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"The Transistor - An Amplifying Crystal"

By the Engineering Department, Aerovox Corporation

AMONG recent technical developments, the "Transistor" or semiconductor triode, will probably have the most far-reaching effects upon every field of electronics. Although still in an embryonic stage comparable to that represented by the deForest "audion" in the development of the vacuum tube, the implications of this tiny, heaterless, vacuumless capsule are so tremendous as to warrant the interest of every worker in the radio field.

Just as the unidirectional conduction of current in the thermionic diode (Edison effect) was known for over 24 years before the addition of a third controlling element in the form of a grid, the rectifying properties of such semiconductors as galena, iron pyrites, silicon and germanium have been used in radio applications for many years. During this time very little thought was given to the possibility of electronically controlling such rectification. However, due to impetus gained through the widespread use of crystals as microwave mixers and detectors during the last war, recent research in the field of semiconductors has resulted in the discovery of the crystal triode, or Transistor.

Physically, the transistor consists of a conventional crystal diode such as was used in great numbers during the last war in radar receivers, modified only by the addition of a second "cat-whisker" contact. This makes contact with the germanium semiconductor at a point very close to the point of contact of the first cat-whisker, but is otherwise insulated from it. It is the addition of this element to the device which permits control of the current flowing to the first and enables it to perform many of the functions of a vacuum tube triode, although in a different way, as will be shown.

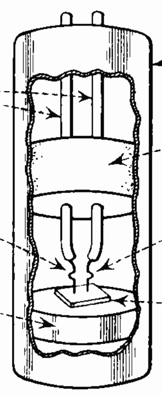
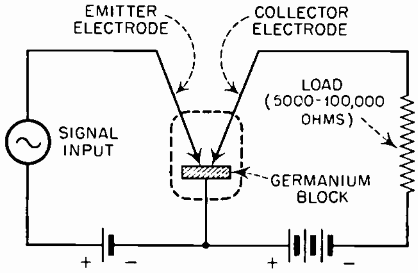


FIG. 1

The construction of the transistor, as pioneered by the Bell Telephone Laboratories, is shown in Fig. 1. This mounting closely resembles the "coaxial cartridge" type commonly used in rectifier crystals, except that two center conductors are used. A small rectangular "wafer" of the semiconductor (germanium crystal) is soldered to a brass disc, which in turn is fitted into one end of a small metal tube approximately 3/16 inch in diameter and 3/4 inch long. Thus the device is comparable in size to a half-watt resistor. The two cat-whiskers are of tungsten wire approximately .002 inch in diameter welded to the ends of rigid wire terminals which in turn are spaced by an insulating bead. This supports them within the metal tube so that both cat-whiskers are brought into contact with the highly polished surface of the germanium. The separation between the points of contact is maintained at between .002 and .005 of an inch. The structure is ruggedized against mechanical shock and vibration by impregnating the capsule with a low-loss wax compound which also renders it moisture proof. It is probable, that, as the development of this mechanically simple device progresses, new applications will dictate radical departures from this preliminary design.

Experimental applications to which the transistor has been adapted include; radio-frequency amplifier stages, audio and r.f. oscillators, intermediate frequency amplifiers, audio amplifier stages and other types of circuitry now commonly employing vacuum tubes. As yet, the upper frequency limit of the transistor is about 10 megacycles per second, but there appears to be no fundamental reason why this range of usefulness cannot be extended into at least the VHF region to include television and f.m. applications. However, transit-time effects, inherent in semiconductor devices as in negative-grid vacuum tubes, will probably limit operation beyond the VHF range. Although diode crystal rectifiers are efficient as detectors and converters of microwave energy at frequencies exceeding 25,000 megacycles/second, the type of high-inverse-voltage germanium semiconductor used in the present transistor is not an efficient rectifier at frequencies much above 60 megacycles/sec.

Another limitation to the use of the transistor in some circuit applications is the excessive noise voltages generated within it at present. This noise is about 70 d.b. above the theoretical thermal or *Johnson Noise*, which is defined as the noise that would be generated in an equivalent resistance due to the random motion of thermally agitated electrons within it. This objectionable noise characteristic is most pronounced at the audio frequencies and appears to decrease somewhat with frequency. Future laboratory work will undoubtedly result in methods of reducing such noise to more usable levels. If noise figures comparable to those encountered in the modern vacuum tube are achieved, the transistor will replace tubes in many low-power applications, since it consumes no heater or filament power, requires no warm-up time, is virtually heatless in operation and is more compact and rugged than even the subminiature vacuum tubes. Because of these advantages, transistors will find use in circuits where economy of power consumption and extreme compactness are desirable. Such circuits may include ultra-portable broadcast receivers using printed wiring and components, electronic computing devices which may require as many as 18,800 vacuum tubes (as in the ENIAC), electronic musical instruments which also use hundreds of vacuum tubes operating at low audio levels and other more conventional applications. The mere fact that the transistor does not require a vacuum is an important advantage, since the production and maintenance of a satisfactory high vacuum is an item of major expense in the manufacture of electron tubes. In addition, the operating efficiency



BASIC TRANSISTOR CIRCUIT
FIG. 2

of the transistor exceeds that of vacuum tubes in many applications, especially when it is considered that no heater power input is required. Operating efficiencies as high as 25% have been observed at output levels of from 10 to 20 milliwatts.

The basic electrical circuit of the transistor is shown in Fig. 2. The input electrode, which is called the "emitter," is maintained at a small positive potential with respect to the germanium block. The impedance to current flow in this direction is low (100-400 ohms) due to the rectifying action of the germanium-tungsten contact. Therefore, this small positive "bias" voltage (.1 to .5 volt) causes an appreciable "forward" current to flow in the emitter circuit. Also, because of this low impedance to forward currents, a small increment in emitter voltage caused by an impressed signal will result in a large increase in electron current flowing from the semi-conductor to the cat-whisker. The static voltage-current characteristic of the emitter circuit, when considered alone, is similar to that of the typical germanium point-contact rectifier, which is shown in Fig. 3. On the other hand the "collector," or output contact of the transistor, is biased negatively with respect to the germanium. At this polarity, the impedance to current flow is relatively high (exceeding 10,000 ohms), so that over 30 volts may be applied to the collector before appreciable "back" current flows in the semiconductor. The dotted portion of Fig. 3 represents the static (no load) characteristic of the collector circuit in the absence of the emitter. The close proximity of the two cat-whiskers with their respective operating voltages modifies these characteristics considerably, however. It is the ability of the transistor to transfer an emitter voltage change to the collector circuit in the form of a resistance change, which gives the device it's name, which means TRANSFER RESISTOR. This property results in effective power gains of 100 times or 20 db being possible.

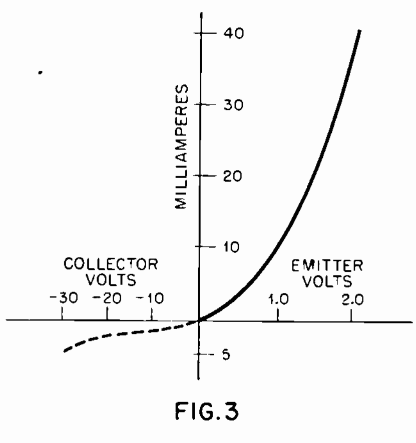


FIG. 3

To understand the mechanism whereby emitter circuit power variations induce relatively larger power variations in the collector circuit and hence, enables the transistor to amplify, it is necessary to examine the fundamental properties of semiconductors. Although the theory of the transistor is still not completely understood and may be subject to frequent revision, a working concept of it's operation can be gained from a simplified analysis and by drawing analogies to vacuum tube circuits.

It will be recalled that the resistance properties of substances depend on the number of free electrons available in the molecular structure for the conduction of current. In some materials the electrons in the outer "shells" or orbits of the atoms are so loosely bound to the nuclei that they are easily removed and may move about between atoms under the influence of thermal agitation. If an external stimulus is applied, such as the connection of a battery across such a material, the random motions of these free electrons within it are coordinated into a unidirectional current flow. The metals, which may have as many as one or two free electrons per atom, are examples of such materials which are good conductors of electricity. Other substances, on the other hand, may have virtually no free electrons available for current conduction and so are classed as insulators. The semi-conductors are intermediate between metals and insulators in the scale of conductivity, having perhaps only one free electron for every million atoms. The extent and type of current conduction possible within them is dependant upon the very minute quantities of inpurities present. Thus, although perfectly pure germanium, (if obtainable), would be a very poor conductor at normal temperatures, the addition of quantities as small as

.001 percent of tin or some other impurity provides enough free carriers for conduction to be possible. The word "carriers" is used here since current in a semiconductor can be carried in two distinctly different ways; by the presence of free electrons within it, or by the absence of some of the "bound" ones. The latter type of conduction the solid-state physicist has termed "conduction by holes." These "holes" are vacancies in the otherwise filled lines of *valence* electrons which make up the interatomic bonds of the crystal, and they constitute *virtual* positive charges. They may move along in a random manner by being filled in by an adjacent electron, which in turn leaves a "hole" behind it. Thus, the process continues with the "hole" moving at rather high speed through the crystal as the atoms attempt to maintain equilibrium between themselves. If a voltage is applied across such a semiconductor, the holes, being positive in nature, are attracted to the negative electrode instead of to the positive electrode as is the case of free electrons. Whether a semiconductor conducts by the extra negative electron process (n-type), or the "positive hole" process (p-type), depends on the kind of impurity added. Thus, silicon "doped" with aluminum or boron impurity is a p-type semiconductor, while silicon containing minute quantities of phosphorus is an n-type. If the added impurity atom has one less valence electron than the semiconductor atom, a p-type ("hole") semiconductor results. If it has one more valence electron, an n-type crystal results. The type of conduction in germanium can also be changed by heat-treatment.

In the transistor, both n-type and p-type current conduction are present. The emitter is biased positively so as to attract free electrons which surmount the rectifying barrier layer at the interface of the semiconductor-to-metal contact and flow in the input circuit. The collector, biased highly negative, attracts a small number of "holes" in the absence of emitter current. The useful property of the transistor arises from the fact that a flow of electron current to the emitter cat-whisker causes the formation of many more electron vacancies or "holes" at the surface of the semiconductor which are gathered by the nearby collector cat-whisker. The result is an increase of output current. A change in the emitter circuit current "modulates" the number of "holes" available to the collector and thus causes a similar change in collector current. Although the current changes in the input and output circuits are of similar magnitude, amplification results since the collector circuit impedance is approximately 100 times that of the emitter circuit. Fig. 4 shows the way in which the collector current and emitter current vary with emitter voltage at given value of collector voltage.

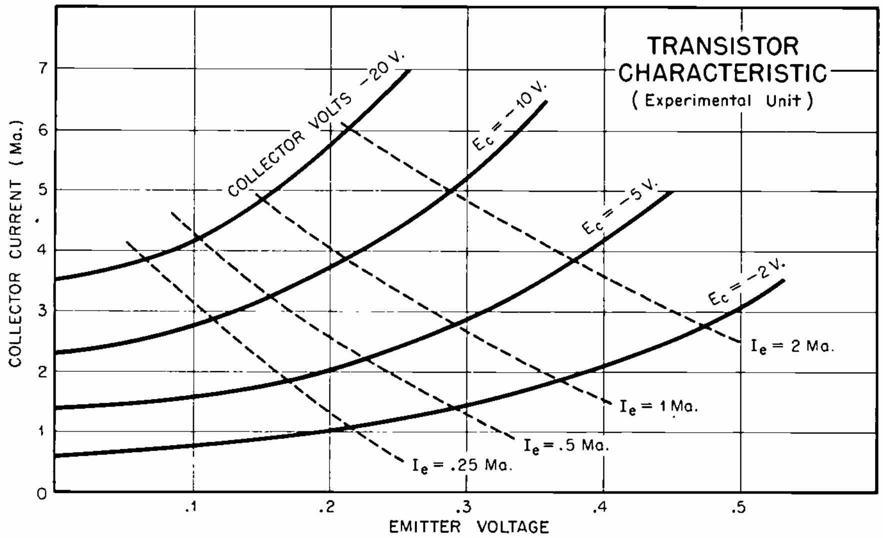


FIG. 4

A vacuum tube circuit which has characteristics closely analogous to the action of a transistor is shown in Fig. 5. In this circuit the transistor is replaced by a dual-diode vacuum tube which contains a small quantity of residual gas. The two small anodes are spaced close together and are biased by voltages of similar polarity to those applied to the two contacts of the transistor. The anode which is at a small positive potential with respect to the cathode has characteristics which are comparable to the emitter electrode; it attracts electrons from the cathode and thus it's circuit presents low impedance to "forward" current flow. The diode plate which is biased negatively is analogous to the collector cat-whisker of the transistor in that the circuit impedance is very high and little current flows in it normally. However, the flow of current in the "emitter" may be made to increase the current flowing in the collector circuit. Electrons being accelerated toward the emitter anode may collide with residual gas molecules, remove electrons from them, and thereby form positive ions which are drawn to the negative collector anode. These ions are roughly analogous to the "holes" in the transistor case since they behave like positive particles and move more slowly than electrons. The number of ions formed depends upon the number of electrons flowing to the emitter anode. Therefore, the input circuit controls the flow of current in the output circuit, just as in the transistor and conventional vacuum tube amplifiers.

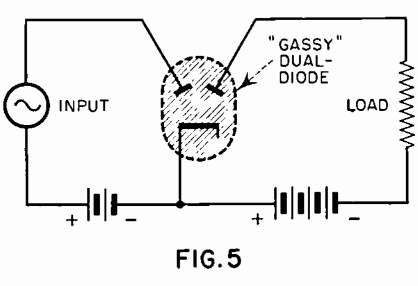


FIG. 5

The advent of the transistor opens fertile fields for future development. Much remains to be done in the adaptation of conventional circuitry for use with this simple device. Problems frequently arise since the electrode voltage polarities and circuit impedances differ so greatly from those encountered in vacuum tubes. The cascading of amplifier stages is complicated by the fact that the input and output impedances do not lend themselves well to the usual schemes of interstage coupling. The possibility of push-pull and paralleled units for increased power output is still to be fully exploited.

Because of it's simple structure and the small amount of test equipment required, the transistor provides a valuable subject for individual experimentation. Transistors have been fabricated for study purposes from germanium removed from standard 1N34 diode crystal rectifiers suitably mounted with two adjustable fine wire cat-whiskers.

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