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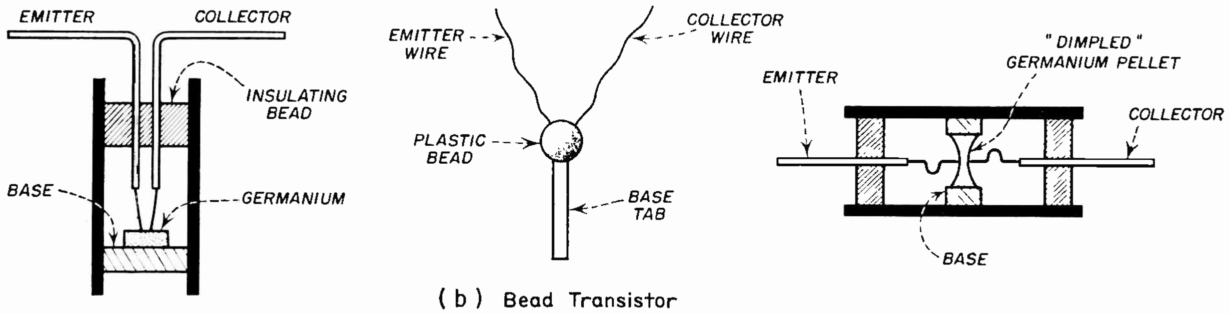
Recent Developments in Transistors

By the Engineering Department, Aerovox Corporation

THE RESEARCH WORKER for February, 1949 contained a discussion of the operating principles of the semiconductor triode, or *transistor*, which had recently been announced and was then making its debut in the field of electronics. At that time, the future of the device was obviously bright, although little was known of its ultimate potentialities nor the seriousness of some of its shortcomings. Now, after only a few short years of intense development, the transistor has emerged from the category of a "crystal ball" innovation to assume the important role predicted for it by the great research organizations which fathered it.

Standardized types of transistors have come into being, and many commercial and military equipments have been completely *"transistorized"*, a new term meaning the replacement of all vacuum tubes by semiconductor diodes or triodes. Although many technical problems still remain to be solved, and the semiconductor triode is still in its infancy, the only factor which prevents its wholesale appearance in hearing aids, midget radios, intercommunications equipment, telephone amplifiers, and many other applications at this time is the problem of availability. When transistor production reaches the point



(a) Type A Transistor (b) Bead Transistor (c) Coaxial Transistor

FIG. 1

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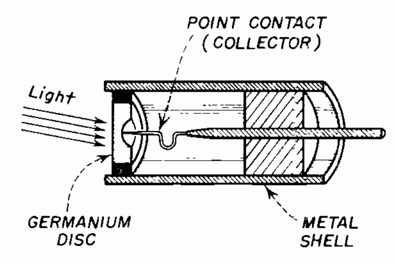


THE PHOTOTRANSISTOR

FIG. 2

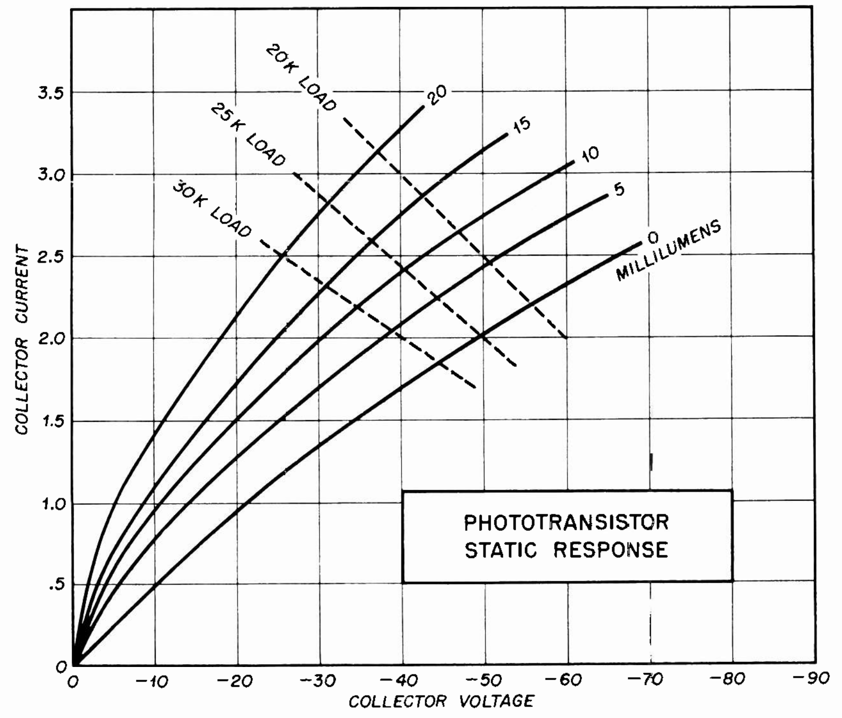
where the supply is sufficient to meet the demand, the man in the field may awaken one day to find himself confronted with the unfamiliar circuitry of the transistor. This issue of the **RESEARCH WORKER** is intended to help its readers meet this eventuality by presenting a condensed review of the present transistor art.

New Transistor Types

The transistor introduced originally was known as the *point contact* type, later designated Type A. The configuration of this type is the familiar double "cat-whisker" arrangement shown in Fig. 1a. Two fine wire probes are arranged in contact with the surface of a pellet of germanium semiconducting material at points only a few thousandths of an inch apart. One of the contacts is designated the "emitter", while the other is called the "collector". The semiconductor block and the metal which provides the electrical connection to it are called the "base".

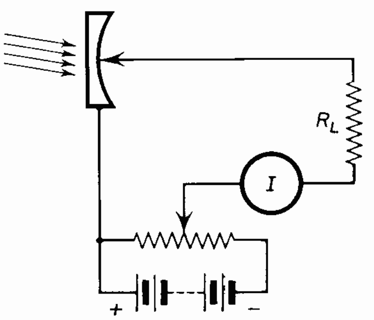
The operation of the Type A transistor was discussed at length in the above mentioned Research Worker. The defects which characterize it are difficulty of construction, low power handling capabilities, poor noise characteristics, and undue temperature sensitivity. At least the first two of these shortcomings are due to the fact that the points of contact with the germanium must be very accurately spaced and are extremely small areas. For this reason, even a few milliamperes flowing through these contacts represent current densities of many *amperes* per square centimeter. The excessive noise, which in instances exceeded 70 decibels above that predicted by theory, and the temperature dependance, may be inherent properties of semiconductors, although subsequent types have been vastly improved in these respects.

A varient of the standard Type A transistor is the "bead type" transistor illustrated in Fig. 1b. This form is a *miniaturized* version of the Type A which has been reduced to its very small size by eliminating the capsule and other non-essential parts. The two phosphor bronze contact wires and the small germanium block, along with a base contact tab, are "potted" in a small bead of insulating material which maintains the proper contact spacings. Bead types have been standardized which compare favorably with the larger sizes in performnace. They are useful in applications where extreme miniaturization is necessary.



PHOTOTRANSISTOR STATIC RESPONSE

FIG. 4



SIMPLE PHOTOTRANSISTOR CIRCUIT

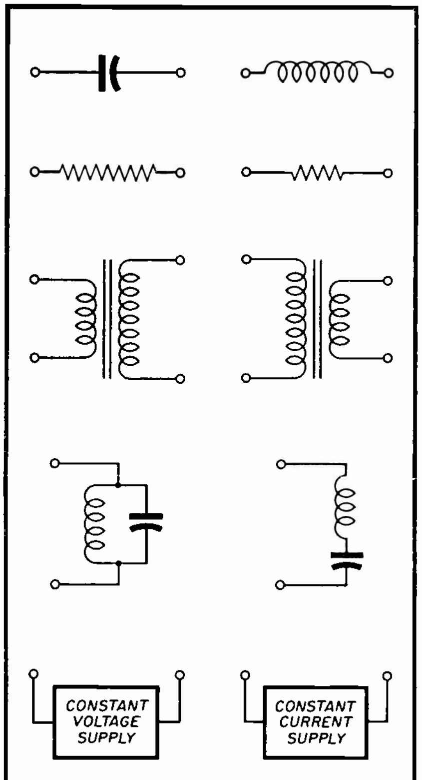
FIG. 3

A third form of the point-contact transistor is the coaxial configuration illustrated in Fig. 1c. Here the two "catwhiskers" make contact with opposite sides of the semiconducting germanium material where it is very thin — about .003 to .005 inch. This thin section is produced by grinding the opposite sides of the pellet to the concave shape indicated in the figure. In this manner, the problem of maintaining the close spacing of the wires is somewhat alleviated and the tendency of the point contracts to slip sideways, as in the type A construction, is minimized because the wires are coaxial and perpendicular to the surface of the semiconductor. Another advantage of the coaxial construction shown in the figure is the fact that the emitter and collector are electrostatically shielded from each other by the semiconductor and the metal shell.

Although comparable in performance, the coaxial transistor does not seem to have found such widespread usage as the type A transistor as yet.

The Phototransistor

An extremely useful by-product of the coaxial embodiment of the point contact transistor is the *phototransistor* illustrated in Fig. 2. This device makes use of the fact that the conductivity of germanium is altered by incident light energy, i.e., germanium is *photoconductive.* This property makes possible a very small photocell built like the coaxial transistor, except that the function of the emitter electrode is performed by a



"DUALS" OF SOME COMMON CIRCUIT ELEMENTS

FIG. 9

input impedance are 1000 ohms for the junction unit and about 2000 ohms for point contacts. The output impedances are about 1 megohms and 10,000 ohms, respectively. A phase reversal does take place between input and output, as in the corresponding triode circuit. Higher power gains are obtained in the grounded emitter circuit, being about 23 db for the point contact transistor connected in this manner and in excess of 50 db for the junction type. Circuit stability is somewhat worse than in the grounded base circuit since the common feed-back element is now the emitter resistance instead of the base resistance. In point contact circuits, the current gain (*alpha*) must sometimes be reduced to near unity to prevent oscillation. This is not necessary in the junction type unit, since the current gain is inherently less than unity. Noise and power handling characteristics are similar to those of the grounded base circuit.

(c) *The Grounded Collector Circuit* has properties similar to the grounded plate "cathode follower" triode circuit. No phase reversal takes place and the output impedance is considerably lower than the input impedance. Input and output impedances are interdependent. Input impedance for the point contact case may be on the order of 40,000 ohms with a corresponling output value of 5,000-10,000 ohms. The step-down ratio for the junction transistor may be even greater — 4500 ohms to as low as 25-30 being possible. As in the cathode follower, the power gain in the grounded collector circuit is low. Figures ranging from 10 to 15 db have been reported for the point contact transistor, and up to 17 db for the junction type. A unique property of the grounded collector transistor occurs when the current gain factor is allowed to exceed 1, which is common in type A units. Under this condition, the amplifier may become *bidirectional*, amplifying signals going in either direction.

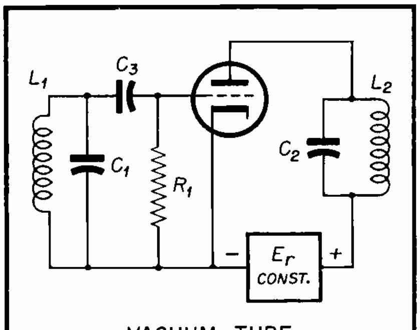
The Duality Principle

The most useful tool which has been used in the development of transistor circuits is the principle of *duality*. By the employment of this technique, standard vacuum tube circuits may readily be "extrapolated" to transistor circuits having similar properties.

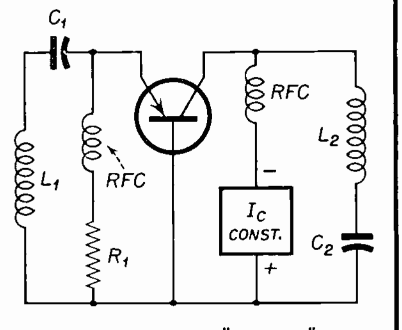
The basic concept in duality is that the transistor is a current operated device rather than a voltage operated device like the vacuum tube. Therefore, replacing circuit elements having certain voltage characteristics in the standard vacuum tube circuits with elements having similar current characteristics, and *vice-versa*, will lead to a circuit which functions well, in a surprising number of cases, when a transistor is substituted for the vacuum tube. This interchangeability of voltage and current functions is quite graphically illustrated in Fig. 8, where the static characteristics of the triode tube and the transistor are compared. Note that emitter *current* bias replaces grid *voltage* bias, collector *current* replaces plate *voltage*, and collector *voltage* is interchanged with plate *current*. Note also that the voltage gain factor of the triode (*mu*), the ratio of plate *voltage* change to grid *voltage* change, has been replaced in the transistor characteristic by *alpha*, the ratio of collector *current* change to emitter current change.

Some of the common circuit elements and their corresponding *duals* are compared in Fig. 9. Note that in each the role of current and voltage are interchanged. The dual of a capacitor, for example, in which the *current* is proportional to the time rate of change of the impressed *voltage*, is an inductance, in which the *voltage* drop is proportional to the time rate of change of the *current*. Similarly, the dual of the conventional parallel resonant circuit used for tuning in vacuum tube circuits because it develops high impedance and voltage) at resonance, is a series resonant circuit in transistor practice since it exhibits low impedance (passing high current) at resonance. Likewise, the dual of a voltage step-up transformer is a current step-up transformer, as shown.

As an example of the use of the duality technique, suppose that it is necessary to convert the standard tuned-plate, tuned-grid vacuum tube oscillator of Fig. 10a into a transistor oscillator. To do this by duality, the circuit elements of Fig. 10a would be replaced by the corresponding dual circuit elements shown in Fig. 9. The parallel resonant combinations L1, C1 and L2, C2 are replaced by low impedance series resonant circuits, the d.c. bias blocking capacitor (C3) is replaced by the r.f. blocking inductance (RFC), the high grid bias resistor (R1) would be replaced by a low resistance, and the constant plate voltage supply would be replaced by a constant current collector supply. The resultant transistor circuit is shown in Fig. 10b.



VACUUM TUBE T.G.T.P. OSCILLATOR



TRANSISTOR "T.E.T.C." OSCILLATOR BY DUALITY

FIG. 10

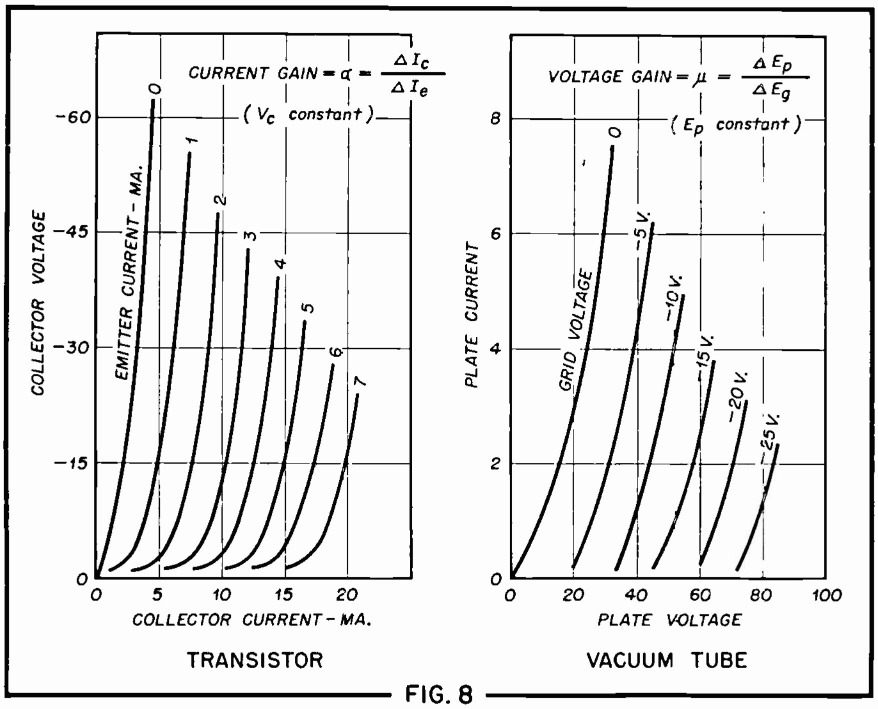
with the n-type point contact transistor and are more similar to the connections made in conventional vacuum circuits.

With the circuit connections shown, current flow in the collector circuit depends upon the availability of free electrons from the base, but since this material is p-type, it has no n-carriers to offer. In other words, the collector is biased in the *reverse* direction and the base-collector impedance is very high; it is sometimes as much as 10 megohms. The emitter circuit, on the other hand, is biased in the *forward* direction so that the base must be made only a fraction of a volt positive in order to cause the free electron (in our vastly simplified example) to flow from the n-type emitter material into the base region. How this electron (or one just like it) can diffuse into the collector region may be visualized by assuming that when it flows across the n-p barrier, it fills the "hole" in the boron impurity atom. This "hole" was on the n-p side of the boron atom near the barrier since it was attracted by the negative potential of the emitter and repelled by the collectors positive charge. When the emitter electron fills the defects or "hole", it weakens the hold which the nucleus of the boron atom has on one of the valence electrons on the collector side of the atom since the positive charge of the nucleus is only 3 and it cannot retain more than three electrons effectively. This electron is thus pulled out by the collector potential and flows into the collector which then migrates back to the emit- germanium. This creates another hole ter side of the base and is thus again in position to "ferry" another electron. Thus, for each electron which flows from the emitter to the base, one is freed to flow from the base to the collector. For this reason, the current gain factor, *alpha*, never exceeds unity in a junction transistor. Very high power gains are possible, however, because of the very high ratios of output circuit to input circuit impedance.

The outstanding characteristics of the junction transistors are low noise figure, higher efficiency, higher gain, and improved power handling capabilities. Its most unique feature is its ability to operate with good efficiency at extremely low power levels-in some cases as low as a few tenth of a *microwatt*. The frequency limitations of the junction transistor may be more severe because of the increased capacitance of the bulk-type junctions.

Transistor Circuitry

The three possible ways a transistor can be connected to function as an amplifier are compared with their nearest vacuum tube analogs in Fig. 7. The transistor symbol used here has been adopted to represent transistors of both the point contact and junction varieties. The emitter is distinguished by an arrow head and the base is represented by a straight line.



TRANSISTOR

VACUUM TUBE

FIG. 8

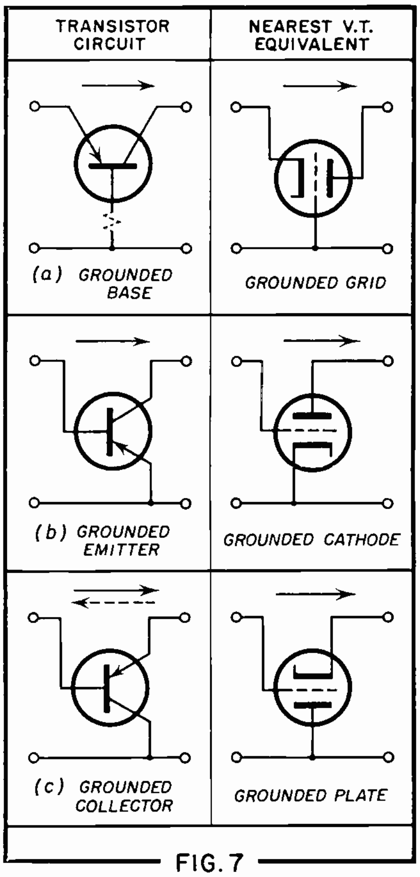


FIG. 7

Each of the three basic transistor circuits, like its vacuum tube counterpart, has certain characteristics not exhibited by the other two. These may be summarized briefly as follows:

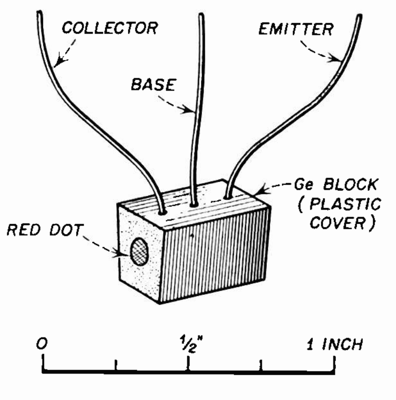
(a) *The Grounded Base Circuit* compares most favorably with the grounded grid triode tube circuit since the input impedance is low, the output impedance is high, and there is no phase reversal through the amplifier. Typical input-output impedance ratios in this circuit would be 400:20,000 ohms for the point contact transistor and about 100: 10,000,000 ohms for the junction type. Power gains are moderate; about 16-18 db for the Type A and 50 db for the junction variety. The operating stability of the grounded base circuit is limited by the *base resistance*, indicated schematically in Fig. 7a by dotted lines. Current flowing through the resistance of the germanium base material produces a regenerative feed-back voltage which can cause oscillation at high gain.

(b) *The Grounded Emitter Circuit* is closely analogous to the triode grounded cathode circuit. The impedance is higher than in the grounded base circuit, and the output impedance is lower. Typical values of beam of light which strikes the semiconductor surface opposite to the one which the collector contacts. The germanium must be ground very thin at this point, as in the coaxial transistor. Otherwise, the "holes" liberated by the impinging light energy would recombine with stray electrons before being collected by the collector. This electrode is biased negatively, as indicated by the simple phototransistor circuit of Fig. 3, so that it will attract the positive "hole" carriers.

The response curve of the phototransistor peaks in the infrared wavelength region (around 1 micron) but also shows satisfactory response in the visible light portion of the spectrum. A unique characteristic of the phototransistor is the small area of its light sensitive surface. Only light falling on that portion of the dimpled germanium pellet immediately under the collector contact will result in an increment in output current. This spot is only .010 inch in diameter. Such localization of the photosensitive region should prove useful in many applications. The response characteristics of a typical phototransistor operating into several different values of load resistance are shown in Fig. 4.

The Junction Transistor

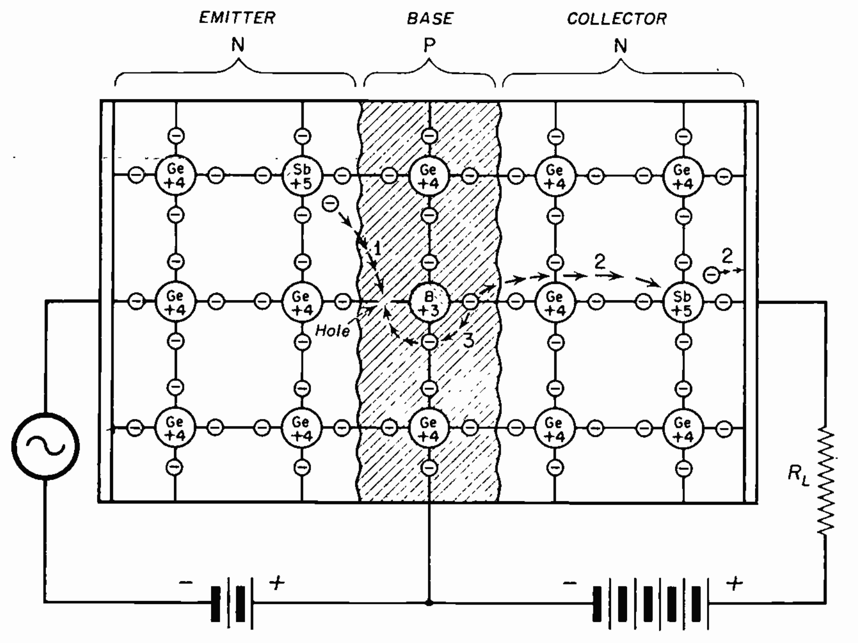
The most significant recent advance in the field of semiconductor devices was the introduction of the *junction-type* transistor. This new form of semiconductor triode immediately overcame several of the serious limitations of the point contact type and put the transistor within "striking distance" of many vacuum tube applications which the point contact varieties had fallen short of fulfilling.



A JUNCTION TRANSISTOR

FIG. 5

The physical appearance of the junction transistor is shown in Fig. 5. It differs from the point contact type in that the rectifying barrier layers are formed by boundaries or junctions between different types of germanium semiconducting material. The junction transistor is a "sandwich" of a thin layer of *p-type* germanium between two layers of *n-type*, or *vice versa*. The three layers must be in very intimate contact; the best results being obtained when all three are formed in a *single crystal* of germanium. Most of the difficulty of fabricating junction type transistors arises in controlling the thickness of these layers, especially the center (p-type) one which may be only .001 inch thick, and in attaching wire leads to them. The transistor is called an "n-p-n" junction type if the layers occur in that order, or a "p-n-p" type if the reverse is true. In the n-p-n kind, which we will discuss here, the thin layer of p-type material is considered the "base", while the n-type germanium on either side are designated the "emitter" and the "collector".



ILLUSTRATING ACTION OF JUNCTION TRANSISTOR

FIG. 6

It will be recalled that the difference between n-type and p-type semiconducting materials results from the nature of the impurities present in the otherwise pure semiconductor crystal structure. For example, in the case of germanium, if only impurities having five valence electrons are present to form electron-pair bonds with the four valence electrons of the germanium atoms, the result will be *n-type* germaniums since the "left-over" electrons are free *negative* carriers. Such *pentavalent* impurities are antimony, arsenic, and phosphorus. On the other hand, if the impurities present are elements which have only three valence electrons, such as gallium, boron, and aluminum, the resulting semiconducting is termed *p-type*. This is because the three valence electrons leave defects, or "holes" in the electron-pair bonds with the *tetravalent* germanium atoms. These "holes" behave like positive charges migrating through the germanium crystal and are attracted to a negative electrode.

It is more difficult to understand the functioning of a junction transistor than the point contact type, since the basic mechanism involved is somewhat more complicated. Some idea of its action can be gained by a careful study of Fig. 6, which shows not only the external circuits involved, but also the highly simplified internal structure of a hypothetical n-p-n junction transistor in which the p-layer is only one germanium atom thick. In this example, one impurity atom of the proper valence is indicated in each of the three layers. In actual practice the ratio may be of the order of one impurity atom for each *ten million* germanium atoms for proper transistor action. Note that the polarities of the applied potentials are opposite to those used

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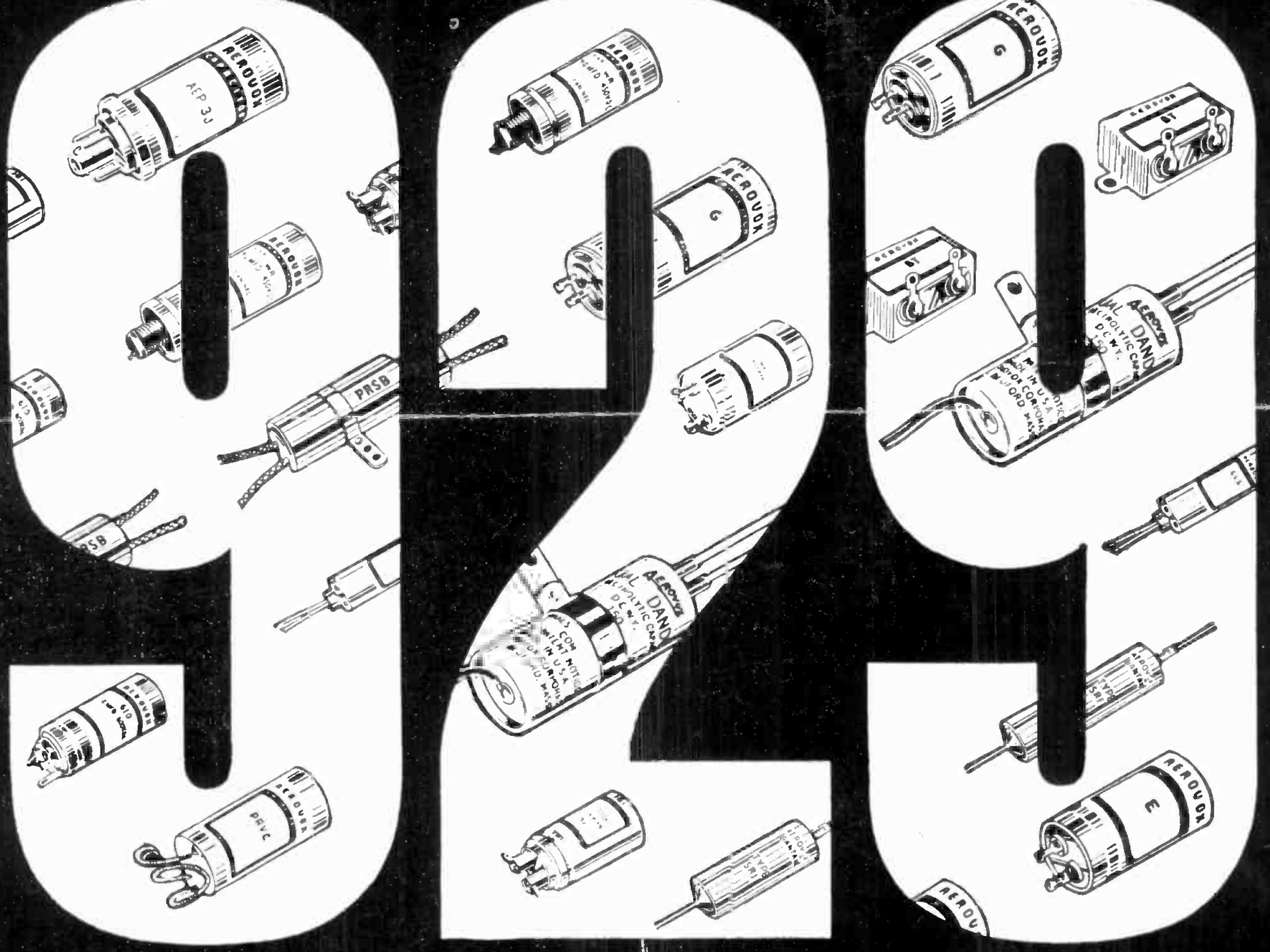

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