistance in the reverse direction of the n-type transistor, therefore, is greater than that of the p-type transistor. The average collector resistance of a group of 40 p-type oscillator transistors was 6400 ohms; that of a corresponding group of n-type transistors was 10,000 ohms. Comparative values of current amplification factor, which indicate the degree of transistor action, may also be obtained from the output characteristics. If a constant operating collector voltage is chosen for both types, and the increase of collector current is measured for a given change in emitter current, the current amplification factor of the n-type transistor is found to be somewhat greater than that of the p-type transistor. For the same groups of 40 units mentioned above, the average current amplification factor of p-type transistors was 2.0 while that of the n-type transistors was 2.8.

Fig. 5 shows the feedback characteristics of both p-type and n-type oscillator transistors. The curves of emitter voltage vs collector current at constant emitter currents are steeper for the n-type transistors than for the p-type units over the operating range. The feedback resistance of the n-type transistors, therefore, is greater than that of the p-type transistors. The group of 40 p-type transistors had an average feedback resistance of 250 ohms; that of the group of 40 n-type transistors was 400 ohms. Although the emitter of the p-type transistor is negatively biased, the high feedback characteristic causes the emitter voltage to increase and become positive over the main operating range of the transistor. The high feedback characteristic of the n-type transistor, on the other hand, causes the positively biased emitter to become negative over the main operating range of the transistor.

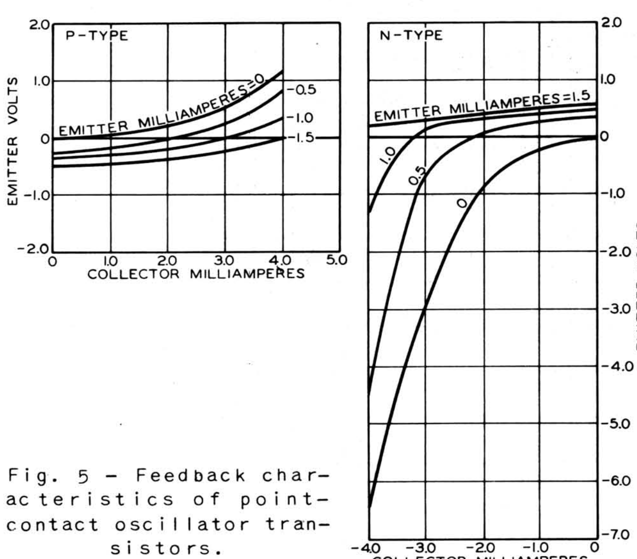

Fig. 5 - Feedback characteristics of point-contact oscillator transistors.

The input characteristics of p-type and n-type oscillator transistors are shown in Fig. 6. The effect of the high feedback resistance on the emitter voltage is also evident in the input characteristics of the two transistor types. The decrease of the emitter voltage of the n-type transistor is more pronounced than the increase of the emitter voltage of the p-type transistor because of the higher feedback resistance of the former.

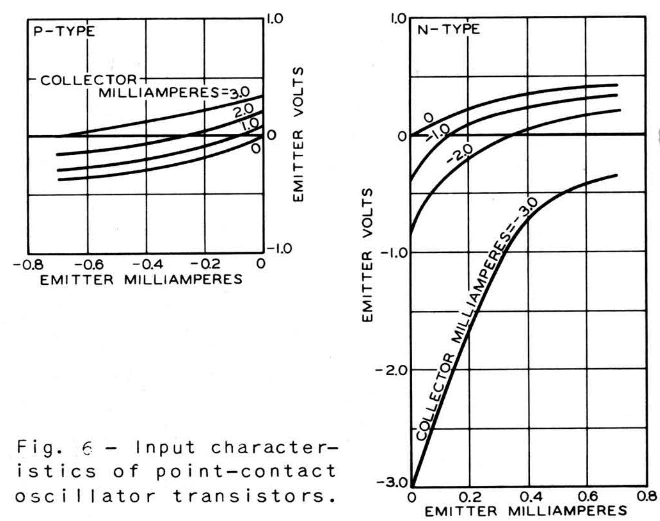

Fig. 6 - Input characteristics of point-contact oscillator transistors.

The n-type oscillator transistor has been reported previously to be capable of oscillating readily at frequencies between 100 and 200 Mc.[8] The highest oscillation frequency attained with these units was 302 Mc. With p-type transistors, however, oscillation frequencies as high as 425 Mc have been obtained. The oscillator circuit used in the measurement of the frequency of the p-type point-contact oscillator transistors was the same as that used for the n-type transistors except that the polarity of the voltage supply was reversed. This oscillator circuit is shown in Fig. 7. Emitter bias is provided by the bypassed re-

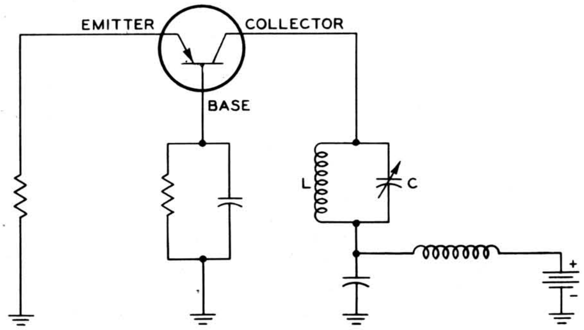

Fig. 7 - Oscillator circuit used in measurement of frequency of point-contact transistors.

sistance in the base circuit and the self-biasing resistance in the emitter circuit. The internal capacitance between emitter and collector provides a feedback path for oscillation. The inductance and the capacitance of the parallel resonant circuit in the collector circuit may be varied to cover an oscillation range from 5 to 425 Mc. The 40 p-type and 40 n-type point-contact oscillator transistors mentioned previously were measured in this oscillator circuit under optimum conditions for maximum oscillation frequency. Fig. 8 shows the percentage of units within given intervals of maximum oscillation frequency. The median value, or the point at which 50 per cent of the units fall above and 50 per cent below, was found to be 149 Mc for the p-type oscillator transistors and 112 Mc for the n-type oscillator transistors.

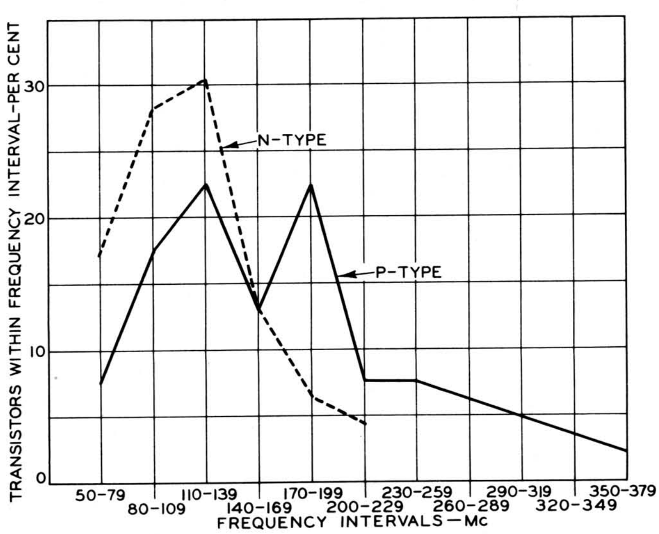

Fig. 8 - Distribution of maximum oscillation frequencies of point-contact oscillator transistors.

Effect of Ambient Temperature

The resistivity of p-type and n-type germanium as a function of temperature has been described by Herkart and Kurshan.[9] At resistivities of 16 ohm-centimeters or less, both p-type and n-type germanium have positive temperature coefficients at 25 degrees Centigrade (room temperature). As the temperature is increased, however, the curve for a given resistivity approaches the negative-slope characteristic of the curve for intrinsic germanium. The resistivity then decreases with increasing temperature. An investigation was made of the effect of ambient temperature on resistivity for both p-type and n-type germanium over the range of resistivities used in making the transistors described above. The results are shown in Figs. 9 and 10. For samples having a given resistivity at 25 degrees Centigrade, the resistivity of the p-type germanium

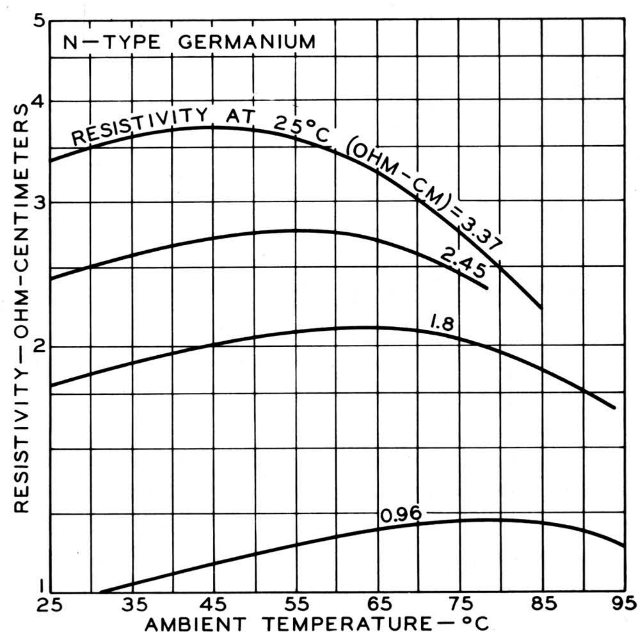

Fig. 9 - Effect of variations in ambient temperature on resistivity of p-type germanium.

increases to a higher temperature than that of the n-type germanium before reaching the negative-slope characteristic. For example, the curve for n-type germanium having a resistivity

[9] P. G. Herkart and J. Kurshan, "Theoretical Resistivity and Hall Coefficient of Impure Germanium Near Room Temperature", *RCA REVIEW*, Vol. 14, No. 3, pp. 427-440; September, 1953.

of 1.8 ohm-centimeters at 25 degrees Centigrade reaches a maximum resistivity of 2.1 ohm-centimeters at 65 degrees Centigrade before decreasing. The curve for p-type germanium having a resistivity of 1.8 ohm-centimeters at 25 degrees Centigrade reaches a maximum resistivity of 2.43 ohm-centimeters at 76 degrees Centigrade. P-type transistors, therefore, appear to be capable of operating at higher temperatures than n-type transistors before the change in characteristics becomes sufficient to make the units inoperable.

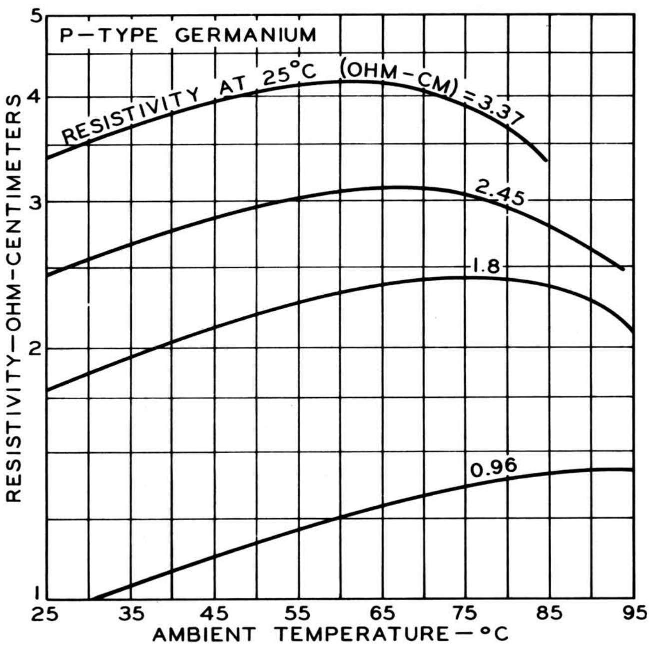

Fig. 10 - Effect of variations in ambient temperature on resistivity of n-type germanium.

Ambient temperature tests were conducted on both p-type and n-type point-contact oscillator transistors. P-type units were operated in the oscillator circuit shown in Fig. 7, and a constant collector-supply voltage of 10 volts was applied. The parallel resonant circuit in the collector was tuned to a resonant frequency of 83 Mc. The ambient temperature was then allowed to rise from room temperature, and relative r-f power output was measured at intervals of 5 degrees Centigrade. Data for four p-type oscillator transistors are shown in Fig. 11a. The r-f power output for these units gradually decreased as the ambient temperature increased until the transistor failed. As the temperature approached 75 degrees Centigrade, all four units were still oscillating satisfactorily at the resonant frequency of 83 Mc.

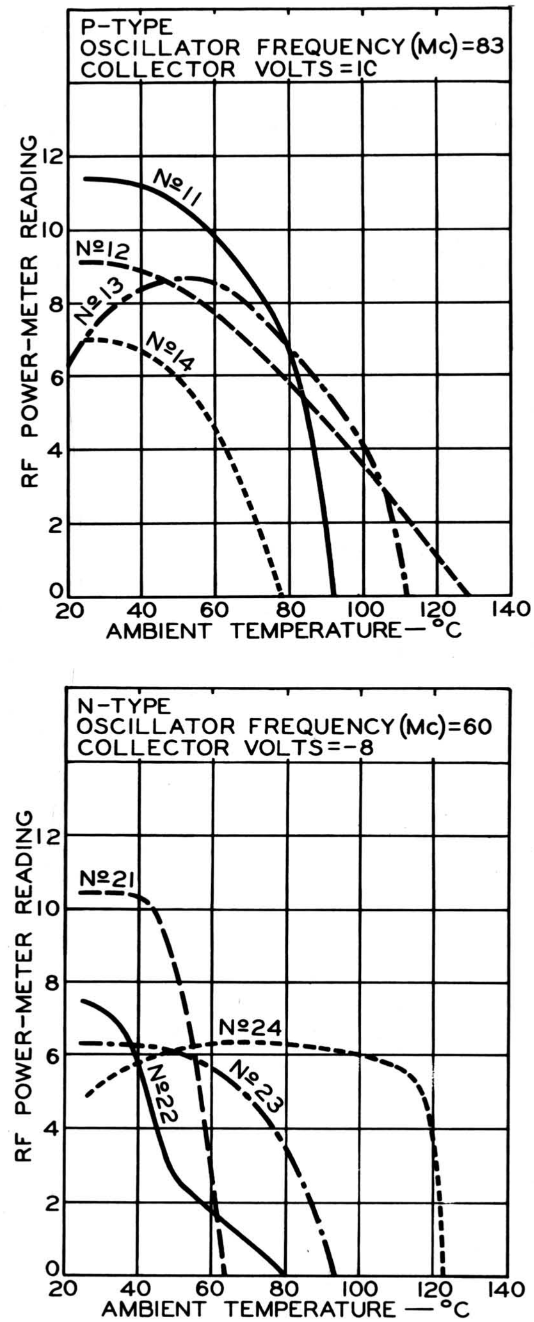

Fig. 11 - Effect of variations in ambient temperature on power output of point-contact oscillator transistors.

The transistors failed at temperatures of 77, 92, 112 and 129 degrees Centigrade. The characteristics of all four units returned to thei original values after the transistors cooled to room temperature.

A similar test was conducted on n-type oscillator transistors; the results are shown in Fig. 11b. The collector-supply voltage for these units was -8 volts, and the resonan frequency was 60 Mc. The r-f power output of n-type transistors also decreased with increasing temperature. The units failed at 64, 80, 93 and 122 degrees Centigrade. The characteristics of the n-type transistors also returned to their original values when the units cooled to room temperature. Although these results show that the p-type oscillator transistors operated satisfactorily at slightly higher temperatures than the n-type units, definite conclusions cannot be made because of some overlapping of the results.

The effect of ambient temperature on other characteristics of p-type point-contact oscillator transistors was also investigated. Fig. 12 shows the small-signal operating power gain as a function of ambient temperature for four p-type oscillator transistors. These transistors were tested in a small-signal amplifier test set at an emitter current of -0.6 milliampere and a collector bias of 10 volts. The operating power gain was measured at intervals of 5 degrees Centigrade and was found to decrease gradually with increasing temperature. All four units were still operating satisfactorily at a temperature of 75 degrees Centigrade.

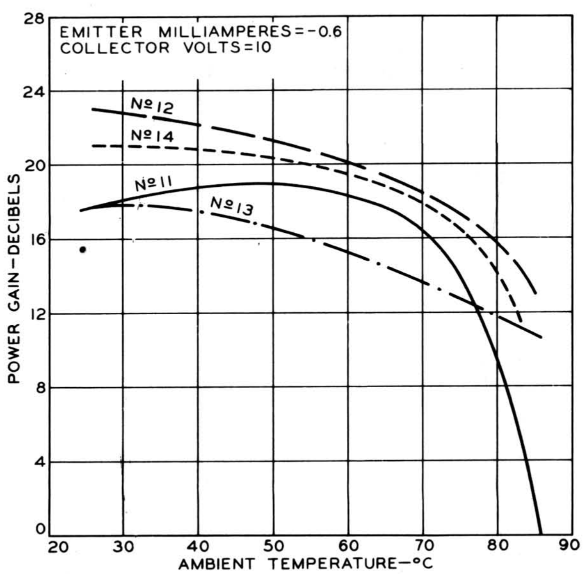

Fig. 12 - Effect of variations in ambient temperature on power gain of p-type point-contact oscillator transistors.

Fig. 13 shows the effect of ambient temperature on the collector current at a collector bias of 15 volts and zero emitter current. The collector current, or I_{co}, of the four transistors tested decreased gradually with increasing temperature.

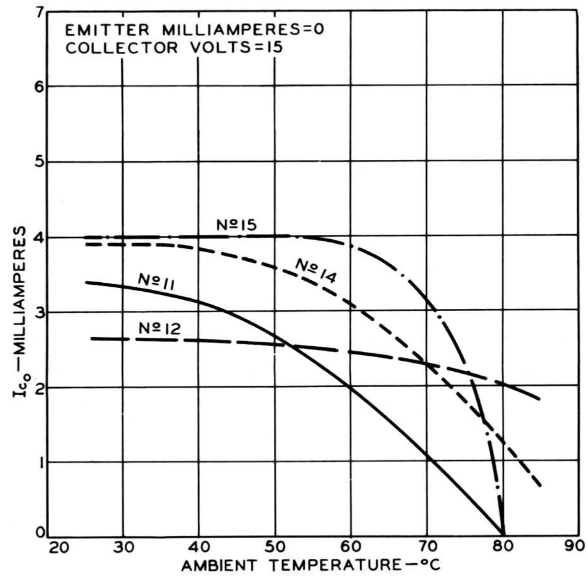

Fig. 13 - Effect of variations in ambient temperature on collector current at zero emitter current for p-type point-contact oscillator transistors.

The collector resistance of p-type oscillator transistors as a function of ambient temperature is shown in Fig. 14. The collector resistance was measured at an emitter current of -0.6 milliampere and a collector voltage of

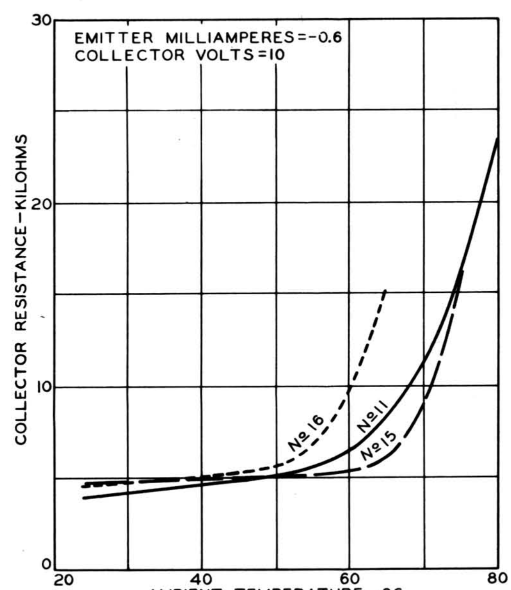

Fig. 14 - Effect of variations in ambient temperature on collector resistance of p-type point-contact oscillator transistors.

10 volts. The collector resistance remained substantially constant to a temperature of 55 degrees Centigrade, and then started rising quite rapidly at higher temperatures.

The curves shown in Figs. 13 and 14 may be explained on the basis of the curves of resistivity vs ambient temperature shown in Fig. 9. Samples of p-type germanium having resistivities less than 1.8 ohm-centimeters at 25 degrees Centigrade were found to have increasing resistivity with increasing temperature up to temperatures of approximately 80 degrees Centigrade before the resistivity began to decrease with higher temperatures. Transistors made with this germanium, therefore, would be expected to have collector resistances having positive temperature coefficients up to temperatures of 80 degrees Centigrade or more. The positive temperature coefficient of the collector resistance also explains the negative temperature coefficient of I_{co} shown in Fig. 13. The increase in the collector resistance shown in Fig. 14 tends to raise the operating power gain shown in Fig. 12 at the higher temperatures. The collector current at this operating point, however, decreases with increasing temperature, as does the I_{co} shown in Fig. 13. The current amplification factor, therefore, decreases sufficiently to compensate for the increase of the collector resistance, causing a gradual drop in the operating power gain. The characteristics of all the transistors used in these ambient-temperature tests returned to their original values when the transistors were cooled to room temperature.

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