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Present Status of Transistor Development

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The invention of the transistor provided a simple, apparently rugged device that could amplify—an ability in which the vacuum tube had long held a monopoly. As with most new electron devices, however, a number of extremely practical limitations had to be overcome before the transistor could be regarded as a practical circuit element. In particular: the reproducibility of units was poor—units intended to be alike were not interchangeable in circuits; the reliability was poor—in an uncomfortably large fraction of units made, the characteristics changed suddenly and inexplicably; and the "designability" was poor—it was difficult to make devices to the wide range of desirable characteristics needed in modern communications functions. This paper describes the progress that has been made in reducing these limitations and extending the range of performance and usefulness of transistors in communications systems. The conclusion is drawn that for some system functions, particularly those requiring extreme miniaturization in space and power as well as reliability with respect to life and ruggedness, transistors promise important advantages.

INTRODUCTION

When the transistor was announced not quite four years ago, it was felt that a new departure in communication techniques had come into view. Here was a mechanically simple device which could perform many of the amplification functions over which the electron tube had long held a near monopoly. The device was small, required no heater power, and was potentially very rugged; moreover, it consisted of materials which might be expected to last indefinitely long, and it did not appear to be too complicated to make.

However, as might be expected for a newly invented electron device, the practical realization of these promises still required the overcoming of a number of obstacles. While the operation of the first devices was well understood in a general way, several items were limiting and puzzling, for example:

a—Units intended to be alike varied considerably from each other—*the reproducibility was bad.*

b—In an uncomfortably large fraction of the exploratory devices, the properties changed suddenly and inexplicably with time and temperature, whereas other units exhibited extremely stable characteristics with regard to time—*the reliability was poor.*

c—It was difficult to use the theory and then existing undeveloped technology to develop and design devices to a varied range of electrical characteristics needed for different circuit functions. Performance characteristics were limited with respect to gain, noise figure, frequency range and power—*the designability was poor.*

Before the transistor could be regarded as a practical circuit element, it was necessary to find out the causes of these limitations, to understand the theory and develop the technology further in order to produce and control more desirable characteristics.

Over the past two years measurable progress has been made in reducing, *but not eliminating,* the three listed limitations.

These advances have been obtained through an improved understanding, improved processes and very importantly through improved germanium materials. As a result:

a—the beginnings of method have evolved in the use of the theory to explain and predict the electrical network characteristics of transistors in terms of physical structure and material properties.

b—It is now possible to evaluate some of the effects and physical meaning of empirically derived processes and thereby to devise better methods subject to control. Previously, inhomogeneities in the material properties masked the dependence of the transistor electrical properties even on bulk properties (such as resistivity) as well as on processing effects.

c—As a result, on an exploratory development level, it is now possible to make transistors in the laboratory to several sets of prescribed characteristics with usable tolerances and satisfactory yields.

d—Such transistors are greatly improved over the old ones in so far as life and ruggedness are concerned, and some reduction in temperature dependence has been achieved. However, it is not to be inferred that all reliability problems are solved.

e—It has become possible in the laboratory to explore experimentally some of the consequences of the theory with the result that point contact devices with new ranges of performance are indicated. Even more importantly, new p-n junction devices have been built in the laboratory and these junction devices have indicated an extension in several performance characteristics.

f—By having interchangeable and reliable devices with a wider range of characteristics, it has become possible to carry on exploratory circuit and system applications on a more realistic basis. Such applications effort is, in turn, stimulating the development of new devices towards new characteristics needed by these circuit and system studies.

It is the purpose of the remainder of this paper to give an over all but brief summary of recent progress made at Bell Telephone Laboratories in reducing the above-mentioned limitations on reproducibility, reliability and performance. Since a fair number of types of devices are currently under development, each with different characteristics to be optimized, the data will be presented as a sort of montage of characteristics of several different types of devices. It is not to be inferred that any one type of transistor combines all of the virtues any more than such a situation exists in the electron tube art. Moreover, it will be impossible in a paper of practical length to present complete detailed characteristics on all or even several of these devices under development; nor would it be appropriate since most of these data are on devices currently under development. Rather, what is desired, is a summary of progress across the board to give the reader an integrated and up-to-date picture of the current state of transistor electronics.

REPRODUCIBILITY STATUS

Description of Transistors

Before quantitative data comparing the characteristics of past with present transistors are presented, it will be useful to briefly review physical descriptions of the various types of transistors to be discussed. Fig. 1 shows a cutaway view of the now familiar point-contact cartridge type transistor. All of the early transistors were of this general construction and the characteristics of a particular one, called the Type A[1], will be used as a reference against which to measure results now obtainable with new types under current development. Fig. 2 is a semi-schematic picture of the physical operation of such a device. Pressing down upon the surface of a small die of n-type germanium are two rectifying metal electrodes, one labelled E for emitter, the other C for collector. A third electrode, the base, is a large area ohmic contact to the underside of the die of germanium. The emitter and collector electrodes obtain their

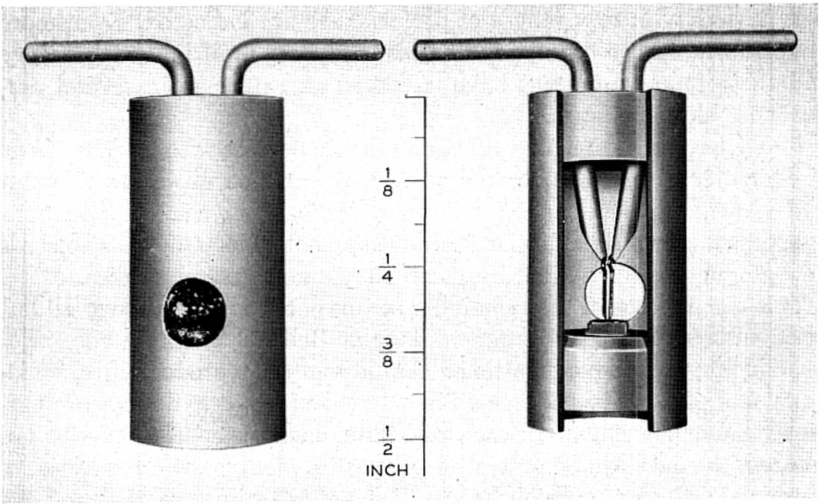

Fig. 1—The type A transistor structure.

rectifying properties as a result of the *p-n* barrier (indicated by the dotted lines) existing at the interface between the *n*-type bulk material and small *p*-type inserts under each point. When the collector is biased with a moderately large negative voltage (in the reverse direction) so that the collector barrier has relatively high impedance, a small amount of reverse current flows from the collector to the base in the form of electrons as indicated by the small black circles. Now, if the emitter is biased a few tenths of a volt positively in the forward direction, a current of holes (indicated by the small open circles) is injected from the

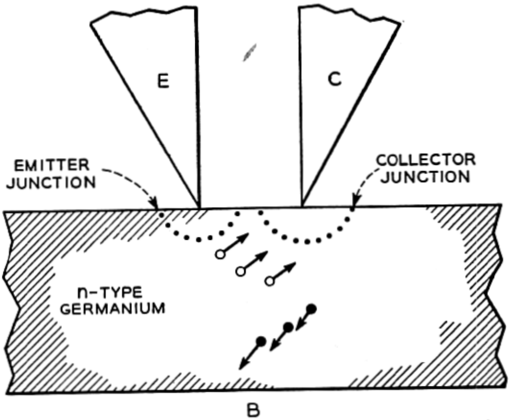

Fig. 2—Schematic diagram of a point-contact transistor.

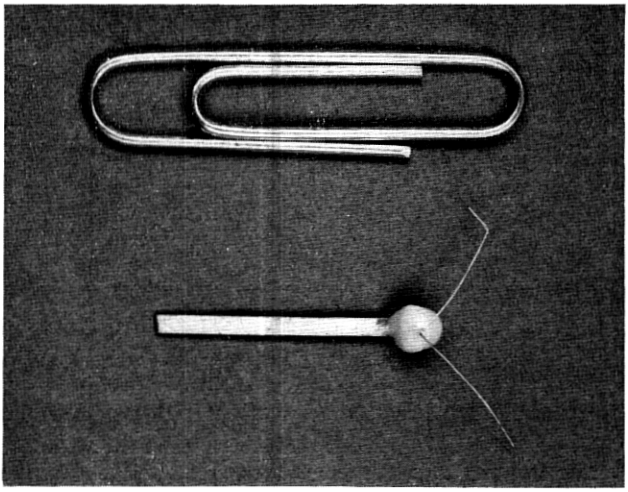

Fig. 3—The M1689 point-contact transistor is typical of those used in miniature packaged circuit functions.

emitter region into the n-type material. These holes are swept along to the collector under the influence of the field initially set up by the original collector electron current—thus adding a controlled increment of collector current. Because of their positive charge these holes can lower the potential barrier to electron flow from collector to base and thus allow several electrons to flow in the collector circuit for every hole entering the collector barrier region. This ratio of collector current change to emitter current change for fixed collector voltage is called alpha, the current gain. In point-contact transistors alpha may be larger than unity. Since the collector current flows through a high impedance when the emitter current is injected through a low impedance, voltage amplification is obtained as well.

Some of the new transistors are point-contact transistors similar in physical appearance to the type A. However, their electrical characteristics will be shown to be significantly improved not over the old type A only insofar as reproducibility and reliability are concerned, but also as to range of performance.

For use in miniature packaged circuit functions, the point contact transistor has been miniaturized to contain only its bare essentials. Fig. 3 is a photograph of a so-called "bead" transistor (compared to a paper clip for size) and several of the current development types are being made in this form.

In Fig. 4 is shown the family of static characteristics representative of the M1689 bead type transistor. Note in particular the collector

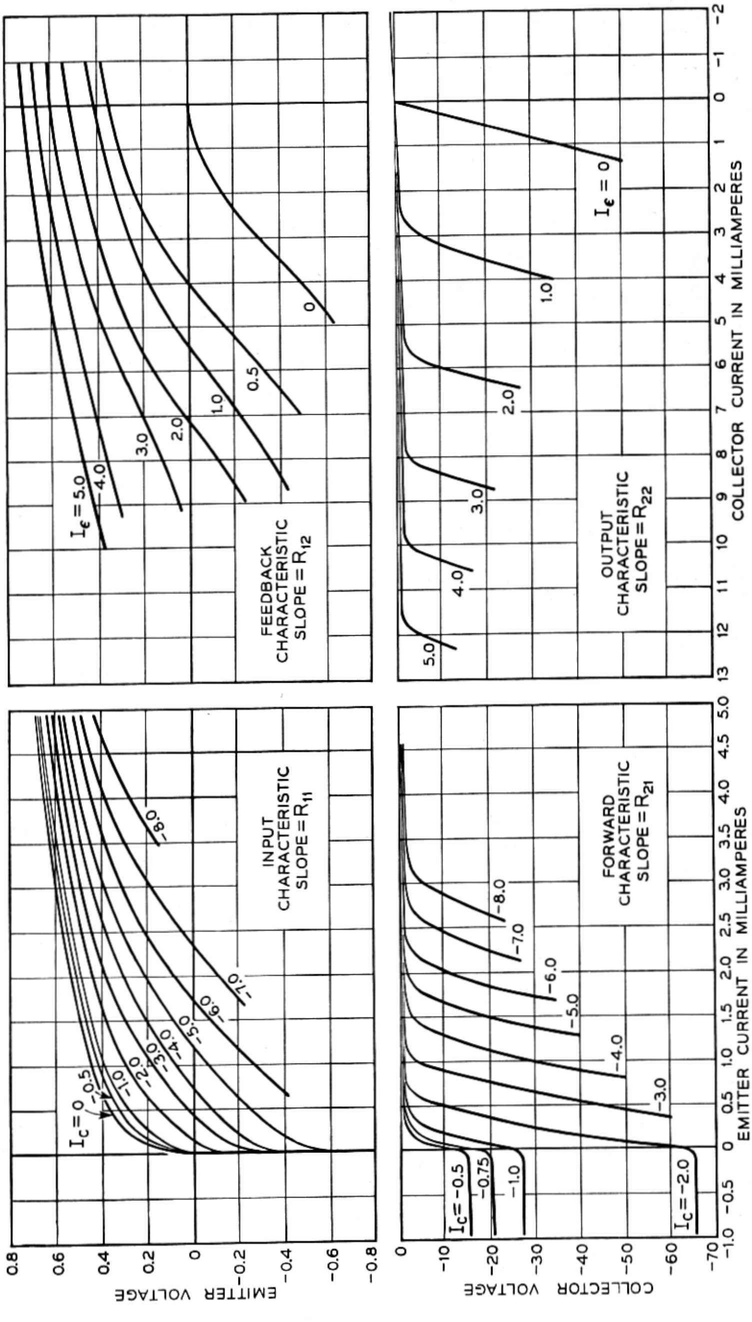

Fig. 4—Static characteristics of the M1689 transistor.

family which gives the dependence of collector voltage upon collector current with emitter current as parameter. These characteristics may be thought of as the dual to the plate family of a triode.[2] The slope of these curves is very nearly the small-signal ac collector impedance of the transistor.* For a fixed collector voltage of −20 volts, when the emitter current is changed from zero to one milliampere, note that the collector current correspondingly changes slightly more than two milliamperes, indicating a current gain, alpha, of slightly more than two.

Newest member of the transistor family recently described by Shockley, Sparks, Teal, Wallace and Pietenpol is the *n-p-n* junction transistor.[3, 4] Fig. 5 is a schematic diagram of such a structure. In the center of a bar of single crystal *n*-type germanium there is formed a thin layer

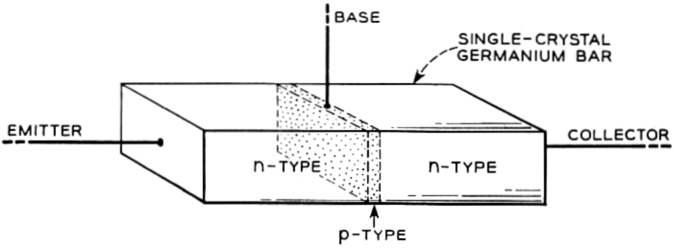

Fig. 5—The *n-p-n* junction transistor

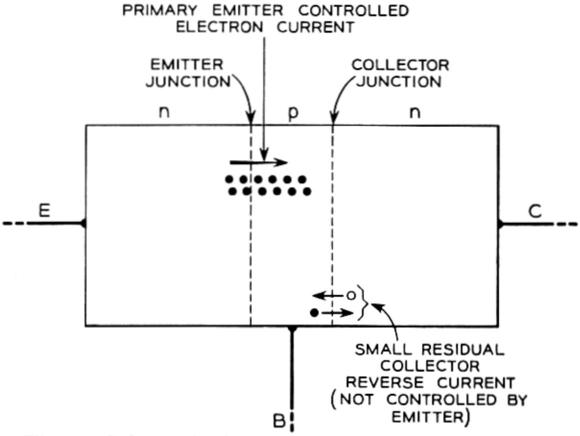

Fig. 6—Schematic diagram of a junction transistor.

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* As shown by Ryder and Kircher,[1] the ac collector impedance, $r_c = R_{22} - R_{12}$, where R_{22} is the open-circuited output impedance and R_{12} is the open-circuit feedback impedance. Usually, $R_{22} \gg R_{12}$.

of *p*-type germanium as part of the same single crystal. Ohmic non-rectifying contacts are securely fastened to the three regions as shown, one being labelled emitter, one base and one collector. In many simple respects, except for change in conductivity type from *p-n-p* in the point-contact (see Fig. 2) to *n-p-n* in the junction type, the essential behavior is similar.

As shown in Fig. 6, if the collector junction is biased in the reverse direction, i.e., electrode C biased positively with respect to electrode B, only a small residual back current of holes and electrons will diffuse across the collector barrier as indicated. However, unlike the point-contact device, this reverse current will be very much smaller and relatively independent of the collector voltage because the reverse impedance of such bulk barriers is so many times higher than that of the barriers produced near the surface in point-contact transistors. Now again, if the emitter barrier is biased in the forward direction, a few tenths of a volt negative with respect to the base is adequate, then a relatively large forward current of electrons will diffuse from the electron-rich *n*-type emitter body across the reduced emitter barrier into the base region. If the base region is adequately thin so that the injected electrons do not recombine in the *p*-type base region (either in bulk or on the surface), practically all of the injected emitter current can diffuse to the collector barrier; there they are swept through the collector barrier field and collected as an increment of controlled collector current. Hence, again, since the electrons were injected through the low forward impedance and collected through the very high reverse impedance of bulk type *p-n* barriers, very high voltage amplification will result. No current gain is possible in such a simple bulk structure and the maximum attainable value of alpha is unity. However, because the bulk barriers are so much better rectifiers than the point surface barriers, the ratio of collector reverse impedance to emitter forward impedance is many times greater, more than enough to offset the point-contact higher alpha; thus, the junction unit may have much larger gain per stage.[1, 3, 4] Fig. 7 is a photograph of a developmental model of such a junction transistor called the M1752.

The upper part of Fig. 8 is a collector family of static characteristics for the M1752 *n-p-n* junction transistor. By way of comparison to those of the point contact family, note the much higher reverse impedance of the collector barrier (relatively independent of collector voltage) and the correspondingly smaller collector currents when the emitter current is zero. In fact, Fig. 9 is an expanded plot of the lower left rectangle of the collector family of Fig. 8. The almost ideal straight-line character

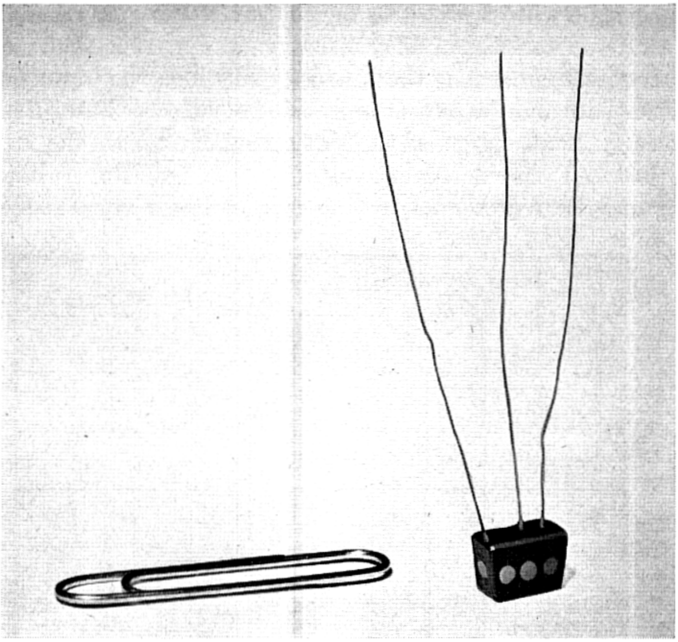


Fig. 7—The M1752 junction transistor.

and regular spacing of these curves persists down to voltages as low as 0.1 volt and currents of a few microamperes. Thus, essentially linear Class A amplification is possible for as little collector power as a few microwatts. Constant collector power dissipation curves of 10, 50 and 100 microwatts are shown dotted for reference.

Reproducibility of Linear Characteristics

In describing progress in the reproducibility of those transistor characteristics pertinent to small-signal linear applications, one possible method is to give the statistical averages and dispersions in the linear open-circuit impedances of the transistor as defined by Messrs. Ryder and Kircher.[1] Such a procedure, of course, implies a state of statistical control in the processes leading to a reasonably well behaved normal distribution for which averages and control limits can be defined. This situation can be said to be in effect for most transistors under current development.

However, for the old type A unit, control simply was not in evidence; so that in quoting figures on type A's, ranges for commensurate fractions of the total family will be given. In order that symbols and terminology will be clear, it will be useful to review briefly the method of defining the linear characteristics of all transistors. In Fig. 10 is shown a generalized network representing the transistor in which the input terminals are emitter-base and the output terminals are collector-base. Then, over a sufficiently small region of the static characteristics, the linear relations between the incremental emitter and collector voltages and currents may be represented by the pair of linear equations shown.[1]

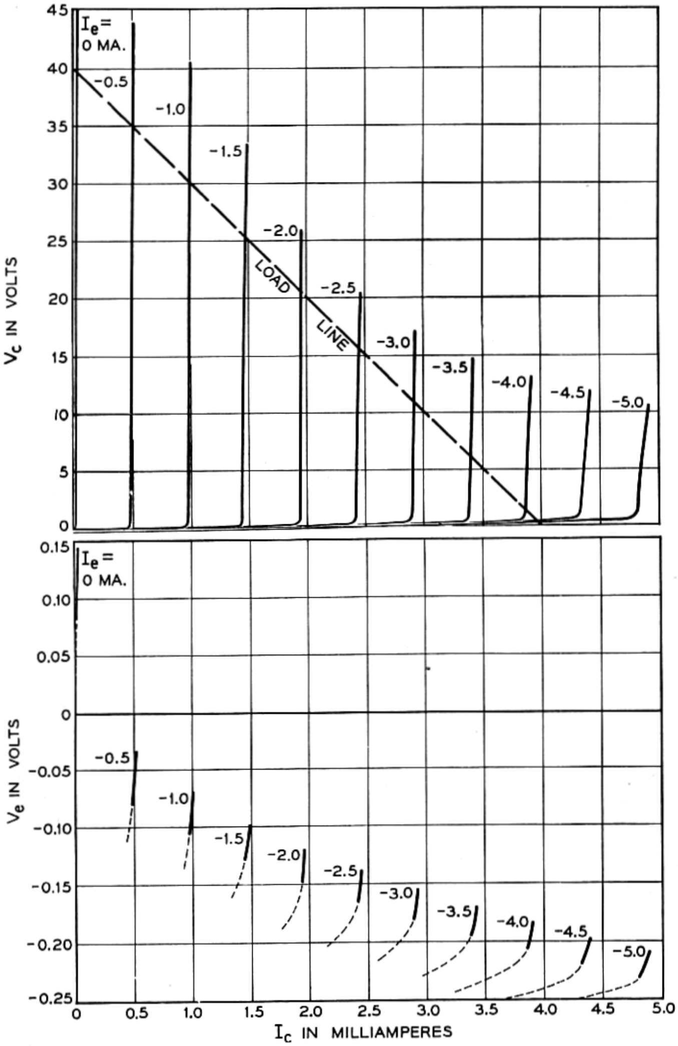


Fig. 8—Static characteristics of the M1752 junction transistor.

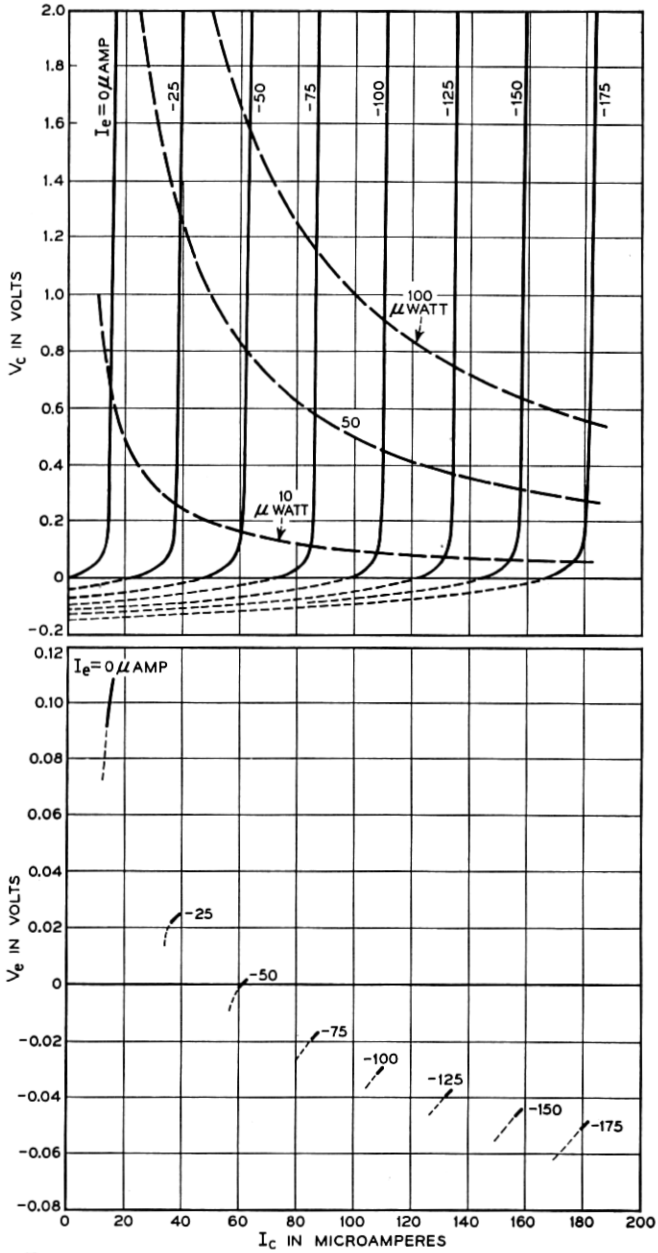
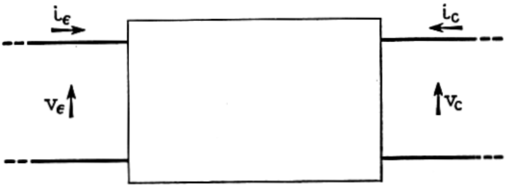


Fig. 9—Expanded plot of the microwatt region of the static characteristics of the M1752 transistor.

The coefficients are simply the open-circuit driving point and transfer impedances of the transistor, or the slopes of the appropriate static characteristics at fixed dc operating currents. These equations may be represented by any one of a large number of equivalent circuits of which the one shown in Fig. 11 is perhaps currently most useful. In this circuit r_e is very nearly the ac forward impedance of the emitter barrier, r_c is very nearly the ac reverse impedance of the collector barrier, r_b is the feedback impedance of the bulk germanium common to both, and a is the circuit current gain representing carrier collection and multiplication if any. It turns out this is very nearly equal to the current multiplication factor a of the collector barrier mentioned before. Average values of these elements for the type A transistor are given in Fig. 11. In Fig. 12 are given the ranges of these parameters for the type A as of September, 1949, and the control limits* for the same characteristics for new point-contact transistors now under development. For September, 1949, the ranges are taken about the average values shown in Fig. 11 for the type A transistor. The control limits given for the present situation apply to a number of different types of point contact transistors so that the present average values of these equivalent circuit elements depend upon the type of transistor considered. In Fig. 13 are given the average values of the characteristics of the M1729 point-contact video amplifier transistor which bears the closest resemblance to the older type A transistor. By way of contrast are given some typical values of the elements for the M1752 junction transistor which is not yet far enough along in its development to have design centers fixed nor reliable dispersion figures available.



$$v_\epsilon = i_\epsilon z_{11} + i_c z_{12}$$

$$v_c = i_\epsilon z_{21} + i_c z_{22}$$

Fig. 10—The general linear transistor.

As Ryder and Kircher have shown,[1] transistors in the grounded-base connection may be short-circuit unstable if $a > 1$ and r_b is too large,

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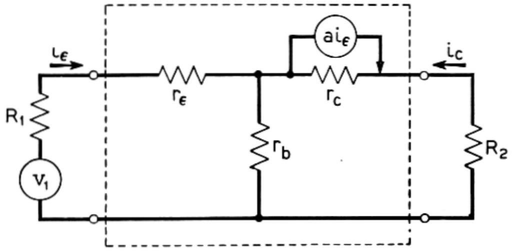
* A.S.T.M. Manual, "Quality Control of Materials," Jan. 1951, Part III, pp. 55–114.

since r_b appears as a positive feedback element. The curve in Fig. 14 is a plot of the short-circuit stability contour when r_e and r_c have the nominal values of 700 and 20,000 ohms. Transistors having a and r_b sufficiently large to place their representative points above this contour will be short-circuit unstable, i.e., they will oscillate when short-circuited. Those having an $a - r_b$ point below the stability contour will be unconditionally stable under any termination conditions. The large unshaded rectangle bounds those values of a and r_b, which were repre-



$\overline{r_\epsilon}$ = 250 OHMS $\overline{r_c}$ = 20,000 OHMS

$\overline{r_b}$ = 250 OHMS $\overline{a}$ = 2

Fig. 11—Equivalent circuit and average element values of the type A transistor.

ELEMENT	RANGE SEPTEMBER 1949	RANGE JANUARY 1952
a	4 : 1	±20 %
r_c	7 : 1	±30 %
r_ϵ	3 : 1	±20 %
r_b	7 : 1	±25 %

Fig. 12—Reproducibility of point-contact linear characteristics.

TYPE	M 1729	M 1752
r_ϵ	120	25
r_b	75	250
r_c	15,000	5×10^6
a	2.5	0.95

Fig. 13—Average characteristics of the M1729 and typical characteristics of the M1752 transistors.

sentative of the type A transistor in September, 1949. It is apparent that the circuit user of type A units had approximately a 50 per cent chance of obtaining a short-circuit unstable unit from a large family of type A units. The smaller shaded rectangle bounds the values of a and r_b now realized in the M1729 transistor presently under development. Not only has the spread in characteristics been greatly reduced as shown, but also the design centers have been moved to a region for which all members of the M1729 family are unconditionally stable.

It is of interest to note that spreads of the order of ±20 to ±25 per cent are of the same magnitude as those dispersions now existing amongst the characteristics of presently available well-controlled electron tubes. These kinds of data on reproducibility of the linear equivalent circuit element values hold for practically all classes of point-contact devices now under development for cw transmission service. While it is too early to prove that such a situation pertains as well to junction transistors, there is every reason to expect similar results after a suitable development period.

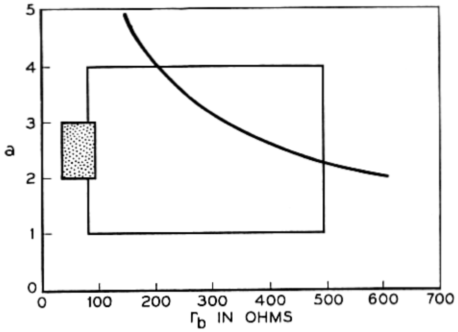


Fig. 14—Stability contour and ranges of a and r_b.

Reproducibility of Large-Signal Characteristics for Pulse Application

When electron devices are employed for large-signal applications, particularly those of switching and computing, it is well known that the characteristics must be controlled over a very broad range of variables from cutoff to saturation. In September, 1949, very little attempt was made to control such pulse use characteristics. In the intervening time, transistor circuit studies have proceeded to the point where it is possible to define certain necessary large scale transistor characteristics which, if met, permit such transistors to be used interchangeably and reproducibly in a variety of pulse circuit functions such as binary counters, bit registers, regenerative pulse amplifiers, pulse delay amplifiers, gated amplifiers and pulse generators. Moreover, it has been possible to meet these requirements on a developmental level with good yields in at least three types of point-contact switching transistors. The scope of this paper will not permit a detailed accounting of the technical features of this situation and such an account will be forthcoming in future papers on these particular studies. However, a brief description of some of the more important pulse characteristics and their tolerances is certainly pertinent.

In practically all of the transistor pulse handling circuits examined to date, one characteristic common to all is the ability of the transistor, by virtue of its current gain, to present various types of two-state negative resistance characteristics at any one or all of its pairs of terminals. A typical simple circuit and corresponding characteristic is shown in Fig. 15 for the emitter-ground terminals when a sufficiently large value of resistance is inserted in the base to make the circuit unstable. In region I where the emitter is negative, the input resistance is essentially the reverse characteristic of the emitter as a simple diode. In region II as the emitter goes positive, alpha, the current gain rises rapidly above unity. If R_b is sufficiently large and alpha, the current gain, is greater

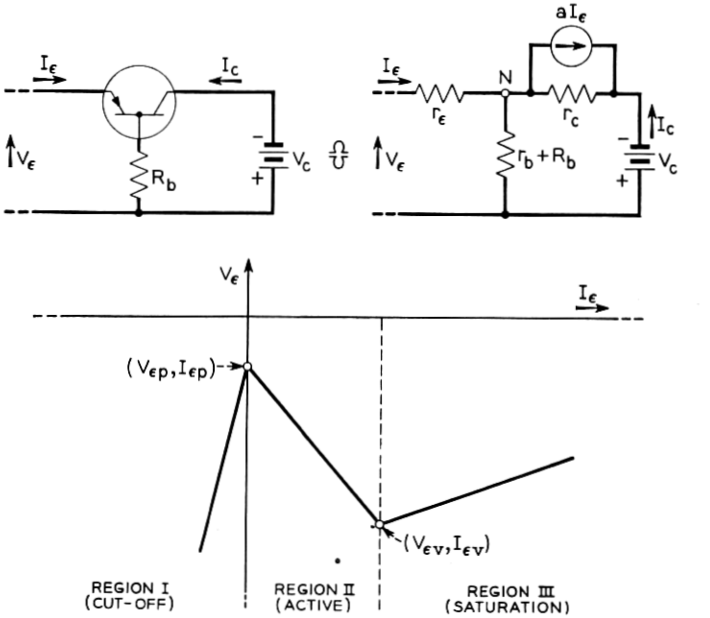


Fig. 15—Emitter-ground negative resistance circuit and characteristic.

than unity the emitter to ground voltage will begin to fall because of the larger collector current increments driving the voltage of the node N negative more rapidly than the emitter current drop through r_e would normally carry it. This transition point is called the peak point. If then $\alpha(r_b + R_b)$ is sufficiently large, in this sense, the input resistance may be negative in this region II. When the internal node voltage has fallen to a value near that of the collector terminal the "valley point" has been reached. At this point, the emitted hole current has reduced the collector impedance to a minimum value beyond which a is essentially zero; the transistor is said to be saturated. From this point on the input impedance again becomes positive and is determined almost entirely by the base and emitter impedances. By terminating the emitter-ground terminals in various ways with resistor-capacitor-bias combinations, such a network can be made to perform monostable, astable or bistable functions. Under such conditions, the emitter current and correspondingly the collector current switch back and forth between cutoff and saturation values. For example, in Fig. 16 is shown a value of emitter bias and load resistance such that there are three possible equilibrium values of emitter current and voltage. It may be shown that the two intersections in regions I and III are stable whereas that in region II is unstable. Hence, if the stable equilibrium is originally in I, a small positive pulse Δ_p applied to the emitter will be enough to switch from stable point I to stable point II and conversely, $-\Delta_v$ will carry it from the high current point to the low current point. The circuit designer is interested in reproducing in a given circuit (with different transistors of the same type) the following points of the characteristic:

a—The off impedance of the emitter—he desires that this be greater than a certain minimum.

b—The peak point V_{ep}—he desires that this be smaller than a certain maximum.

c—The value of the negative resistance—he desires that this be greater than a certain minimum.

d—The valley point V_{es}, I_{es}—he desires that these be greater than certain minima, and

e—The slope in region III—he desires that this be smaller than a certain maximum so that he may control it by external means.

It may be shown that these conditions can be satisfied for useful circuits by specifying certain maximum and minimum boundaries on the static characteristics. Fig. 17 is an idealized set of input or emitter characteristics. By specifying a minimum value for the reverse resistance in region I, condition (a) above is satisfied. By specifying a maximum slope in region II and III, condition (e) is satisfied. Now refer to the idealized collector family in Fig. 18; by specifying a maximum value to V_{C3}, it is possible to insure condition (d) and by specifying a minimum value for r_{co}, condition (b) can be satisfied. Finally, in Fig. 19 by de-

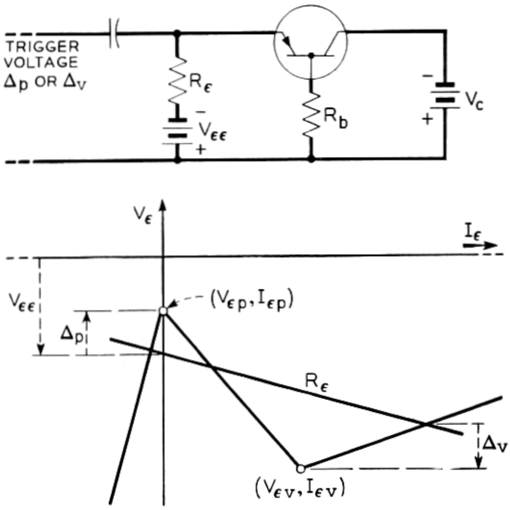


Fig. 16—Bistable circuit and characteristics showing trigger voltage requirements.

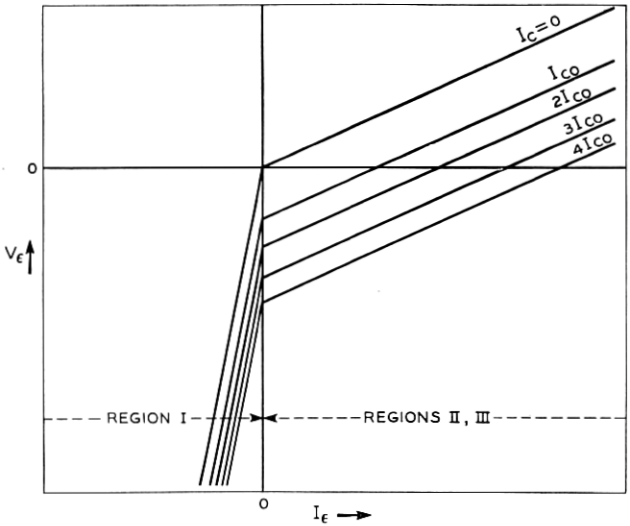


Fig. 17—Idealized emitter characteristics — slope = R_{11}.

manding that alpha, as a function of I_e, go through a transition from a negligible value (at small negative I_e) to a value well in excess of unity (at a correspondingly small positive value of I_e) and maintain its value well in excess of unity at large values of I_e, conditions (b) and (c) can be met.

In Fig. 20 are given the characteristic specifications which must be met by the M1689 bead type switching transistor now under development. With these kinds of limits, circuit users find it possible to interchange such M1689 units in various pulse circuits and obtain overall circuit behavior reproducible to the order of about ±2 db.

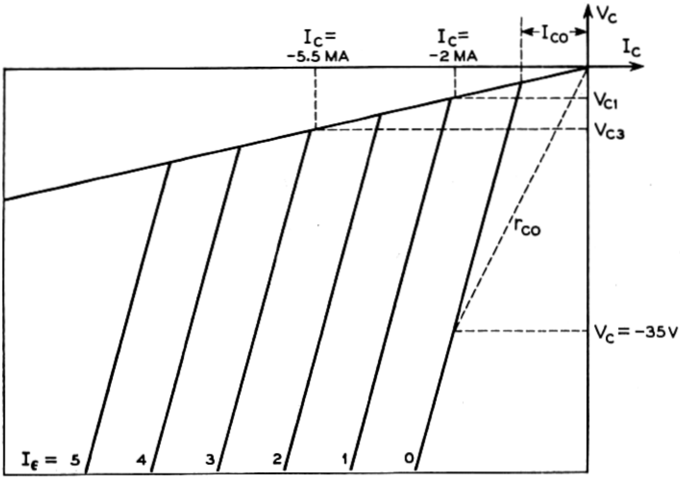


Fig. 18—Idealized collector characteristics.

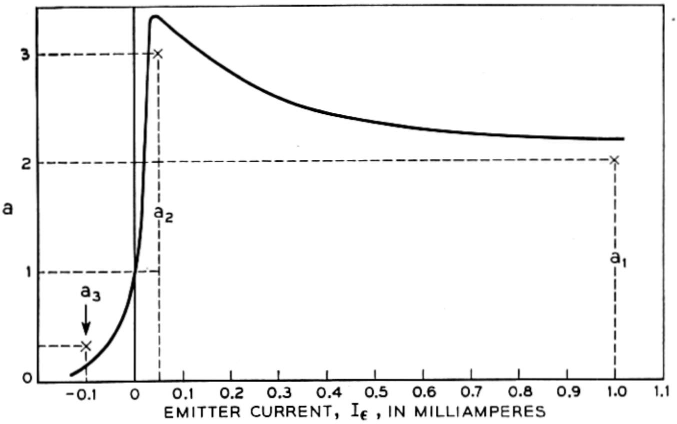


Fig. 19— Effective alpha characteristic.

TEST	CONDITIONS	MINIMUM	MAXIMUM
r_{co} – OFF COLLECTOR DC RESISTANCE	$V_c = -35$ V DC $I_\epsilon = 0$ MA DC	17,500 OHMS	—
V_{c1} – ON COLLECTOR VOLTAGE	$I_c = -2$ MA DC $I_\epsilon = 1$ MA DC	—	−3V DC
V_{c3} – ON COLLECTOR VOLTAGE	$I_c = -5.5$ MA DC $I_\epsilon = 3$ MA DC	—	−4V DC
OFF EMITTER RESISTANCE	$V_c = -10$ V DC	50,000 OHMS	—
ON EMITTER RESISTANCE R_{11}	$V_c = -10$ V DC $I_\epsilon = 1$ MA DC	—	800 OHMS
a_1	$V_c = -30$ V DC $I_\epsilon = 1.0$ MA DC	1.5	—
a_2	$V_c = -30$ V DC $I_\epsilon = +0.05$ MA DC	2.0	—
a_3	$V_c = -30$ V DC $I_\epsilon = -0.1$ MA DC	—	0.3
R_{12} – OPEN CIRCUIT FEEDBACK RESISTANCE	$V_c = -10$ V DC $I_\epsilon = +1$ MA DC	—	500 OHMS
R_{21} – OPEN CIRCUIT FORWARD RESISTANCE	$V_c = -10$ V DC $I_\epsilon = +1$ MA DC	15,000 OHMS	—
R_{22} – OPEN CIRCUIT OUTPUT RESISTANCE	$V_c = -10$ V DC $I_\epsilon = +1$ MA DC	10,000 OHMS	—

Fig. 20—Tentative characteristics for the M1689 switching transistor.

RELIABILITY FIGURE OF MERIT	SEPTEMBER 1949	JANUARY 1952
AVERAGE LIFE	≐ 10,000 HOURS	> 70,000 HOURS
EQUIVALENT TEMPERATURE COEFFICIENT OF r_c	−1% PER DEG C	−¼% PER DEG C
SHOCK	?	> 20,000 G
VIBRATION	?	20–5000 CPS NEGLIGIBLE TO 100 G

Fig. 21—Reliability status.

RELIABILITY STATUS

Life

Reliability figures of merit are not too well defined for electron tubes and the same situation certainly holds at present for transistors. However, insofar as these quantities can be presently defined, Fig. 21 shows a comparison between the present status and that in September, 1949. Estimates of the half-life of a statistical family of devices are at best arbitrary and necessarily amount to extrapolations of survival curves assuming that a known survival law will continue to hold.* In September, 1949, life tests on type A units had been in effect some 4000 hours. With the assumption of an exponential survival law, it was not possible, on the basis of a 4000 hour test, to estimate the slope sufficiently accurately to warrant a half-life estimate in excess of 10,000 hours. These same type A units have now run on life test for approximately 20,000 hours. With the more reliable estimate of survival slope now possible, the half-life is now estimated to be somewhat in excess of 70,000 hours. It should be emphasized, however, that these are type A units of more than two years ago made with inferior materials and processes. It is believed that those units under current development, being made with new materials and processes, are superior; but, of course, life tests are only a few thousand hours old. Although these new data are encouraging, it is still too early to extrapolate the data such a long way.

Temperature Effects

Transistors like other semiconductor devices are more sensitive to temperature variations than electron tubes. In terms of the linear equivalent circuit elements, the collector impedance, r_c, and the current gain, a are the most sensitive. Over the range from $-40°$C to 80°C the other elements are relatively much less sensitive. For type A transistors these temperature variations in r_c and a are shown in Fig. 22. While these curves are definitely not linear, an average temperature coefficient for r_c of about -1 per cent per degree was estimated for the purpose of easy tabulation and comparison in Fig. 21.

Thus, for the early type A, r_c fell off to about 20 to 30 per cent of its room temperature value when the temperature was raised to $+80°$ C; at the same time a increased from 20 to 30 per cent over the same temperature range. Today, this variation has been reduced by a factor of about four for r_c in most point-contact types, the variations in the current gain being relatively unchanged. Fig. 23 illustrates the temperature dependence of r_c and a for the M1729 transistor now under development. Again, for purposes of easy comparison in Fig. 21, the actual dependence of Fig. 23 was approximated by a linear variation and

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* Estimates of life, of course, depend upon definitions of "death". For these experiments, the transistors were operated as Class A amplifiers. A transistor is said to have failed when its Class A gain has fallen 3 db or more below its starting value.

only the slope given in Fig. 21. For linear applications such as the grounded base amplifier, the Class A power gain is approximately proportional to $a^2 r_c$; hence the gain of such an amplifier will stay essentially constant within a db or two over the temperature range from -40°C to $+80$°C. For pulse applications, and of importance to dc biasing with point-contact transistors, is the fact that the dc collector current (for fixed emitter current and collector voltage) will change at about the

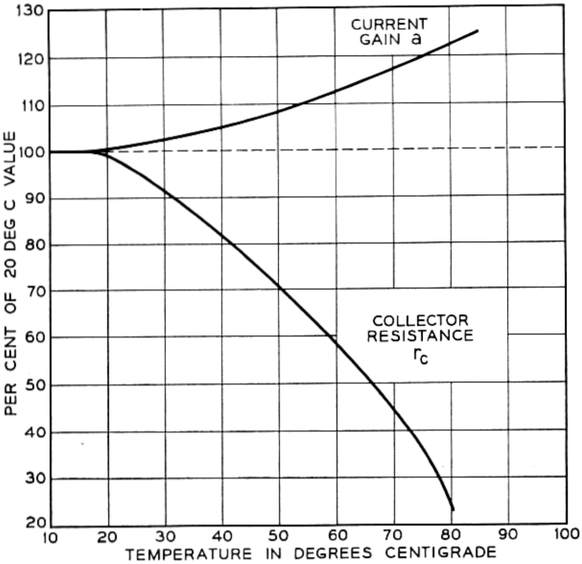

Fig. 22—Collector resistance and a versus temperature for type A transistor

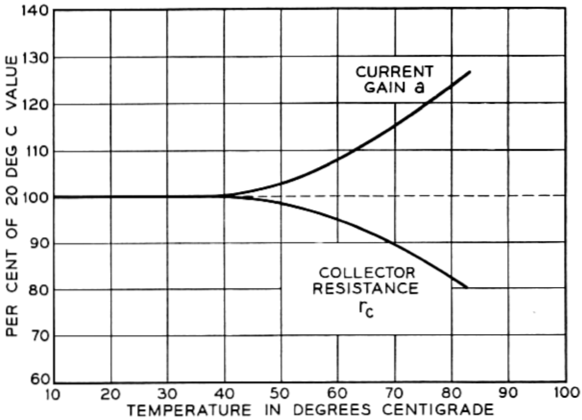

Fig. 23—Collector resistance and a versus temperature for type M1729 transistor.

same rate as does r_c, the small signal collector impedance. Similar improvements have been made in these variations for switching transistors and Fig. 24 is a series of graphs showing how the M1689 bead type switching transistor changes the pulse characteristics defined in Fig. 20 with respect to temperature. For those switching functions examined to date, it is believed that these data mean reliable operation to as high as +70°C in most applications and perhaps as high as +80°C in others.

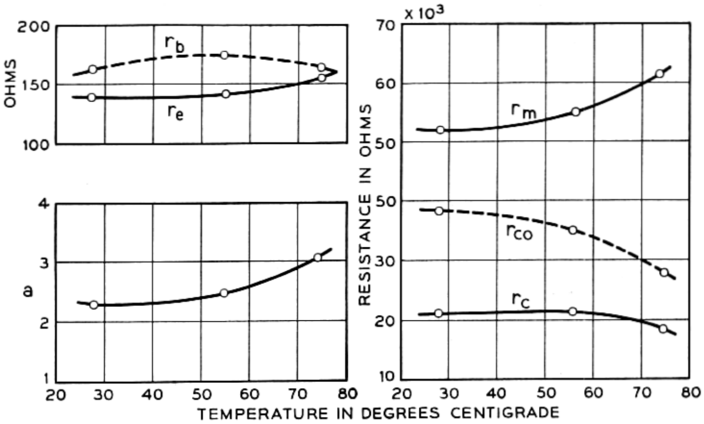

Fig. 24—Temperature behavior of the M1689 transistor.

In junction transistors the laws of temperature variation are not so well established, the device being in a much earlier stage of development. Preliminary data indicate smaller variations in the small signal parameters such as a and r_c. On the other hand, variations in the dc current, particularly I_{co}, are many times greater, of the order of 10 per cent per degree centigrade.* The only saving grace here is the fact that I_{co} is normally very much less than the actual operating value of I_c.

In summary, it may be said that while significant improvements have been made in temperature dependence to the point where many applications appear feasible, it is not to be inferred that the temperature limitation is completely overcome. Much more development work of device, circuit and system nature is required to bring this aspect of reliable operation to a completely satisfying solution.

Shock and Vibration

With regard to mechanical ruggedness, current point-contact transistors have been shock tested up to 20,000 g with no change in their

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* I_{co} is the collector current at zero emitter current.

electrical characteristics. Vibration of point-contact and junction transistors over the frequency range from 20 to 5000 cps at accelerations of 100g produces no detectable modulation of any of the transistor electrical characteristics, i.e., such modulation, if it exists, is far below the inherent noise level. At a few spot frequencies in the audio range, vibration tests up to 1000g accelerations similarly failed to produce discernible modulation of the transistor characteristics.

MINIATURIZATION FIGURE OF MERIT	TYPE A SEPTEMBER 1949	JANUARY 1952	NEW DEVELOPMENT TYPE
VOLUME	$\frac{1}{50}$ IN^3	$\frac{1}{2000}$ IN^3	POINT - M1689
		$\frac{1}{500}$ IN^3	JUNCTION - M1752
MINIMUM COLLECTOR VOLTAGE FOR CLASS A OPERATION	30 V	2 V	POINT - M1768, M1734
		0.2 V	JUNCTION - M1752
MINIMUM COLLECTOR POWER FOR CLASS A OPERATION	50 MW	2 MW	POINT - M1768
		10 μW	JUNCTION - M1752
CLASS A EFFICIENCY	20 %	35 %	POINT - M1768, M1729
		49 %	JUNCTION - M1752

Fig. 25—Miniaturization in space and power drain.

MINIATURIZATION STATUS

Space Requirements

In smallness of size, the transistor is entering new fields previously inaccessible to electron devices. The cartridge structure (see Fig. 25), such as the type A, has a volume of $\frac{1}{50}$ cubic inch, compared to about $\frac{1}{8}$ cubic inch for a sub-miniature tube and about 1 cubic inch for a miniature tube. Under current development, the M1689 bead point-contact transistor has substantially similar electrical characteristics to the M1698* cartridge switching unit but occupies only about $\frac{1}{2000}$ cubic inch. The M1752 junction bead transistor has a volume of approximately $\frac{1}{500}$ cubic inch but this may be reduced to the same order as the point-contact bead if necessary. For further substantial size reductions in equipment, the next move must comprise the passive components. It should be pointed out that the low voltages, low power drain, and correspondingly lower equipment temperatures should make possible further reductions in passive component size.

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* The M1698 transistor is a cartridge type point-contact transistor with electrical characteristics designed for switching and pulse applications. This unit is proving useful in the laboratory development of new circuits or in cases where miniature packages are unnecessary.

Power Requirements

The transistor, of course, has the inherent advantage of requiring no heater power; moreover, significant advances have been made in the past two years in reducing the collector voltage and power required for practical operation. Consider the minimum collector voltage for which the small-signal Class A gain is still within 3 to 6 db of its full value. In September, 1949, the type A transistor could give useful gains at collector voltages as low as 30 volts. Today, several point-contact devices (M1768 and M1734) perform well with collector voltages as low as 2 to 6 volts even for relatively high-frequency operation. One junction transistor, the M1752, can deliver useful gains at collector voltages as low as 0.2 to 1.0 volt. Under these same conditions, the minimum collector power for useful gains may be as low as 2–10 mw for point-contact devices and as low as 10 to 100 μw in the case of the junction transistors.* Class A efficiencies have been raised for the point-contact devices to as high as 30–35 per cent and for junction transistors this may be as high as 49 per cent out of a maximum possible 50 per cent. Class B and C efficiencies are correspondingly close to their theoretical limiting values.

PERFORMANCE STATUS

Exact electrical performance specifications for the transistor depend, of course, upon the intended applications and the type of transistor being developed for such an application. These types are beginning to be specified; and in fact, they are already so numerous that mention of only a few salient features of some of them will be attempted. Bear in mind, as was pointed out before, that no one transistor combines all the virtues any more than does any one tube type. Fig. 26 attempts to compare the progress made in several important performance merit figures by development of several point-contact and junction types during the last two years. Again the reference performance is that of the type A as of September, 1949.

Some switching and transmission applications need transistors having high current gain. By going to a point-junction structure, useful values of alpha as high as 50 are now possible with laboratory models.

For straight transmission applications, the single stage gain of point-contact types (M1768, M1729) has been increased to 20–24 db, whereas for the M1752 junction type the single stage gain may be as high as 45–50 db.

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* In some special cases, depending upon the application, practical operation may be obtained for as little as 0.1 to 1.0 microwatt.

PERFORMANCE FIGURE OF MERIT	TYPE A SEPTEMBER 1949	JANUARY 1952	NEW DEVELOPMENT TYPE
a - CURRENT GAIN	5 X	50 X	JUNCTION
SINGLE STAGE CLASS A GAIN	18 DB	22 DB	POINT - M1729, M1768
		45 DB	JUNCTION - M1752
NOISE FIGURE AT 1000 CPS	60 DB	45 DB	POINT - M1768
		10 DB	JUNCTION - M1752
FREQUENCY RESPONSE f_c	5 MC	7-10 MC	POINT - M1729
		20-50 MC	POINT - M1734
CLASS A POWER OUTPUT	0.5 WATT	2 WATTS	JUNCTION
SWITCHING CHARACTERISTICS	NONE	GOOD	POINT - M1698, M1689 M1734
FEEDBACK RESISTANCE r_b	250 OHMS	70 OHMS	POINT - M1729
$\frac{\text{LIGHT}}{\text{DARK}}$ PHOTOCURRENT RATIO	2:1	20:1	JUNCTION - M1740

Fig. 26—Performance progress.

For high-sensitivity low-noise applications, the point-contact devices have been improved to have noise figures of only about 40–45 db, whereas the M1752 *n-p-n* transistor has been shown to have noise figures in the 10–20 db range. All such noise figures are specified at 1000 cps and it should be remembered that they vary inversely with frequency at the rate of about 11 db per decade change in frequency.

For video, I.F., and high-speed switching applications, measurable improvement has been attained in the frequency response. For video amplifiers up to about 7 mc, the M1729 point-contact transistor is capable of about 18-20 db gain per stage. For high-frequency oscillators and microsecond pulse switching, the M1734 point-contact transistor is under development. Preliminary models of 24 mc I.F. amplifiers using the M1734 have been constructed in the laboratory, these amplifiers having a gain of some 18–24 db per stage and a band-width of several megacycles. However, more work needs to be done on the M1734 to reduce its feedback resistance. For pulse-handling functions, such M1734 units work very nicely as pulse generators and amplifiers of $\frac{1}{2}$ microsecond pulses, requiring only 6–8 volts of collector voltage and 12–20 mw of collector power per stage. The amplified pulses can have amplitudes as large as 4–5 volts out of a total collector voltage of 6 volts and rise times as little as 0.01–0.02 microsecond.

By increasing the thermal dissipation limits of junction transistors, the Class A power output has been raised to 2 watts in laboratory models. This, however, does not represent an intrinsic upper limit but rather a design objective for a particular application.

Characteristics suitable for switching are now available in the M1698, M1689 and M1734 point-contact types, as previously described, but this is a continually evolving process and more work certainly remains to be done. At present it is possible to operate telephone relays requiring as much as 50 to 100 ma with M1689 and M1698 point-contact transistors.

New junction-type phototransistors[5] represent a marked advance over the earlier point-contact type.[6] While their quantum efficiencies are not as high as those of the point-contact types, nevertheless the light/dark current ratios are greatly improved and the collector impedance has been raised 10–100 times thus making possible much greater output voltages for the same light flux.

SOME SELECTED APPLICATIONS

Data Transmission Packages

To determine the feasibility of applying transistors in the form of miniature packaged circuit functions, several of the major system functions of a pulse code data transmission system have been studied. This investigation has been undertaken under the auspices of a joint services engineering contract administered by the Signal Corps.

It was desired that these studies should lead to the feasibility development of unitized functional packages combining features of miniaturization, reliability and lower power drain. Accordingly, it was necessary to carry on in an integrated fashion activities in the fields of system, circuit and device development to achieve these ends. In particular, circuit and system means have been developed to perform with transistors the functions of encoding, translation, counting, registering and serial addition. The M1728 junction diode, M1740 junction photocell and M1689 bead switching transistor are direct outgrowths of this program and are the devices used in the circuit packages.

At this point, the major system functions shown in Fig. 27 have been achieved with interchangeable transistors. These major system functions are in turn built up of some seven types of smaller functional packages listed in Fig. 28. The end result of this exploratory development can be said to have demonstrated the feasibility of such a data transmission system in the sense that a workable (though not yet optimal) system can be synthesized from reproducible transistor-circuit packages which have been produced at reasonable yields and with reasonable (though not yet complete) service reliability. Further development work would be needed in all phases to make such a system of packages suitable for field use. It is estimated that the present laboratory model requires about one-tenth the space and power required to do the same job with present tube art. Fig. 29 is a photograph of a transistor bit-register package and Fig. 30 is another photograph of such packages showing both sides of the various types employed.* Actual final packages would

1. 4 DIGIT REVERSIBLE BINARY COUNTER
2. 6 DIGIT ANGULAR POSITION ENCODER
3. 6 DIGIT GRAY-BINARY TRANSLATOR
4. 5 DIGIT SHIFT REGISTER
5. 2 WORD SERIAL ADDER

Fig. 27—System functions tested.

DEVELOPMENT PACKAGE TYPE	PACKAGE FUNCTION	DEVELOPMENT TRANSISTOR, DIODE TYPES USED
M 1731-1	REGENERATIVE GATE	M 1689 M 1727
M 1732-1 M 1736 M 1790	BIT REGISTER	M 1689 M 1727 M 1734
M 1733-1 M 1792	PULSE AMPLIFIER	M 1689
M 1735-1 M 1747-1 M 1748-1 M 1751-1 M 1751-2 M 1751-3	DIODE GATE	M 1727 400 A
M 1745-1 M 1791	BINARY COUNTER	M 1689 400 A
M 1749-1	PHOTOCELL READOUT	M 1740
M 1746-1	DELAY AMPLIFIER	M 1689

Fig. 28—Development transistor—circuit packages.

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* The Auto-Assembly Process used in the construction of these packages is a Signal Corps Development.

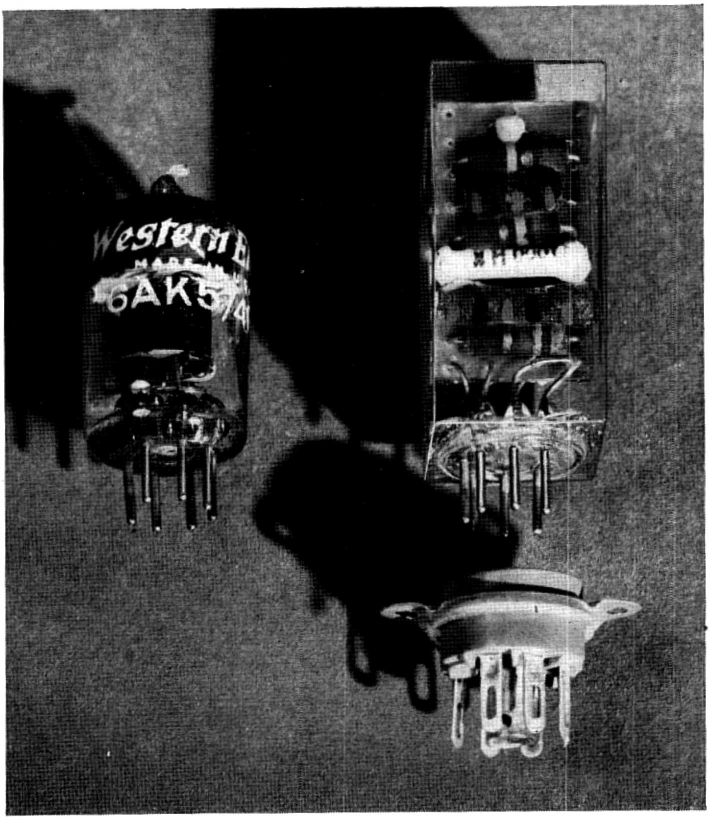

Fig. 29—Bit register package.

probably not use such clear plastics and Fig. 31 shows some packages in which the plastic has been loaded with silica to increase its strength and thermal conductivity. The assembly in Fig. 31 consists of a six-digit position encoder at the left, followed by six regenerative pulse amplifiers which in turn feed a six-digit combined translator-shift register.

N-P-N *Transistor Audio Amplifier and Oscillator**

To the right in Fig. 32 is shown a transformer-coupled audio amplifier employing two M1752 junction transistors. This amplifier has a pass band from 100–20,000 cps and a power gain of approximately 90 db. Its gain is relatively independent of collector voltage from 1–20 volts,

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* The material of this section represents a summary of some work by Wallace and Pietenpol described more completely in Ref. 4.

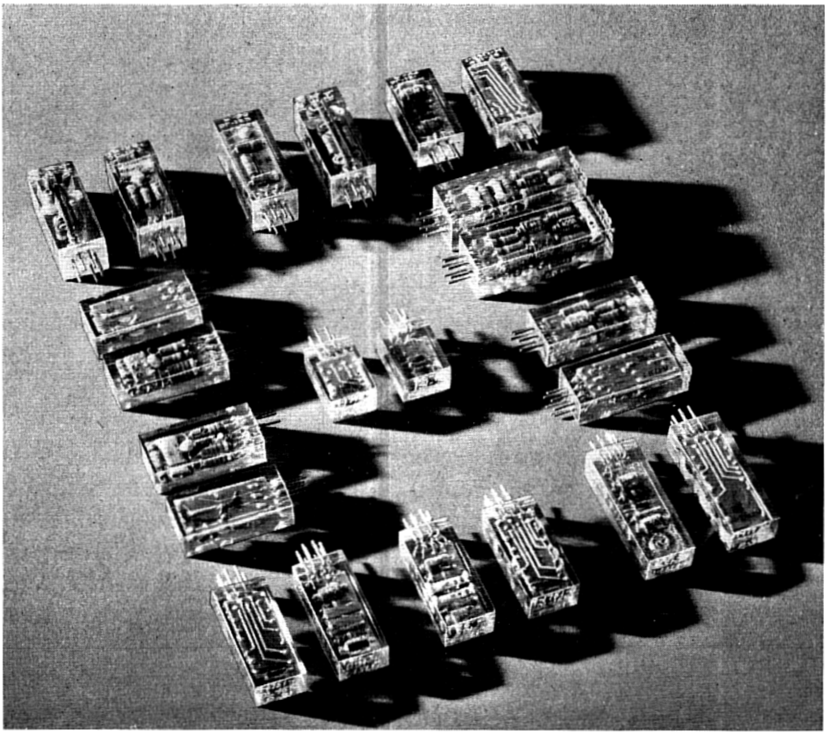

Fig. 30—Package construction illustrated.

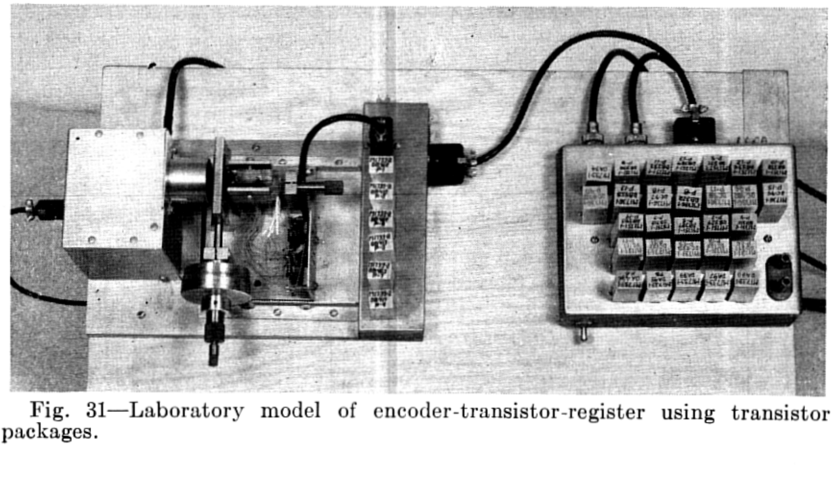

Fig. 31—Laboratory model of encoder-transistor-register using transistor packages.

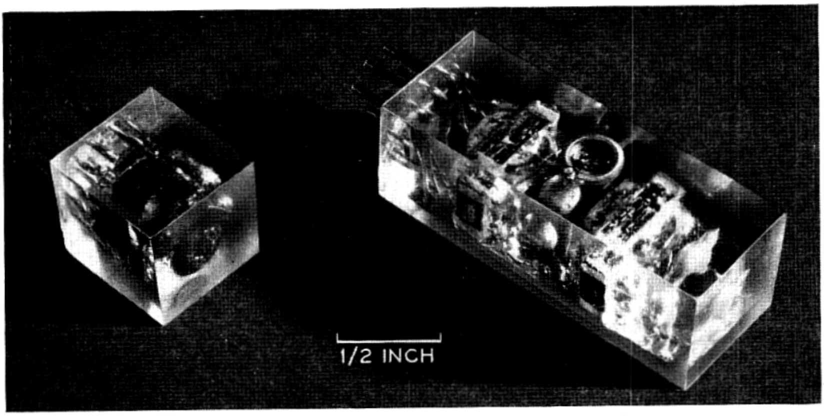

Fig. 32—Packaged oscillator and amplifier using junction transistors.

only the available undistorted power output increasing as the voltage is increased. At a collector voltage of 1.5 volts it draws a collector current of approximately 0.5 ma per unit for a total power drain of 1.5 milliwatts. Under these conditions it will deliver Class A power output of about 0.7 milliwatt. The noise figure of such an amplifier has been measured to be in the range from 10–15 db at 1000 cps depending upon the operating biases.

To the left of Fig. 32 is shown a small transistor audio oscillator having a single M1752 transistor, a transformer and one condenser. To see just how little power was the minimum necessary to produce stable oscillations such an oscillator was tried at increasingly lower collector supply voltages. It was found that stable oscillations could be maintained down to collector supply voltages as low as 55 millivolts and collector current as low as 1.5 microamperes for a total drain of 0.09 microwatt.

SUMMARY

With respect to reproducibility and interchangeability, transistors now under development appear to be the equal of commercial vacuum tubes.

With regard to reliability, transistors apparently have longer life and greater mechanical ruggedness to withstand shock and vibration than most vacuum tubes. With regard to temperature effects, transistors are inferior to tubes and present upper limits of operation are 70–80°C for most applications. This restriction is often reduced in importance by the lower power consumption which results in low equipment self-heating. This, however, is the outstanding reliability defect of transistors.

With regard to miniaturization, the comparison figures are so great as to speak for themselves. Operation with a few milliwatts is always feasible and in some cases operation at a few microwatts is also possible.

With regard to performance range, it is believed that the above results imply the following tentative conclusions:

In pulse systems (up to 1–2 mc repetition rates) transistors should be considered seriously in comparison to tubes, since they provide essentially equal functional performance and have marked superiority in miniature space and power. Bear in mind that in some reliability figures they are superior whereas in the matter of temperature dependence they are inferior to tubes.

In CW transmission at low frequencies (<1 mc) essentially the same conclusions are indicated, primarily because of junction transistors. In the range from 1–100 mc, tubes are currently superior in every functional performance figure (except perhaps noise and bandwidth) so that for transistors to be considered for such applications, much greater premium must be placed on miniaturization and reliability than for the first two applications areas.

Thus, it might be assumed that, even though there are many outstanding development problems of a circuit and device nature to be solved, it is appropriate for circuit engineers to explore seriously the application possibilities of transistors—not only in the hope of building better systems, but also to influence transistor development towards those most important systems for which their intrinsic potentialities best fit them. It should not be inferred that all important limitations have been eliminated—nor, on the other hand, that the full range of performance possibilities have been explored.

If one remembers the history of engineering research and development in older related fields, it seems apparent that a relatively short time has elapsed since the invention of the first point-contact transistor. Already, new properties and new types of devices are under study and some have been achieved in the laboratory. It therefore is possible, and certainly stimulating, to infer that more than a single new component is involved; that much more lies ahead than in the past; that, indeed we may be entering a new field of technology, i.e., "transistor electronics".

ACKNOWLEDGMENTS

It was stated earlier that these advances in the development of transistors have resulted from improved understanding, materials and processes. These improvements have been made through the efforts of a large

number of workers in physical research, chemical and metallurgical research and transistor development. In reality, these colleagues are the authors of this paper; and it is to them the writer owes full and appreciative credit for the material that has made possible this report of progress in transistor electronics.

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