Survey of Transistor Development

Parts I, II, and III

By

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Part 1. Details on a component which may change the radio industry. This article covers the basic crystal types, their preparation, and fabrication.

Fig. 1. RCA's apparatus for "growing" single germanium crystals used in making transistor units.

As A RESULT of the progress made in the design and manufacture of the transistor, a germanium-crystal triode, this electronic device looms today as a desirable supplement to the electron tube in many applications. The development of the transistor may make possible new types of electronic equipment which will use not only transistors, but also electron tubes, and other electronic components in increasing quantities. In fact, the commercial application of transistors appears to be not too distant, although a considerable amount of time is probably still required before these units become commercially available on any sizable scale.

The intense interest in the transistor shown by electron-tube research and development engineers may be attributed to the fact that the transistor performs functions similar to those of triode-type electron tubes, although the mechanism of conduction is quite different. The transistor is of particular interest to equipment designers, who see many circuit possibilities in its characteristics. It is very small in size, and the power requirements for its operation are extremely low. When suitable circuits are developed, space and power requirements for complex electronic equipment may be simplified to a large degree by the use of transistors. Another promising feature is that the operating life of certain types of transistors shows indications of being very long, thus minimizing replacement problems. The physical ruggedness of the transistor offers other obvious advantages. In addition, the transistor requires no "warm up" time but will operate instantaneously upon application of voltage to its electrodes.

The limitations of the present developmental transistors, however, must not be overlooked. Transistor characteristics vary with ambient temperature changes, the noise is high compared with that of electron tubes, and the power output is relatively low. Nevertheless, when the favorable characteristics of the transistor are weighed against its limitations, it appears that this device, even in its present developmental stage is destined for use in many applications. Further improvements in its characteristics undoubtedly will create new and expanding fields for its use. At the same time, the principles of semi-conduction in solids may be expected to play an increasing part in the development of many new electronic devices, of which the present transistor is but the first.

Two types of transistors, the point-contact type and the junction type, will be discussed in this series. The point-contact transistor will be discussed first, and at greater length, because the development of this device has reached a more advanced stage and more is known about its performance with respect to frequency of operation, life, and uniformity of characteristics. However, the junction transistor promises to be at least as important as the point-contact transistor in many applications.

The heart of the transistor is the germanium crystal. Germanium is a semi-conductor, a metallic-like substance having conductivity greater than that of an insulator but less than that of a conductor. Its resistance, in contrast with that of metals, decreases as its temperature is raised. Other types of semi-conductors, such as silicon, lead sulphide, and selenium, have been used in transistor work, but, to the present time, germanium has proved the most successful.

Germanium is known mostly for its use in point-contact diode rectifiers which have been available commercially for several years. These devices have achieved widespread use in many present-day applications.

In the United States germanium is obtained most frequently as a by-product of zinc mining. It has also been obtained in considerable quantities in Great Britain from flue dust residue. Manufacturers of germanium products receive this substance in the form of a germanium dioxide powder. The conversion of the dioxide into crystals for use in transistors involves some of the most important and critical processes in the manufacture of germanium devices. The electrical characteristics of the transistor are dependent to a considerable degree upon the characteristics of the germanium. The control of transistor characteristics to acceptable tolerances depends upon the uniformity of the germanium.

The resistivity of the germanium, an important factor in transistor operation, is dependent upon the presence in the germanium of minute quantities of certain impurities. If no impurities are present in the germanium crystal, no transistor action takes place. If too many impurity atoms are present, however, the germanium becomes too conductive and transistor action is adversely affected. The impurities which enhance the transistor operation should be present in the ratio of less than one atom to every 10,000,000 germanium atoms. Because of their exceedingly low concentration, it is quite difficult to detect the quantity of impurities present in the germanium crystal. Some of these

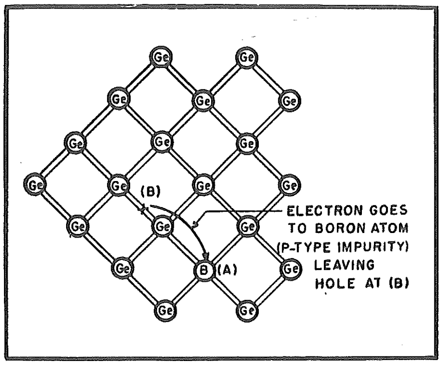


Fig. 2. The effect of "p"-type impurities on the conductivity of the germanium.

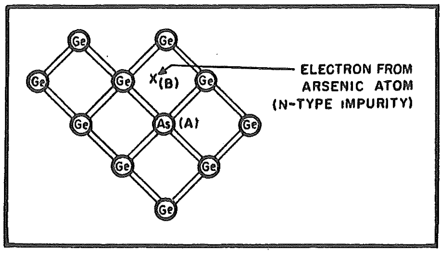


Fig. 3. The effect of "n"-type impurities on the conductivity of germanium crystals.

MATERIAL	RESISTIVITY (ohms per cm^3)
Semi-conductor:	
Germanium	60
Insulator:	
Glass	9×10^{13}
Mica	9×10^{15}
Conductor:	
Copper	1.7×10^{-6}
Platinum	10×10^{-6}

Table 1. Resistivity of pure germanium, insulators, and conductors compared.

impurities are actually present in the germanium dioxide as it is delivered to the manufacturer. It is desirable, however, to remove as many impurities as possible by purification techniques so that controlled amounts of them may be added to obtain the desired values of resistivity.

The initial process in the conversion of germanium dioxide to the final crystals for transistor use is the reduction of the dioxide to a germanium metallic powder. This process is performed in a hydrogen atmosphere at a temperature of approximately 650 degrees Centigrade. The powder is then melted at a temperature of approximately 960 degrees Centigrade and is formed into ingots. After the ingots are formed, they may be subjected to one or more stages of purification. In one type of purification process, the germanium ingot is placed in a furnace in an inert-gas atmosphere, is melted, and then is progressively cooled from one end to the other. During this cooling process, impurities present in the germanium tend to concentrate at each end of the ingot. The inner portion of the ingot, therefore, has a higher purity than the ends where the impurities are concentrated. The low-purity ends of the ingot may be cut off and the process repeated if additional purification is needed.

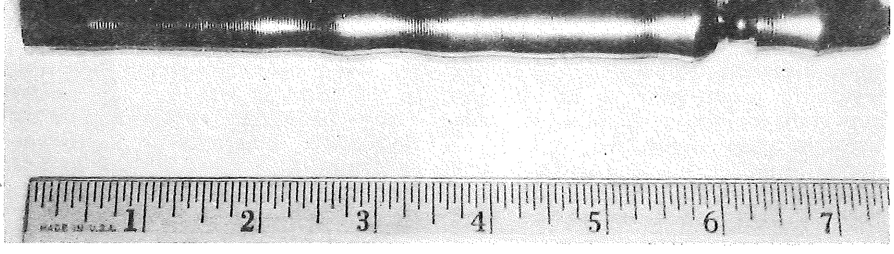
The germanium ingot formed by these purification techniques is polycrystalline. Greater uniformity is obtained in a further process in which a single crystal is formed from this polycrystalline ingot. In this process the polycrystalline germanium is placed in a graphite pot and melted. A small single crystal of germanium is dipped into the surface of the melt, then withdrawn very slowly, pulling with it some molten germanium which solidifies on the crystal seed. The speed of withdrawal may be about ¼ inch per minute. The temperature of the germanium is controlled very closely during the crystal "growing," with a permissible variation of no more than ±1 degree Centigrade.

Fig. 1 is a photograph of a crystal-growing apparatus. Single crystals ranging in diameter from 0.050 inch to one inch and having lengths up to many inches have been formed using this method. Fig. 4 is a photograph of the part of a single crystal which subsequently is to be cut into pellets for assembly into transistors.

At the present time the price of the germanium dioxide powder is about 300 dollars per kilogram. The quantity of germanium used for each transistor, however, is very small (about 0.002 gram). The single crystal pictured in Fig. 4 can provide as many as 7000 pellets for as many transistors, and many single crystals of this size can be obtained from one kilogram of germanium dioxide. Although a portion of the germanium is scrapped during the processing from powder to final crystal form, much of this germanium may be reclaimed for further use.

The finished crystal specimen is tested electrically to determine whether it has the proper impurity concentration, resistivity, and physical characteristics for use in transistors. The crystal is then sliced into wafers about 0.020 inch in thickness and diced into small pellets approximately 0.050 inch square. The pellets are chemically etched before the transistor is assembled to insure the absolute cleanliness of the crystal surface so necessary for good transistor operation.

Fig. 4. A single germanium crystal grown in the crystal-growing apparatus (Fig. 1).



Conductivity in Germanium

The germanium crystal is composed of millions of germanium atoms, each consisting of a positively charged nucleus and a number of negatively charged electrons. All but four of the electrons are tightly bound to the nucleus and cannot enter into chemical reactions with electrons of other atoms. The remaining four electrons, which are able to enter into chemical processes, are called valence electrons. In the pure germanium crystal, however, the atoms are arranged in such a fashion that the valence electrons are fixed in place and contribute only slightly to electrical conductivity. The resistivity, which is the reciprocal of conductivity, of the pure germanium, therefore, is higher than that of germanium containing impurities.

Fig. 5 is a photograph of a model of the atomic structure of a tiny portion of the germanium crystal. Each round ball represents the nucleus of an atom, and each bar connecting two nuclei represents two valence electrons, one from each of the two atoms joined by the bar. Each of the four valence electrons of an atom forms a bond with a valence electron from an adjacent atom. Electrons which are fixed in these electron-pair bonds cannot contribute to the conductivity of the crystal except under the influence of an applied force. This condition is similar to that existing in an insulator, where there are no conduction electrons and, consequently, there is little or no conductivity. If sufficient electrical or thermal energy is exerted on the germanium crystals, however, the forces holding the electrons in their bonds can be overcome, and a fow electrons may be released from their bonds. Because of the release of electrons by thermal energy at room temperature, germanium does have some conductivity even in its pure state. The resistivity of pure germanium, a semi-conductor, is 60 ohms per centimeter cube at room temperature. The resistivity of insulators is much higher than that of semi-conductors; that of metal conductors is much lower. In a metal conductor, there are a large number of conduction electrons which are not bound in a fixed position but are free to flow throughout the metal, thus contributing to a very low resistivity. Table 1 gives a comparison of resistivities at room temperature of pure germanium, insulators, and conductors.

The normal conductivity of germanium must be increased to obtain transistor operation. This additional conductivity is obtained by adding impurities to the crystal, as was mentioned previously. The impurities which may be present in germanium are of three types. Fig. 3 illustrates how one type of impurity can add conduction electrons to the crystal. If impurities having five valence electrons per atom are added, each impurity atom (A) takes the place of a germanium atom and four of the five valence electrons form bonds with four electrons of adjacent germanium atoms. The fifth electron (B) from the impurity atom is free to wander about the crystal and contributes to its conductivity in a manner similar to that of free electrons in a metallic conductor. As more impurity atoms of this type are added, the conductivity of the germanium increases and the resistivity decreases. Germanium having an excess of electrons due to the addition of such impurities is known as "n"-type germanium, that is, germanium having an excess of negative charges. "N"-type impurities are also known as "donor" impurities because they donate electrons to the crystal conductivity. Typical donor impurities are arsenic, antimony, and phosphorus.

Conduction in germanium may also be increased by adding a second type of impurity such as aluminum, boron, or indium. Fig. 2 illustrates how these impurities, known as "p"-type impurities, create a deficiency of electrons. If impurities having three valence electrons per atom are added, each impurity atom (A) takes the place of a germanium atom and its three valence electrons form electron-pair bonds with electrons of neighboring germanium atoms. In order to fit completely into the valence bond structure of the crystal, the impurity atom borrows an electron from an electron-pair bond from somewhere else in the crystal (B), thus leaving a net positive charge in the half-empty bond. This positive charge is known as a "hole"; these holes contribute to the conductivity of the crystal in much the same manner as electrons because they also can move from atom to atom. As more "p"-type impurities are added, more holes are formed and the conductivity of the crystal is increased. The main distinction between the two types of germanium is that the "n"-type has an excess of electrons while the "p"-type has an excess of holes. Both "n" and "p" types are used in transistors; in certain types of transistors both exist in different parts of the same crystal. The "n"-type germanium is used predominantly in the present point-contact transistors.

The third type of impurity includes those which do not have three or five valence electrons. These impurities, which are present in very small quantities, may not affect the conductivity of the germanium, but may disturb the crystal structure and adversely affect transistor properties.

The role which "p"-type and "n"-type impurities play in determining the resistivity of germanium may be appreciated by noting the change in resistivity which occurs with a change in the ratio of impurity atoms to germanium atoms. The density of germanium atoms in pure germanium is approximately 4.5×10^{22} atoms per cubic centimeter; there are approximately 3.7×10^{19} germanium atoms in the average pellet used for a transistor. If 4.5×10^{14} "n"-type impurity atoms are added to each cubic centimeter of pure germanium, or one impurity atom for every 100,000,000 germanium atoms, the resistivity of the germanium drops from 60 ohms per centimeter cube to approximately 3.8 ohm per centimeter cube, a value which is satisfactory for use in a point-contact transistor. If 4.5×10^{15} impurity atoms are added to the germanium, however, the resistivity drops to 0.38 ohms per centimeter cube, a value which is too low for transistor use. This example illustrates how critical are the quantities of impurities which must be added. The problem is further complicated by the fact that "p"-type impurities may be present in the germanium ingot when the "n"-type impurities are introduced, and the holes and electrons furnished by the two types of impurities may cancel each other out. If both types of impurities were present in equal amounts, the resistivity would be the same as if no impurities were present.

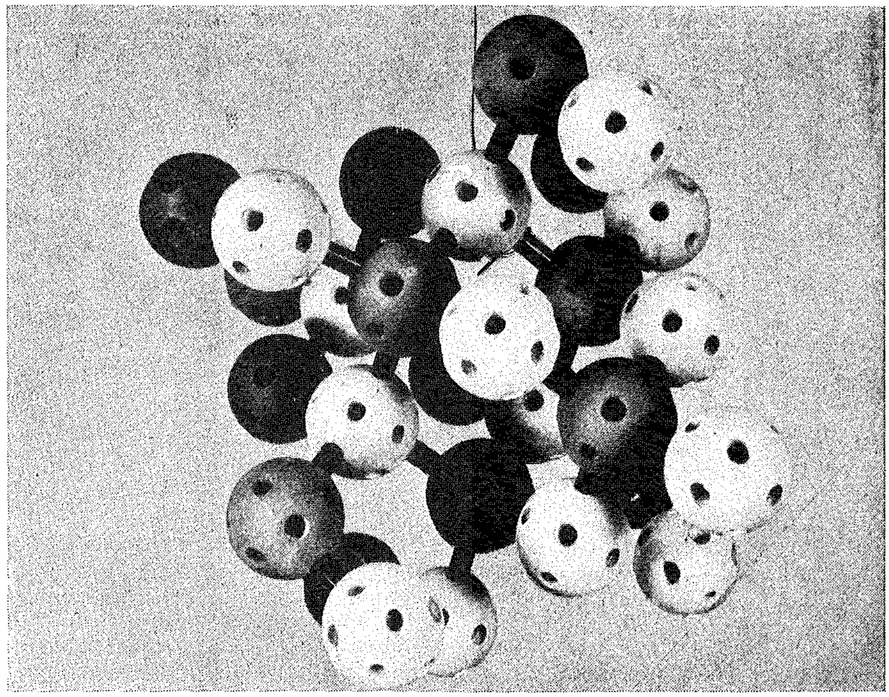


Fig. 5. A three-dimensional model of the atomic structure of germanium crystal.

Fabrication Process

An appreciation of some of the unique characteristics of the transistor may be obtained from an examination of its construction. A photograph of an *RCA* developmental point-contact transistor is shown in Fig. 7. Fig. 6 is a diagram of its construction. This transistor consists essentially of two rectifying point electrodes which make contact with a small pellet of germanium. These electrodes are known as the emitter and the collector. A third electrode, the base, is in low-resistance contact with the germanium crystal. The emitter, collector, and base form the three electrical connections to this germanium-crystal triode. The complete assembly is then embedded in a

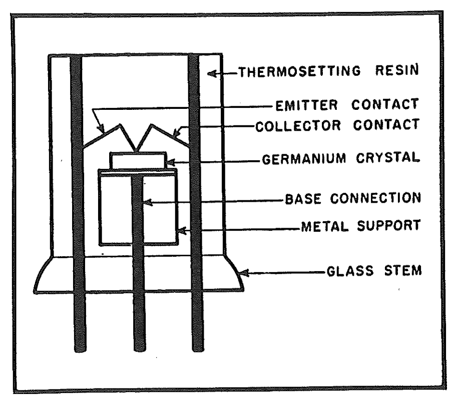
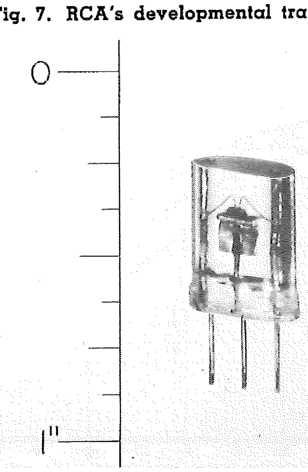


Fig. 6. Construction details of the RCA developmental point-contact transistor.

Fig. 7. RCA's developmental transistor.



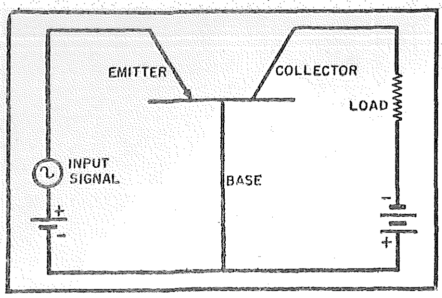


Fig. 8. Transistor amplifier circuit.

thermosetting plastic to provide ruggedness and freedom from atmospheric contaminants. The final process, and one of the most important, in transistor fabrication is electrical forming. In this process, relatively large surges of current are passed through the collector to the base. The importance of "electrical forming" will be explained shortly.

Point-Contact Rectification

Before the operation of the transistor in specific circuits is covered, it is important to discuss briefly the current rectification obtained when the metal point electrode makes contact with the germanium-crystal surface. When this contact occurs, a nonlinear relationship exists between a voltage applied to and the current flowing through the point of contact. A so-called "barrier" to the flow of current will be present or absent depending upon the polarity of the voltage applied to the metal point. For instance, if a metal point contacts the surface of an "n"-type germanium, the barrier will be absent and a large forward current will flow if the metal point is biased positively with respect to the crystal. If the point is biased negatively with respect to the crystal, the barrier will be present and only a small reverse current will flow. If the germanium is a "p"-type, the forward current will flow when the point is biased negatively with respect to the crystal. One explanation of this barrier is that it is a very thin layer at the surface of the crystal which acts as an insulating layer. If the germanium resistivity is too low, this insulating barrier at the surface does not exist because of the large number of current carriers present both in the interior and on the surface of the germanium, and poor rectification results.

Fig. 8 is a diagram of a transistor amplifier circuit utilizing the "n"-type transistor. In this circuit the collector is biased negatively with respect to the base. The emitter, also shown in Fig. 8, is biased positively with respect to the base. If we first assume that no voltage is applied to the emitter, the collector will draw approximately 0.5 milliampere if a negative voltage of 25 volts is applied to the collector contact. Then, if a positive voltage is applied to the emitter contact, electrons will be drawn into the emitter and a flow of holes from the emitter will be attracted to the negative field of the collector, thereby increasing the collector current appreciably. Now, with both the emitter and collector drawing current, a small signal voltage is applied to the transistor as indicated in the circuit diagram. As the applied voltage swings positive, the emitter current will increase, thereby increasing the collector current by supplying additional holes. On the negative swing of the signal voltage, the collector current will decrease. If the assumption is made that every unit of hole current which leaves the emitter reaches the collector, it follows that a small change in emitter current will result in an equivalent change in collector current, producing a current amplification factor of one. The current amplification factor is defined as the ratio of the change in collector current to a change in emitter current when the collector voltage is maintained constant. A very significant characteristic of the transistor, however, is that this current amplification factor may actually be two or greater. Factors greater than unity are made possible by the electrical "forming" process previously described. One explanation of the results of this process is that a space charge of holes is formed around the collector point. It appears that this positive charge increases the electron flow from the metal collector to the germanium and accounts for the increased current amplification.[1]

The transistor amplifies not only input current, but also power. Because the emitter is biased in the forward direction, only a small impedance to the flow of current exists; therefore, the input impedance of the transistor is fairly low, on the order of 500 ohms. The collector, on the other hand, is biased in the reverse direction; it offers a higher impedance, therefore, to the flow of current. The collector resistance comprises the greatest portion of the output impedance of the transistor. The load resistance, to provide a proper impedance match, must be fairly high, on the order of 10,000 to 20,000 ohms. With the input signal applied to the transistor at a low impedance and the output taken from a high impedance, power amplification results.

In the "p"-type transistor, electrons are emitted from a negatively biased emitter and are collected at a positively biased collector. In general, the "p"-type transistor[2] has characteristics similar to the "n"-type unit, except that in operation all battery polarities are reversed. This type need not be discussed in detail here.

1. *Shockley, W.; "Electrons and Holes in Semiconductors," D. Van Nostrand, 1950*
2. *Pfann, W. G. and Scaff, J. H.; "The P-Germanium Transistor," Proceedings of the I.R.E., Vol. 38, pages 1151-1154, October, 1950*

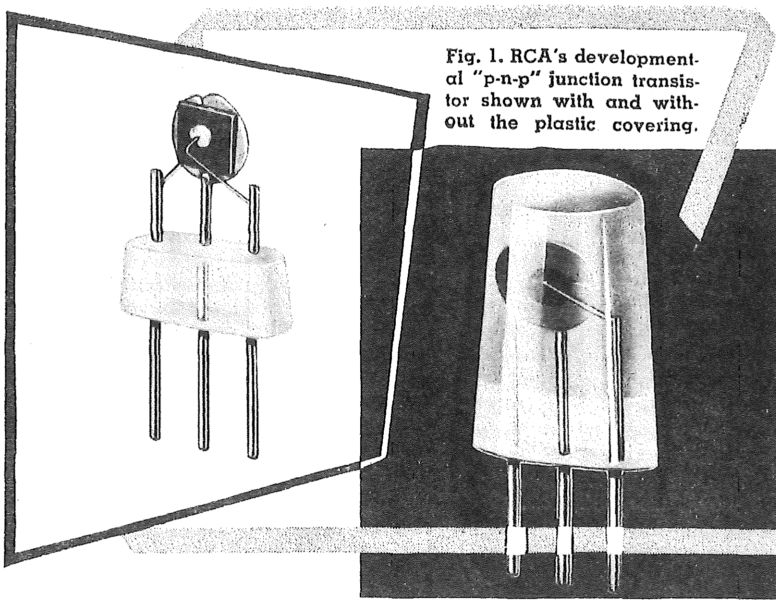


Fig. 1. RCA's developmental "p-n-p" junction transistor shown with and without the plastic covering.

SURVEY OF TRANSISTOR DEVELOPMENT

By

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Part 2. A resumé of point-contact characteristics, its frequency response, and power considerations.

IN THE first article of this series the preparation of germanium crystals, the conductivity of germanium, the fabrication of the point-contact transistor, point-contact rectification, and the operation of the point-contact transistor were covered. This article will consider the characteristics of a point-contact transistor, transistor frequency response, and power considerations of this unit.

Characteristic Curves

The electrical characteristics of the point-contact transistor may be described by static characteristic curves having slopes equal to the open-circuit resistances. For example, the input characteristic, illustrated by the curves in Fig. 2, is defined as the emitter voltage *vs* the emitter current for several values of constant collector current. The slope of the curve taken at any point is defined as the open-circuit input resistance because the output circuit is an open circuit for a.c. currents.

The feedback characteristic is illustrated in Fig. 3. The slope of this curve is the internal feedback resistance which is mutual to both input and output circuits. This resistance is a measure of the effect of collector current upon the voltage drop at the emitter point. It acts as a positive feedback element, and, if it becomes too large, the transistor may become unstable.

The output characteristic curve is given in Fig. 5. The slope of this curve is the open-circuit output resistance. This resistance is approximately equal to the collector resistance, or the a.c. impedance which exists at the collector contact. The current amplification factor which is a measure of the effect of the emitter current upon the collector current, may also be measured from the output characteristic. Along a line of constant collector voltage, a change in collector current for an increment of emitter current may be measured. The current amplification factor is equal to the change in collector current divided by the change in emitter current. The output characteristic curve is similar to the curves of the plate family of the electron tube except that the voltages are plotted as a function of the currents for the transistor while the currents are plotted as functions of the voltages for the vacuum tube. An oscillogram of the output characteristic of a typical point-contact transistor is shown in Fig. 4.

Because a transistor may have a negative input resistance, it is possible to obtain two sets of currents for one set of voltages. This effect is shown in the curve of emitter voltage *vs* emitter current for a constant collector voltage, in Fig. 7. As the emitter and collector currents increase, the voltage across the internal feedback resistance becomes larger. Since this voltage is negative with respect to the base and is in series with the applied emitter voltage, a point is reached where the total emitter voltage decreases with increasing emitter current, resulting in a negative input resistance. For an emitter voltage of 0.26 volt and a collector voltage of −20 volts there are two values of emitter current which may be selected from the curve shown in Fig. 7: 0.6 milliampere and 2.2 milliamperes. There will also be different collector currents for these values of emitter current (2.0 and 5.0 milliamperes, respectively). Because there is only one set of voltages for a given set of currents, it is desirable to plot the voltages as a function of currents. It is also highly important that constant-current rather than constant-voltage sources be used. If fixed voltages were applied directly to the emitter and collector, any slight increase in collector current would tend to increase the emitter current due to the effects of feedback. This increase would, in turn, increase the collector current and considerable instability would result. In junction transistors, which will be discussed later, neither the negative input resistance nor the positive feedback exist. Therefore, constant voltage supplies may be used with no possibility of instability.

The transfer resistance is defined as

Fig. 2. Input characteristic of the RCA developmental point-contact transistor.

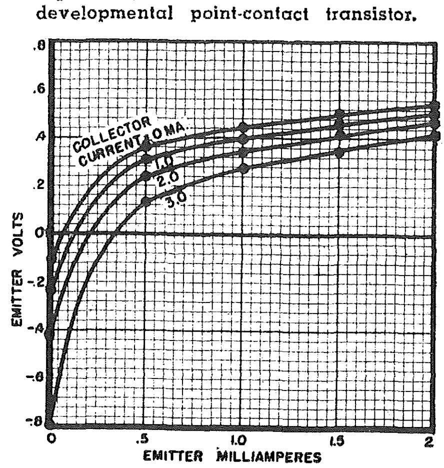
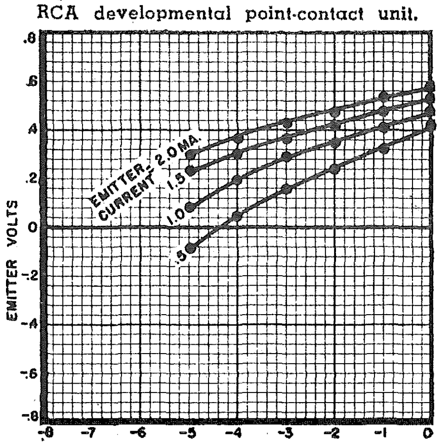


Fig. 3. Feedback characteristic of the RCA developmental point-contact unit.



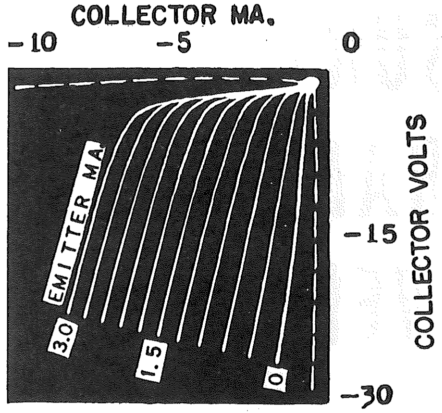


Fig. 4. Oscillogram of output characteristics of RCA developmental transistor.

the slope of the transfer characteristic curve which is illustrated in Fig. 6. This resistance is also equal to the product of the current amplification factor and the output resistance.

Some typical values of open-circuit resistances for a point-contact transistor are: input resistance, 300 ohms; output resistance, 20,000 ohms; feedback resistance, 120 ohms; and transfer resistance, 40,000 ohms.

Because of feedback effects, the optimum input and output impedances for maximum gain in an amplifier circuit using this transistor are slightly less than the open-circuit resistance values. However, an input impedance of 200 to 500 ohms and an output load impedance of 10,000 to 20,000 ohms would result in a power gain of approximately 20 db which is close to the maximum available gain.

The power gain of the transistor depends upon three major factors. First, the gain varies almost directly with the ratio of output impedance to input impedance. This ratio may be on the order of 100 to 200 to 1 in point-contact transistors; in junction transistors the ratio may be on the order of 10,000 to 1. Secondly, the power gain varies as the square of the current amplification factor, which may be on the order of 2 or 3 for point-contact transistors and slightly less than one in junction transistors. Thirdly, the positive feedback of the transistor accounts for several decibels in power gain. The amount of the gain due to feedback depends upon the magnitude of the internal feedback resistance and the current amplification.

Transistor Frequency Response

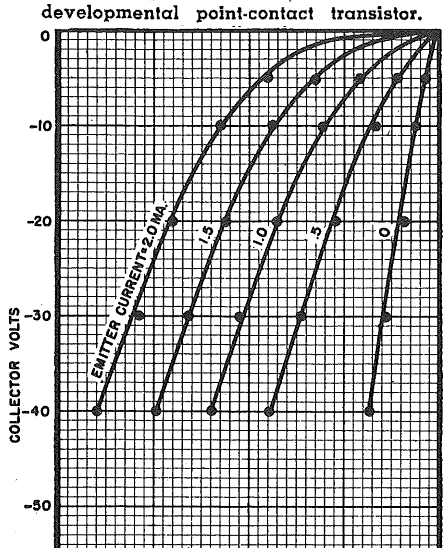
The frequency response of the point-contact transistor is limited by the transit time of the holes or electrons; transit time is the time it takes the holes or electrons to travel from the emitter to the collector. The transit time in seconds may be calculated approximately through use of the expression $S^3/\rho\mu I_e$, where S is the contact spacing or the distance between the emitter and collector in centimeters, ρ is the resistivity of the germanium in ohm-centimeters, μ is the mobility of the holes or electrons in centimeters squared per volt-second, and I_e is the emitter current in amperes. Since an improved frequency response results from a small transit time, it can be seen from this expression that the response can be improved by using germanium of high resistivity and small contact spacings. The mobility of the holes or electrons is the velocity with which they move through the germanium when an electric field is applied. In the case of "n"-type germanium, holes travel from the emitter to the collector; in the case of "p"-type germanium, electrons travel from the emitter to the collector. The mobility of electrons is greater than that of holes and, consequently, the frequency response of "p"-type germanium is slightly better than that of "n"-type germanium, provided that the contact spacings and resistivities are comparable.

The frequency response may be defined as the measure of the change in current amplification with increasing frequency. The current amplification factor of certain types of close-spaced point-contact transistors drops approximately 3 db. at 10 mc. A 3-db. drop in gain has been chosen to define the cutoff frequency. This method of measuring frequency response, however, defines only one parameter as a function of frequency. If the power gain of the device is measured as a function of frequency in an amplifier with a high-impedance load, the response of the transistor deteriorates more rapidly. A transistor having a 3-decibel drop in the current amplification factor at 10 megacycles may have a cut-off of voltage or power gain at 4 megacycles or less.

Wide-Spaced Transistors

The frequency of operation of point-contact transistors decreases fairly rapidly with increased point spacings. Since the transit time of the electrons or holes increases as the point spacing increases, in theory the frequency response of the transistor varies inversely as the cube of the spacing. However, some interesting studies have been made of "n"-type transistors having wide spacings between contacts,[1] and these devices appear to have some useful characteristics. If germanium having high resistivity is used, transistor power gain and current amplification are relatively independent of the separation of the points up to approximately 0.015 inch. As the spacings increase, however, the effect of the collector upon the emitter decreases, that is, the feedback resistance decreases. A transistor having a feedback resistance of 200 ohms at 0.002-inch spacing of the contacts would have only 50 ohms at 0.015-inch spacing. This value of feedback resistance for the wide-spaced transistors is low enough to assure short-circuit stability while values of power gain as high as 23 decibels are maintained. Even though the frequency-response limit varies inversely with the point spacing, the cut-off of the current amplification factor of the wide-spaced transistor is approximately 100 kilocycles because the resistivity of the germanium is higher than that used in narrow-spaced units. The other characteristics, except for the low internal feedback, are similar to those of the close-spaced transistor.

Fig. 5. Output characteristics of the RCA developmental point-contact transistor.



Power Considerations

The power capabilities of point-contact transistors are low and considerably limit the use of these devices. Most point-contact transistors do not withstand a collector power dissipation greater than 200 milliwatts. If the efficiency of operation as a class A amplifier is assumed to be 30 per-cent, only 60 milliwatts of power output may be obtained from one stage of a transistor amplifier. A conservative figure for operation would be somewhere between 30 and 40 milliwatts. There are, however, many applications in which some benefit may be obtained from a device which operates at low power dissipations. Consequently, the greatest opportunities for the use of point-contact transistors lie in those applications where power output is of relatively little importance and conservation of power is of primary importance.

The power-handling capacity of the point-contact transistor is limited largely because of thermal effects at the collector point. Considerable heat is generated at this point of contact when a current is passed through it. Germanium is a fair conductor of heat and, consequently, some of the heat is conducted away from the point of contact through the germanium crystal and away from the crystal by the metal support. If too large a value of current is passed, however, the germanium and adjacent parts are unable to carry the heat away rapidly enough.

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1. *Slade, B. N.; "A High Performance Transistor with Wide Spacing Between Contacts," RCA Review, Vol. XI, No. 4, page 517, December, 1950*

If the collector point becomes too hot, the collector resistance decreases and a change occurs in the collector bias current and also in the voltage drop across the collector. Some permanent damage may occur if the transistor is operated at too high a dissipation. It is desirable, therefore, that the mechanical construction of the transistor be designed for the best possible heat conductivity away from the crystal. By increasing the size of the crystal support and adding cooling fins, the allowable dissipation of the transistor may be increased to 500 milliwatts or more, thus increasing the power output of the transistor.

The amount of conduction of heat away from the contact area varies inversely with the ambient temperature. As the ambient temperature is increased, the temperature at the point of contact becomes too great and the collector resistance is reduced. Changes in other properties of the transistor, such as the emitter resistance, transfer resistance, and internal feedback resistance, may also occur. The net result of these changes is a loss of power gain, changes in bias conditions, and possible permanent damage to the transistor. For best operation, germanium transistors should be operated at temperatures below 60 degrees centigrade. The maximum dissipation ratings of the device should also be reduced as ambient temperatures are increased above normal room temperature. At ambient temperatures below 25 degrees centigrade the situation is less critical, and if the temperature is low enough higher dissipations may be used without loss of stability.

Life Considerations

The life of the point-contact transistor is largely dependent upon electrical and physical considerations. The most obvious requirement for long life is that the transistor be physically very rugged. The slightest shifting of the point contacts may result in large changes in transistor characteristics. The *RCA* developmental transistors[2] which are illustrated here are embedded in a thermosetting plastic or resin. As a result of this embedding process, the transistor may be subjected to severe impacts with no damage to the physical and electrical characteristics of the transistor. Centrifugal forces with accelerations as high as 31,000*g*, and impact tests with accelerations as high as 1900*g*, have been applied to these transistors with no effect upon their characteristics, irrespective of the directions of the applied forces.

Experience has indicated that one of the most important causes of slump and failure in transistor operation is the attack of moisture and other chemical agents of the atmosphere upon the point-contact area of the transistor. A transistor which is completely unprotected may fail in relatively high humidity in a few hours. It has become necessary, therefore, to prevent this moisture attack as much as possible by enclosing the point-contact area in waxes or resins having low moisture-absorption properties. Developmental *RCA* resin-embedded transistors have been subjected to continuous exposure at 95 per-cent relative humidity and immersion in water for periods of several months with practically no effect on transistor characteristics. Under normal conditions, transistors may be expected to survive with little change in characteristics for a long time. Predictions of point-contact transistor life of more than 70,000 hours either on the shelf or in operation do not seem at all unlikely if the transistors are operated within their ratings.

The resin-embedded transistors also withstand temperatures lower than –70 degrees centigrade and higher than 100 degrees centigrade during storage with no damage. Operation at the low values of temperatures is practical, but operation at high ambient temperatures is not feasible, as was mentioned before. These developmental transistors have also been subjected to temperature cycling between –70 degrees centigrade and 100 degrees centigrade with no change in transistor electrical or physical properties resulting.

Uniformity

If the transistor is to compete with other electron devices, uniformity and reproducibility of its characteristics are essential. The uniformity of transistors may be influenced to a large degree by the proper control of point spacing, point pressures, and the fabricating techniques employed. The uniformity of the germanium itself, however, is probably the most important factor in obtaining reproducible transistor characteristics. The art of germanium-crystal growing is rapidly progressing, and the uniformity of germanium has improved to the point where various transistor characteristics, such as current amplification, power gain, feedback resistance, and input and output resistance, have been controlled to within ±25 per-cent. Uniformity comparable to that of the electron tube seems entirely possible.

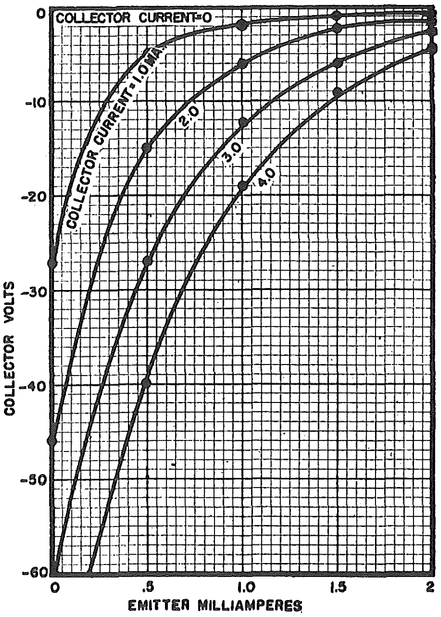


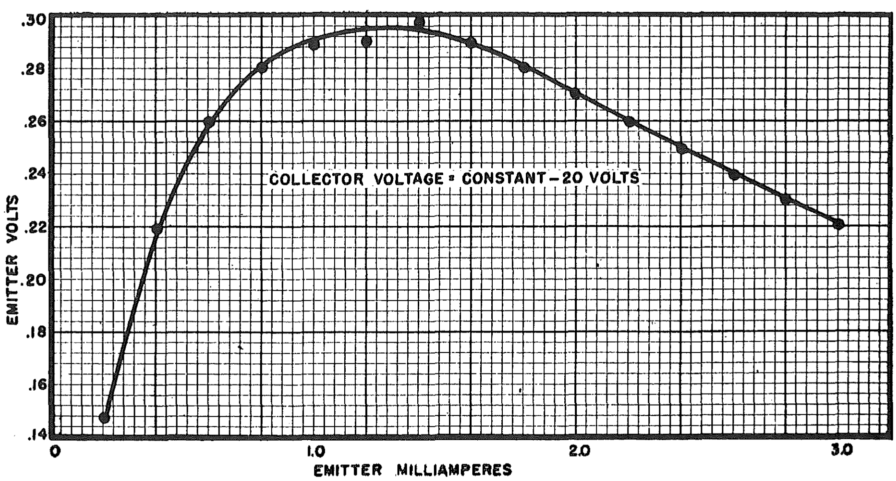
Fig. 6. The transfer characteristic of RCA's developmental point-contact transistor.

Junction Transistors

Other developmental germanium-crystal devices, known as "p-n" junction transistors, have somewhat different characteristics from those of the point-contact transistor. In comparison with currently produced point-contact types, the junction transistors have lower noise, higher power gain, greater efficiency of operation, and higher power-handling capabilities. These improved characteristics, however, are not obtained without some loss in frequency response. Table 1 compares average values of several characteristics of the two types of transistors.

Two types of junction transistors have been developed. The "n-p-n" junction transistor[3] is composed of al-

Fig. 7. Negative input-resistance characteristics of the point-contact transistor.



2. *Slade, B. N.; "A Method of Improving the Electrical and Mechanical Stability of Point-Contact Transistors," RCA Review, Vol. XII, No. 4, pages 651-659, December, 1951*

3. *Wallace, R. L., Jr. and Pietenpol, W. J., "Some Circuit Properties and Applications of N-P-N Transistors," Proceedings of the I.R.E., Vol. 39, No. 7, pages 753-767, July, 1951*

	POINT-CONTACT TYPE	JUNCTION TYPE
Power Gain (Grounded base)	23 db	40 db
Current Amplification Factor	2.5	0.98
Noise Figure (db above thermal at 1000 cycles)	55 db	10 db
Minimum d.c. dissipation for satisfactory operation.	5 to 15 mw.	0.6 microwatt
Efficiency, Class A operation	30%	49%
Frequency Cut-off (3 db down in current amplification factor)	10 mc.	1 mc.

Table 1. Average values of several characteristics for two types of transistors.

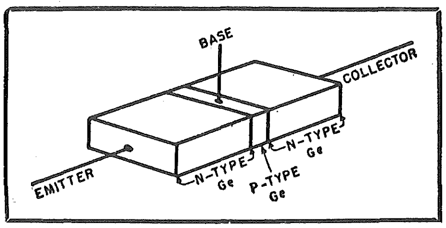


Fig. 8. Arrangement of "n" and "p" layers in an "n-p-n" type junction transistor.

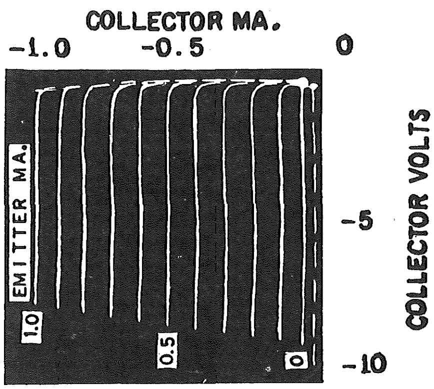


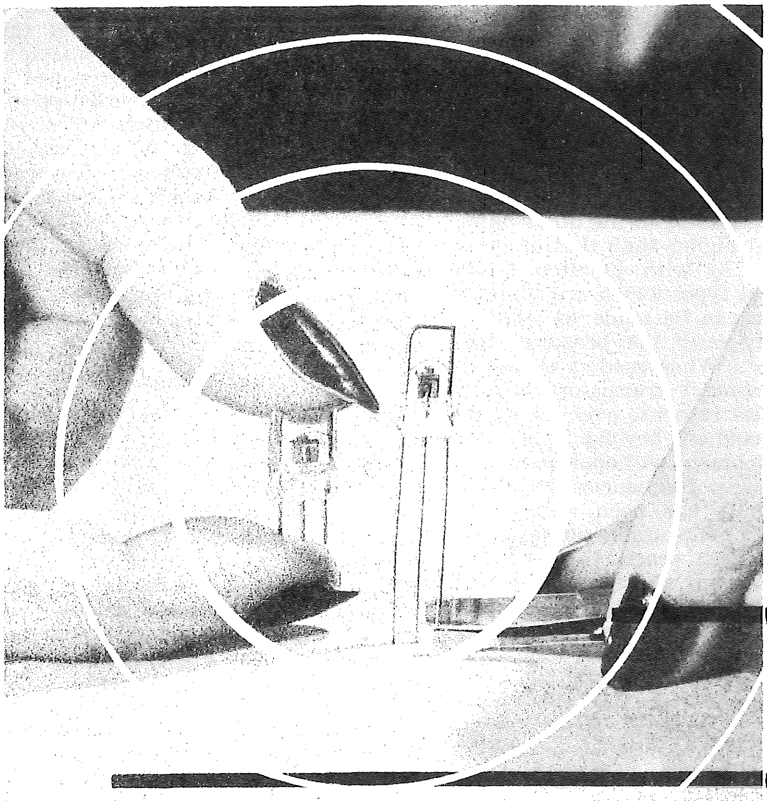
Fig. 9. Oscillogram of output characteristics of RCA's "p-n-p" junction transistor.

ternate n, p, and n layers of germanium grown from a single crystal, as illustrated in Fig. 8. The center layer of "p"-type germanium is very thin; its thickness may be as little as 0.001 inch. Low-resistance contacts to the "n"-areas form the emitter and collector, and a low-resistance connection to the "p"-layer constitutes the base terminal. The principle of operation of the junction transistor is somewhat different from that of the point-contact transistor in that the rectification takes place at the junctions between the p- and n-type layers rather than at point contacts. In the point-contact transistor, holes or electrons drift from the emitter to the collector under the influence of electric fields. In the "n-p-n" junction transistor, electrons diffuse through the p-type layer and are attracted to the collector. The center layer has an excess of holes, but if this layer is thin enough, most of the electrons entering the base region from the emitter will reach the collector region without recombining with the holes. Practically all the electrons leaving the emitter reach the collector, thus resulting in a current amplification of approximately one, but this type of transistor cannot attain current amplifications greater than one unless more complex junctions are introduced. High power gains are obtained as a result of the tremendous impedance step-up between input and output circuits. The emitter junction is biased in the forward direction, and since the forward resistance of the junction is very low, the input impedance of the device is as low as 25 to 100 ohms. The resistance of the collector junction, which is biased in the reverse direction, is very high, on the order of several megohms, thus resulting in a very high output impedance. This tremendous difference in impedances can result in power gains of over 40 decibels.

Another junction device, the "p-n-p" transistor, illustrated in Fig. 1, is formed by diffusing two "p"-type impurity metals on opposite faces of a piece of "n"-type germanium. Atoms diffuse from these impurity metals into the germanium at high temperatures converting a portion of the "n"-type germanium to "p"-type, thus forming "p-n" junctions.[4] In this transistor, the emitter is biased positively with respect to the base, and the collector is biased negatively with respect to the base. Hole carriers are injected by the emitter and arrive at the collector, resulting in a current amplification factor of approximately one, as in the "n-p-n" transistor.

An appreciation of some of the most outstanding qualities of the junction transistor may be obtained from a study of the output characteristics given in Fig. 9. This family of curves indicates that the junction transistor has a constant current amplification factor and output resistance down to very low collector voltages. Operation with power inputs as low as 0.6 microwatt have been reported. This input is about one-ten-thousandth the power dissipation required to operate the point-contact transistor, and less than one-millionth the power required to heat the cathode of most vacuum tubes. The almost ideal static characteristics show that the junction transistor can operate close to 50 per-cent efficiency as a class A amplifier. Although the junction transistors for which these characteristics are plotted can operate at only limited power dissipations, approximately 50 milliwatts, design of these devices for operation at 2 watts or greater is possible.

4. *Saby, J. S.; "Recent Developments in Transistors and Related Devices," Tele-Tech, Vol. 10, No. 12, December, 1951*



SURVEY OF TRANSISTOR DEVELOPMENT

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Part 3. Concluding article covers simple transistor amplifier circuits and designs for other applications.

Two views of an RCA transistor. The unit at the left is complete, with components embedded in plastic. Unit at right is still under construction.

IN THIS, the concluding article in this series, we will consider some simple transistor amplifier circuits, other transistor circuit applications, and several other types of germanium devices.

Transistor Amplifier Circuits

It is interesting to compare the amplifier circuit properties of the point-contact transistor and the junction transistor. A number of amplifier circuit connections are possible to obtain several combinations of input and output impedances. In the case of the point-contact transistor, however, special consideration must be given to the circuitry. If the internal feedback resistance is too large, and if the current amplification factor is greater than unity, the circuit may become unstable and oscillations will occur. It can be seen in the curves in Fig. 3, Part 2 (September issue, page 64) that the internal feedback resistance varies with the operating point. The current amplification factor may also vary somewhat with collector voltage, thus making the circuit stability dependent upon the d.c. biases. Resistance placed in series with the emitter and collector leads helps to suppress these oscillations, but may decrease the power gain of the circuit. For example, the input impedance to the grounded-base amplifier circuit shown in Fig. 1 is approximately 500 ohms and the output impedance is approximately 10,000 ohms. If the internal feedback resistance is too large, additional resistance necessary to stabilize the circuit will exceed these impedance values and, therefore, reduce the gain of the circuit. Point-contact transistors which have a very low value of internal feedback resistance, less than 100 ohms, for example, usually have such low feedback that amplifier circuits require no special stabilization. It is desirable in some r.f. circuits, particularly, that the transistor be stable under low impedance conditions such as off-resonance of a parallel-tuned circuit.

In the case of the simple junction transistor, the current amplification factor is always less than unity, and oscillations cannot occur. Ryder and Kircher[1] have pointed out that the grounded-base circuit is analogous to an electron-tube grounded-grid circuit if the emitter, base, and collector of the transistor are compared to the cathode, grid, and plate of the electron tube, respectively. The grounded-grid electron-tube circuit also has a low input and high output impedance. The comparison is particularly appropriate in the case of the junction transistor, which, like the tube circuit, is stable even under extreme short-circuit conditions.

If the emitter is grounded, as in Fig. 2, higher input impedances and lower output impedances may be obtained. Higher power gains may be obtained with this circuit configuration than with the grounded-base circuit, but in point-contact transistors the feedback may become large and lead to instability. If junction transistors are used, this type of circuit is similar to an electron-tube grounded-cathode circuit.

Higher input impedances and lower output impedances may also be obtained if the collector is grounded, as in Fig. 3. This circuit can become unstable if a point-contact transistor is used, and the power gain which may be obtained is low. However, the junction transistor can be used to good advantage in this circuit, because power gains ranging from 10 to 20 db may be obtained with input impedances and output impedances on the order of 200,000 and 50,000 ohms, respectively. In fact, appreciable gain may be obtained using equal input and output matching impedance, thus making cascading of several stages of amplification feasible. This circuit is similar to the electron-tube grounded-plate or conventional cathode-follower circuit.

Table 1 shows typical values of input and output impedances and power gains for all three types of circuits for both junction-type and point-contact transistors. It will be noted that in the grounded-emitter and grounded-base circuits the input and output impedances of the point-contact transistor may actually become negative values, a condition which indicates that these circuits are potentially unstable. These characteristics of the point-contact types, which lead to potential instability in amplifiers, are of

1. *Ryder, R. M. and Kircher, R. J.; "Some Circuit Aspects of the Transistor" Bell System Technical Journal, Vol. XXVIII, pages 367-401, July, 1949*

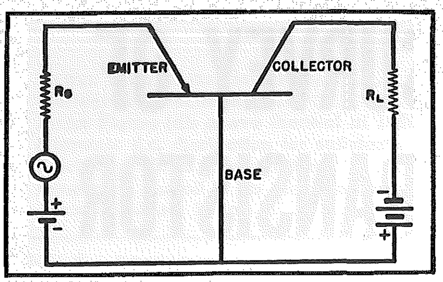

Fig. 1. Layout whereby the transistor is used in grounded-base amplifier circuit.

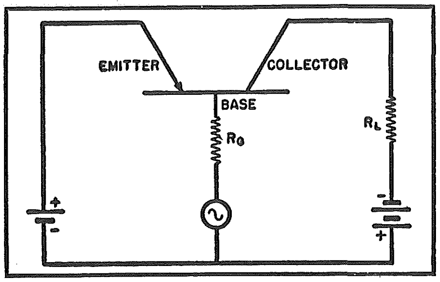

Fig. 2. A transistor grounded-emitter amplifier circuit, as discussed in the text.

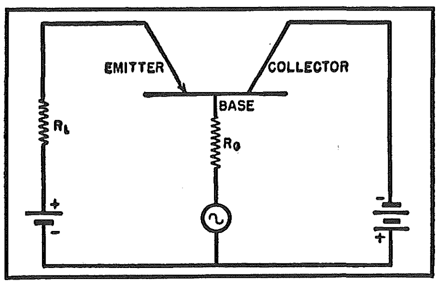

Fig. 3. The transistor grounded-collector amplifier circuit. See text for details.

great advantage in oscillators and trigger devices.

Other Circuit Applications

When considering the possible circuit applications for the two types of transistors, one must be aware of the advantages and limitations of both types.

At the present time, the advantages of high gain, low noise, and greater stability of the simple junction transistor can be utilized at frequencies up to several megacycles in applications such as r.f. and i.f. amplifiers of standard broadcasting receivers. In addition, power outputs greater than one watt appear to be possible in oscillator and amplifier applications in the audio frequency and low frequency ranges. Another feature of the junction transistor is its ability to amplify and oscillate with microwatt power inputs.

The frequency response of the point-contact transistors, on the other hand, is somewhat higher than that of junction types. As with junction types, point-contact types which are currently available can be made to oscillate and amplify over the broadcast-frequency band. When used as an amplifier, point-contact transistors have a relatively flat response over the entire broadcast band and beyond. Types now under development will operate at considerably higher frequencies. Feedback in these units has been reduced to values which make stable operation at radio frequencies practical. The point-contact transistor, therefore, may also have considerable application in radio circuits and may be used in intermediate-frequency amplifiers, radio-frequency oscillators, and other circuits not associated with the high-power stages of r.f. systems. Point-contact transistors have been developed which are capable of oscillating at frequencies well over 100 mc. Oscillations at frequencies higher than 200 mc. have been obtained; one developmental unit has oscillated at a frequency over 300 mc.

One of the most important uses of the point-contact transistor probably will be in counter circuits. A number of recent publications[2] describe some basic circuits which utilize the negative resistance properties of one or more transistors. These circuits generate pulses of various waveforms, store information for varying periods of time, add, subtract, multiply, and divide. Up to the present time these functions, and many others, have been performed in electronic computers by large numbers of electron tubes for which the heater-power supplies alone have been considerable. Use of the transistor would obviously alleviate this situation since no heater power is required. Furthermore, little d.c. power is necessary for operation. The adverse characteristics of transistors with regard to frequency response, noise, and power output are relatively unimportant factors in computer circuits. Computers which employ germanium devices would have the advantages of small size, ruggedness, and economy of operation and maintenance.

2. *Eberhard, E., Endrey, R. O., and Moore, R. P.; "Counter Circuits Using Transistors," RCA Review, Vol. X, No. 4, page 459, December, 1949.*
3. *Saby, J. S.; "Recent Developments in Transistors and Related Devices," Tele-Tech, Vol. 10, No. 12, December, 1951.*
4. *Shive, J. N.: "The Phototransistors," Bell Laboratories Record," Vol. XXVIII, No. 8, pages 337-342, August, 1950.*

Table 1. Input and output impedances and power gains for three circuit applications.

	Junction Transistors	Point-Contact Transistors
GROUNDED-BASE AMPLIFIER CIRCUIT		
Input Impedance	90 ohms	180 ohms
Output Impedance	0.4 megohm	14,000 ohms
Power Gain	37 decibels	20 decibels
GROUNDED-EMITTER AMPLIFIER CIRCUIT		
Input Impedance	620 ohms	1800 ohms
Output Impedance	54,000 ohms	—8000 ohms
Power Gain	41 decibels	28 decibels
GROUNDED-COLLECTOR AMPLIFIER CIRCUIT		
Input Impedance	40,000 ohms	—37,000 ohms
Output Impedance	1000 ohms	—10,000 ohms
Power Gain	17 decibels	14 decibels

Other Germanium Devices

The progress in the field of germanium devices is not limited to the field of transistors. While the point-contact germanium diode has already attained commercial acceptance, new types of diodes utilizing the "p-n" junction rectification characteristics are being developed. One diode power rectifier which utilizes a p-type or acceptor impurity metal diffused onto a pellet of germanium has already been described.[3] Peak inverse voltages of 400 volts are permissible with these devices which have very low resistances in the forward direction and current-carrying capabilities as high as 350 milliamperes. When the relative infancy of the germanium power rectifier is considered, it is difficult to estimate the ultimate importance of these devices. Because of improved efficiency, however, they appear to be suitable both as a replacement for the selenium rectifier and as an advantageous substitute for certain types of rectifier tubes.

Another germanium device of considerable significance is the phototransistor.[4] This photocell is a photo-conductive device and operates on the principle that light absorbed by germanium changes its conductivity. In the phototransistor, a point contact acts as the collector and draws a small amount of current. Light in the vicinity of the collector increases the conductivity of the germanium and the current through the collector.

The first transistor was announced only three and one-half years ago. Great strides have been made in learning the fundamental theory of operation of transistor devices, and much progress has been made in the knowledge of the control of transistor characteristics and manufacturing processes. There appear to be a number of fields in which transistors will be used widely and to great advantage. Further improvements in their characteristics may be expected as research and development continue.

Acknowledgment

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