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LB-905

POWER JUNCTION TRANSISTORS BY THE ALLOY PROCESS

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Approved

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ERRATA

I. LB-905, *Power Junction Transistors by the Alloy Process.* In Fig. 4, p. 7, the curve labels $V_c=10_v$ should read $V_c=3_v$. The labels *p-n-p* and *n-p-n* should be interchanged.

II. LB-872, *Balance Measurements on Balun Transformers.* In Fig. 8, p. 8, the following changes and addition should be made:

1. In detail 12, make *.120 DIA* read *.139 DIA.*
2. In detail 13, make *.139 DIA* read *.120 DIA.*
3. In detail 7, draw *.875 DIA* center hole as in detail 5.

Power Junction Transistors by the Alloy Process

Introduction

The junction transistors described in earlier bulletins have been restricted to power levels below 50 milliwatts, but this is not a fundamental limitation. The power capabilities of the laboratory units described in this bulletin have been extended to the order of 1 watt by proper design for high currents and provision for effective cooling.

Both n-p-n and p-n-p power transistors of the alloy junction type are discussed and laboratory methods for their construction are described. In a first cooling method, the heat is transferred to a relatively large metal enclosure by liquid convection and, in a second method, to a relatively large metal surface by metallic conduction. The transistor units are made basically as described in LB-868[1] and LB-903[2] except for larger junction areas and slight modifications in processing.

The transistors have been operated at one-watt dissipation and, in some experiments, up to 3 watts with additional cooling. Power gains of the order of 30 decibels and audio outputs of about half a watt are obtained in class A operation at 1 watt d-c input. A special liquid cooled p-n-p version for experimental low-power television scanning circuits has a cut-off collector current of less than 1 milliampere with 100 volts bias on the collector.

Design Considerations

Three important factors to be considered in the design of power transistors are (a) the effects of high operating temperatures; (b) limitations in current and voltage and (c) the influence of the base lead resistance on the operation of the units.

(a) An increase in the operating temperature, aside from possibly destroying the transistor, has two main consequences. The reverse saturation current to the collector junction (e.g., with emitter open-circuited) increases rapidly due to increased thermal generation of hole-electron pairs in the germanium. Also, both the a-c impedance of the collector junction, r_c, and the base lead resistance decrease.

Except in special applications, the increase in the reverse saturation current to the collector has only a slight effect on the output circuit of power transistors, since they are usually operated at currents much greater than these saturation values. However, the reverse collector current appears also as base current. The effect here is more important and will be discussed along with base lead resistance problems under (c).

[1] LB-868, *Germanium p-n-p Junction Transistors.*

[2] LB-903, *A Germanium n-p-n Junction Transistor by the Alloy Process.*

The decrease in r_c is reflected chiefly in a reduction in the small-signal matched output impedance. Since the load impedance is considerably below the small-signal matched output impedance in most power applications this is of minor importance. Therefore, it is possible to operate junction transistors at temperatures approaching 100 degrees C with only slight effects on the output circuit.

(b) The second aspect of power transistor design that must be considered is the current and voltage limitations of the units. The collector-to-emitter current-gain factor, α_{ce}, or the related collector-to-base current-gain factor, α_{cb}, decreases at large emitter current densities. If transistors are to be operated as large-signal devices, it is desirable that variations in current-gain factor be reduced to a minimum over the entire range of currents to be used. This necessitates the use of large enough junctions to reduce the current density. For the low-power general purpose units described in *LB-868* and *LB-903*, the drop in current gain with increasing current was greater for p-n-p than n-p-n transistors. However, the firing schedule given herein for the p-n-p power units has been modified from that of the general-purpose units to reduce the current-gain fall-off. There is now little difference between the two types in this respect.

The voltage that may be applied to the collector depends upon the resistivity of the germanium, the firing schedules and the type of unit. The p-n-p units will withstand higher voltages than n-p-n units and the maximum voltage increases with the resistivity of the base germanium. However, the aforementioned current-gain fall-off with current also increases with germanium resistivity. A proper balance must therefore be sought, based on the desired operation characteristics.

(c) In Fig. 1 is shown an equivalent network of an alloy junction transistor. The element, $r_{bb'}$† is due principally to the series resistance of the germanium between the junction areas and the point at which the base lead connection is made. This resistance, which can be of the order of several hundred ohms, decreases somewhat as the operating temperature increases, due to the decrease in the resistivity of the germanium. However, the change is not large enough to seriously modify the following discussion.

†For methods of measuring $r_{bb'}$, $(\frac{1}{g_{bb'}})$, see LB-900.

The base lead resistance influences the operation of power transistors in two ways. First, the increase in the reverse saturation current to the collector at high operating temperatures appears also as an increased d-c base current passing through the base lead resistance. This causes a shift in the internal emitter bias that can be very serious. For example, the emitter-to-base bias required to draw 50 milliamperes emitter current is about 0.50 volt in average units. However, at 100 degrees C the base current is about 2.0 ma which passing through an $r_{bb'}$ of 200 ohms would cause a bias shift of 0.4 volt. This change in bias is in the direction to increase emitter current, leading to still more dissipation and still higher operating temperatures. The transistor thus might "run away" even when used in a circuit with no external base d-c resistance, unless the emitter current were controlled by using some sort of constant current supply.*

The second effect of the base lead resistance is best shown by referring again to Fig. 1. It is seen that the output current generator is proportional only to that portion of the input voltage that is developed across the internal transistor. In other words, $r_{bb'}$ acts like an attenuator. Thus the presence of a base lead resistance requires a higher driving power for a given output. This is equivalent to a decrease in power gain.

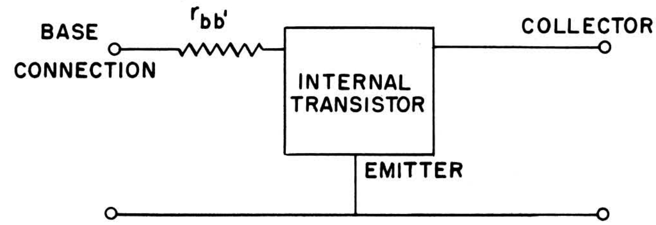

Fig. 1 - An equivalent circuit of a junction transistor for the common-emitter connection.

The base lead resistance may be decreased by increasing the thickness of the wafer, by decreasing the resistivity of the germanium and by plating the germanium wafer with a low resistivity metallic layer, thus bypassing some of the wafer resistance. The germanium thickness is, however, controlled by the amount of alloying penetration that may be obtained under

*The effect is analogous to grid-emission in electron tubes except that, in the transistor case, part of the d-c resistance is inherent in the unit.

practical conditions. Reducing the germanium resistivity is limited by factors, not well understood, which result in an increasing percentage of poor junctions. In addition the maximum collector voltage decreases rapidly with decreasing germanium resistivity and current-gain values become generally lower. In the design of practical transistors all factors are combined for most effective reduction of the base lead resistance under given operating conditions. Typical values of $r_{bb'}$ range from 50 to 250 ohms, depending on the resistivity of the germanium used in the transistor.

Methods of Cooling

The effects of increased operating temperature on transistors emphasize the need for cooling the elements if increased power dissipation is to be obtained. Experience indicates that the temperature of the transistor wafer should not exceed 80 degrees C, unless special circuit provisions to control biases are used. In the present work, the heat dissipation of transistors has been increased either by immersion in a cooling liquid, or by soldering a cooling fin to the wafer, or by soldering a cooling fin to the collector contact. Because of the simplicity of the mounting procedure, the liquid cooled version was developed first. In this method the basic transistor unit is immersed in a cooling liquid contained in a metal shell. The heat generated in the transistor is transferred to the metal shell by liquid convection, and from the shell by air convection. The requirements for the liquid coolant are (1) low viscosity to allow rapid circulation, (2) high heat capacity for efficient heat transfer, (3) boiling point well above the operating temperature and (4) excellent electrical insulation properties, since it is in direct contact with the junction surfaces. Benzene, toluene, and xylene are suitable coolants. Toluene has proved the most successful due to its low viscosity and relatively high boiling point. Although the liquid-cooled version is not rugged mechanically and, in addition, uses an inflammable liquid, the junctions suffer very little deterioration during mounting. Consequently this type of mounting has been used for power units with very low collector reverse saturation current requirements.

The other cooling methods, which use a metallic conduction path to transfer the heat, are rugged and contain no inflammable liquid. However, they are more difficult to apply than liquid cooling. The heat is transferred by metallic conduction to a large metal fin or enclosure, which may be attached directly to the germanium wafer. However, since most of the heat is generated at the collector junction, it is advantageous to attach the cooling metal to the collector directly. The most successful version consists of a copper cup to the inside of which the transistor is attached by a solder, which is initially a liquid, between the collector and the bottom of the cup. The liquid solder, a saturated solution of indium in mercury, forms a good electrical and thermal contact between the collector and metal cup. The cup is then filled with a molding resin to mechanically protect the unit. In subsequent operation of the device at higher operating temperature, enough of the impurity material diffuses into the liquid solder to finally form a solid metallic bond.

Processing Techniques

The basic laboratory transistor unit consists of a germanium wafer on which two alloy junctions are made on opposite faces, in the same manner as the low power types described in *LB-868* and *LB-903*. The power units use larger and thicker germanium wafers, larger area junctions, and the firing schedules are modified slightly. The units are fired in a dried, deoxidized hydrogen atmosphere in suitable graphite boats. Examples of part specifications and processing data are given in the following table.

Table I

Part Specifications and Processing Data

Germanium	p-type single crystal	n-type single crystal
Resistivity Range*	1-7 ohm-cm	1-7 ohm-cm
Wafer dimensions	0.25"x0.25"x0.005"	0.25"x0.25"x0.010"
Disk material	10% antimony, 90% lead alloy	indium
Emitter disk dimensions	0.060" dia.x0.015" thick	0.100" dia.x0.025" thick
Collector disk dimensions	0.100" dia.x0.015" thick	0.150" dia.x0.025" thick
First firing (emitter only)	680°C for 5 min.	605°C for 1 min.
Second firing (both junctions)	680°C for 10 min.	500°C for 2 min.
Etch	See LB-903	See LB-868

*Depending on characteristics desired in particular applications

Details of the mechanical handling techniques and etching solutions are the same as those for the low power types. This information may be found in *LB-868* and *LB-903*.

After etching, the wafers may be copper plated on the collector side to reduce the base lead resistance. The junction areas are first masked with Microstop masking lacquer[3] to protect them from the copper plating. After plating, the masking lacquer is removed by dissolving it in acetone and the wafers are then washed in running hot water to remove all traces of plating salts. This plating process reduces $r_{bb'}$ to about $\frac{1}{2}$ of its original value.

The liquid cooled version is mounted on a three-lead header[4] (type 1451-2) in the same fashion as the low power transistors. The nickel tab is spot welded to the center pin and leads from the outer pins are connected to the impurity dots with Cerrobend solder.[5] A metal can[4] (type 1012), $\frac{3}{4}$-inch deep is soldered to the header rim. This must be done rapidly with a very hot soldering iron to prevent overheating the transistor unit. Double distilled toluene is then added through a copper tube on top of the can, using a hypodermic needle. During the filling process the whole assembly is kept at a temperature above 60 degrees C, to prevent build up of pressure during future operation of the unit. The copper tube is then pinched off. In those special cases where very low collector reverse saturation current is desired, the assembly should be flushed with toluene prior to the final filling to eliminate all moisture residues. Fig. 2

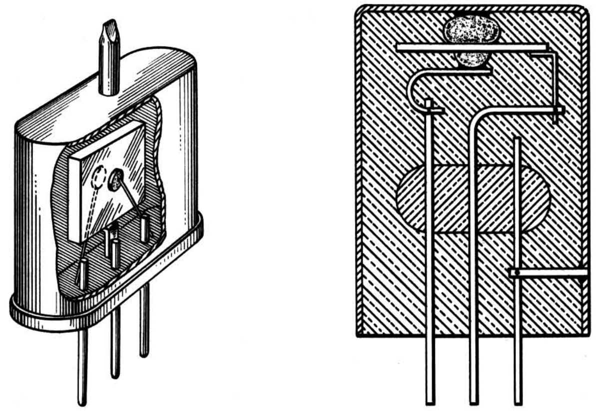

Fig. 2 - Assembly details of liquid cooled (left) and metallic conduction cooled (right) power transistors.

[3] Available from Michigan Chrome Chemical Co., Detroit, Michigan.

[4] The headers and cans are available from Hermetic Seal Products Co., 29 South 6th Street, Newark 7, New Jersey.

[5] Available from Cerro de Pasco Copper Corp., 40 Wall St., New York 5, N. Y.

shows the structure and Fig. 3 is a photograph of the two types of power transistors.

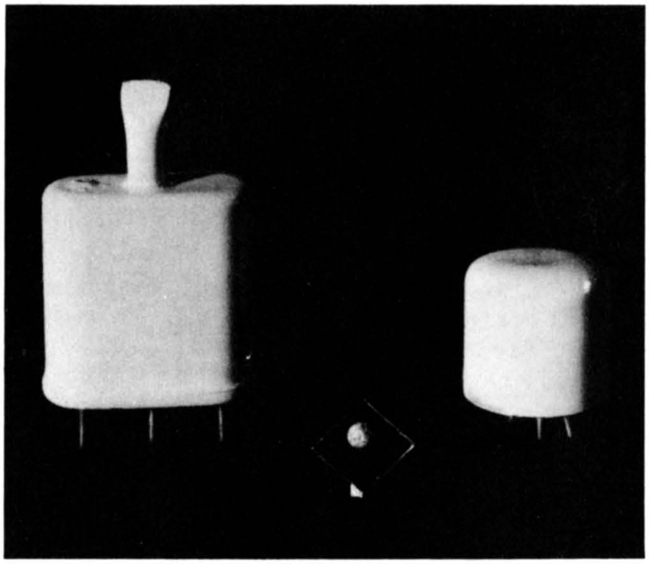

Fig. 3 - Photograph of liquid cooled (left) and metallic conduction cooled (right) power transistors and element (center).

In the case of transistors to be mounted using metallic conduction cooling, the wafers are prepared for mounting by first coating them with Amphenol coil dope, No. 912, leaving only the tops of the impurity dots exposed. A small amount of a saturated solution of indium-in-mercury solder is put on the top of each of the impurity dots and worked into the dots with the tips of tweezers. The transistor is then mounted on a three-lead glass stem as shown in Fig. 2 by spot welding the nickel tab to the center lead on the stem and then spot welding a 0.005-inch diameter tungsten wire to the other lead so the wire tip rests in the solder on top of the emitter dot. This mounted unit is next inserted into a copper container approximately 5/8 inch O.D. x 5/8 inch deep, which has been previously tinned on the bottom with the same liquid solder. The mount is placed so that the collector is in contact with the bottom of the copper can and the open lead on the stem is spot welded to the side wire on the container, as shown in Fig. 2. After protecting the wafer and connections by another coating of coil dope, the copper can is filled with a casting resin just as used in *LB-868* (CN 502[6] with added titanium dioxide). This is a room temperature setting resin. When hardened it supplies mechanical protection to the mount and the solder contact to the copper cup allows the heat to flow to the copper from whence it is dissipated into the air.

[6] Available from the Ciba Co., Summit, New Jersey.

Electrical Characteristics

The laboratory-type power transistors described in this bulletin can operate at about one watt dissipation. Experimentally, they have been operated up to three watts with additional forced-air or water cooling. From a purely dissipation point of view, it is irrelevant whether high voltage and low current are used or vice versa. However, junction tran-

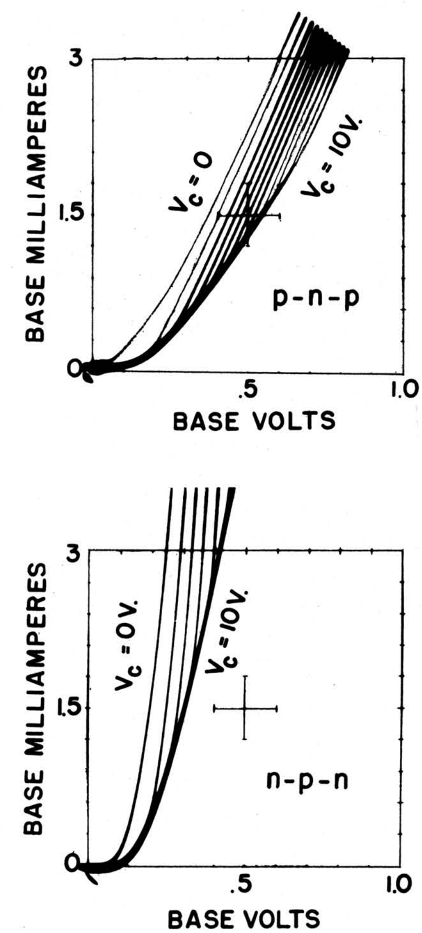

Fig. 4 - Input characteristics for $V_c = 0$ to $V_c = 3$ volts in ten equal steps for n-p-n and p-n-p junction power transistors.

sistors, in contrast to electron tubes, are able to operate unusually well at low voltages and low output impedances so that one ordinarily uses relatively high currents.

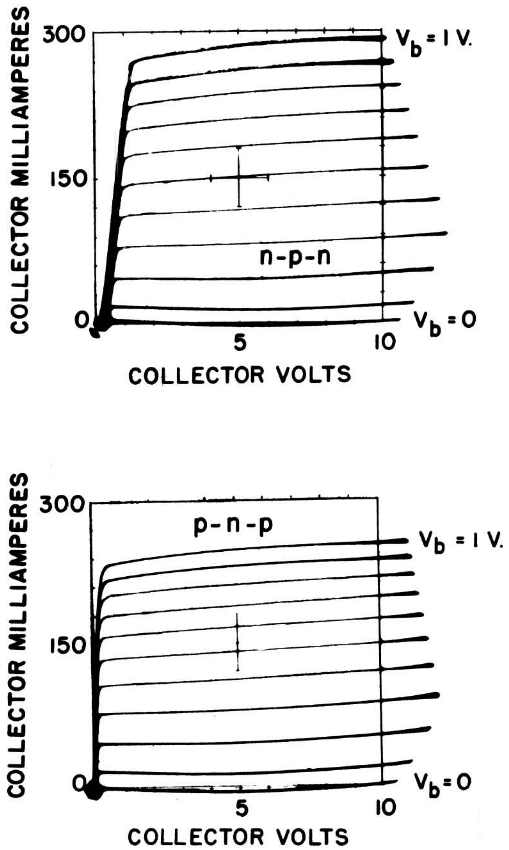

Fig. 5 - Output characteristics for $V_B = 0$ to $V_B = 1$ volt in ten equal steps for n-p-n and p-n-p junction power transistors.

As discussed previously, the processing parameters may be varied to obtain units that will meet various application requirements. Thus for power units that will operate at high currents and low voltages, for example 6-volt applications, low resistivity germanium (1-2 ohm-cm) is used. On the other hand, 5-7 ohm-cm resistivity n-type germanium was used for some special transistors used in horizontal deflection circuits for television receivers. The requirements for these units were ability to withstand 100 volts on the collector with less than 1 milliampere cut-off current, and a collector-to-emitter current gain factor greater than 0.90 with 100 milliamperes emitter current. These latter units were mounted for liquid cooling.

The performance of a transistor may be evaluated with the help of static characteristics, to which different load lines and bias conditions may be applied. Three of the important static characteristics are shown in Figs. 4-6 inclusive, in each of which an n-p-n and a p-n-p type are represented. Since the laboratory experiments did not extend to substantial numbers of transistors of any one design, the curves are representative but do not convey specific information on standardized models. Fig. 7 shows the type of variation in current gain α_{ce} as a function of emitter current for both n-p-n and p-n-p power transistors.

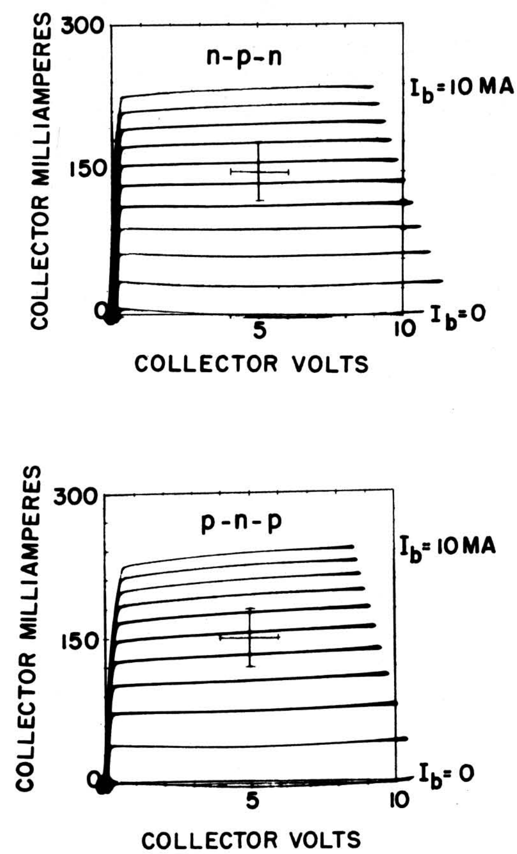

Fig. 6 - Output characteristics for $I_b = 0$ to $I_b = 10$ ma in ten equal steps for n-p-n and p-n-p junction power transistors.

Small-signal power-gain curves were taken with nearly matched impedances, as a function of power dissipation, with varying emitter current and collector potential and are shown in Figs. 8 and 9. The base input, common emitter circuit was used.

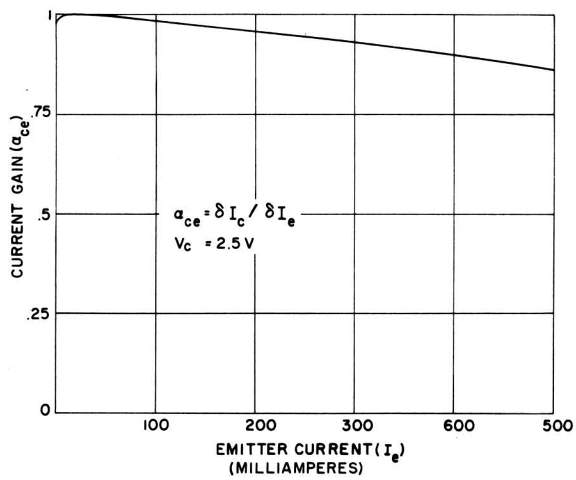

Fig. 7 - Current gain α_{ce} as a function of emitter current for n-p-n or p-n-p power transistors.

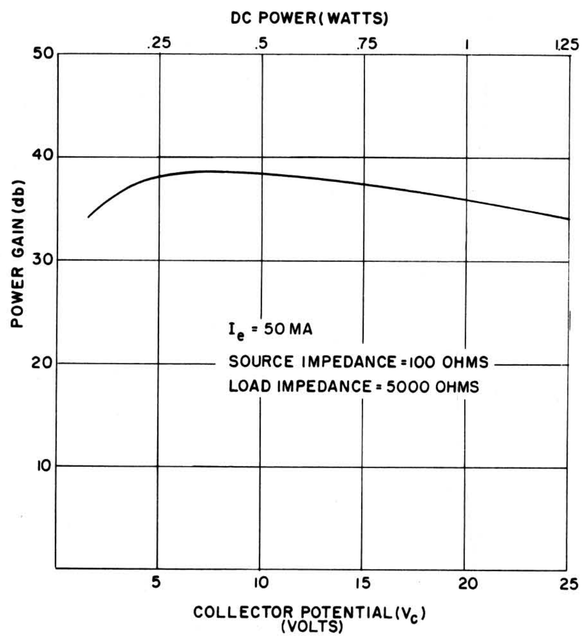

Fig. 8 - Small-signal power gain as a function of collector voltage with constant emitter current for n-p-n or p-n-p power transistors.

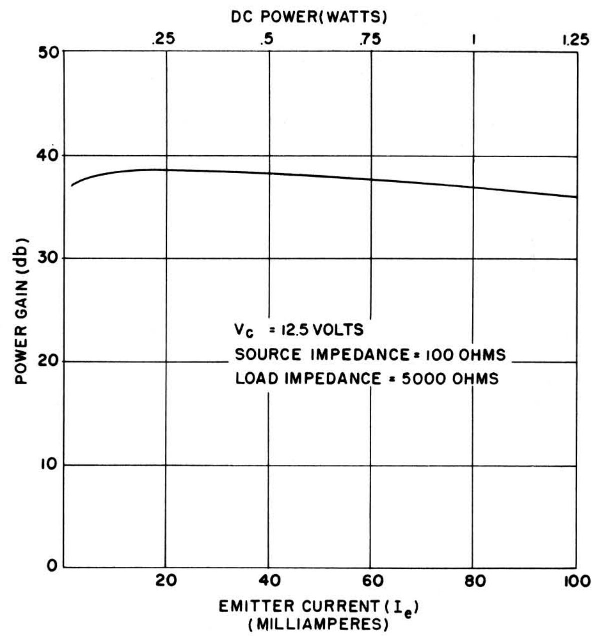

Fig. 9 - Small-signal power gain as a function of emitter current with constant collector voltage for n-p-n or p-n-p power transistors.

Table II

Performance Data

Unit	Collector Volts	Collector Milliamperes	ohms Load Resistance	mw Input Power	mw Output Power	db Power Gain
p-n-p	7.2	130	100	0.94	340	26
p-n-p	17	65	400	0.30	430	32
p-n-p	28	35	800	0.37	560	32
n-p-n	10.5	100	100	0.45	480	30
n-p-n	22	40	400	0.20	420	33

Of greater interest for power units is the behavior as a class A audio amplifier into loads giving reasonable audio outputs. With common emitter connection, constant-current d-c emitter supply and about one-watt d-c input to the collector, the data in Table II are presented as indicative of the performance obtained. In each case the input was increased to the point of 10 per cent distortion.

Life Performance

In a laboratory development, such as described in this bulletin it is frequently desirable to report results before all important aspects of transistor operation have been thoroughly investigated and explored. This is particularly true as regards life testing which must normally be extended over a protracted period.

Life tests at one watt dissipation on a few of the p-n-p type units have reached 1000 hours without failure at the time of writing. On the basis of limited life tests on n-p-n units it appears that results are variable. While some units have operated several hundred hours, others exhibit an aging effect which has resulted in early failure. The factors which contribute to such behavior are not yet fully understood and cannot be evaluated at this time.

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