

understanding transistors



Allied's handbook of
transistor fundamentals



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UNDERSTANDING TRANSISTORS

Allied's Handbook of Transistor Fundamentals

by

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UNDERSTANDING TRANSISTORS

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Seven typical transistors are shown in the front row. Left to right: NPN power, PNP power, NPN computer, PNP medium-power audio, RF-IF NPN, NPN switching and PNP audio. The tubes in second row show relative size of tubes and transistors—left to right: transmitting, octal receiving and miniature receiving.

TRANSISTORS

The development of the transistor in 1948 is destined to be one of the great achievements of 20th Century electronics. If we consider the vacuum tube as man's first significant advance into the field of communications, then the transistor must certainly be heralded as man's second most important step. For here, surely, is as radical a departure from what has heretofore been done as the discovery of the triode by Dr. Lee De Forest in 1906.

The most obvious advantages of transistors lie in their higher operating efficiency and smaller size than comparable electron tubes. A transistor, being a solid, requires no special envelope surrounding a vacuum; furthermore, it requires no filament heating element to serve as the provider of electrons. The latter fact alone represents a considerable saving in power, since in most standard receiving tubes, as much or more power is expended in heating the filament as in drawing current through the tubes. Add to this a volume which is on the order of one-thousandth that of a vacuum tube and a weight which is reduced by a factor of 100 and the benefits of the transistor become quite evident.

Operation of vacuum tubes depends upon the flow of electrons from filament to plate and the control of this flow by intermediate grids. Operation of the transistor is also largely dependent upon an electronic flow, although there are considerable differences between the two units. In order to appreciate these differences, it is best to review what we know concerning the structure of matter and the role the electron plays in that structure.

Atoms and Molecules. Every substance or material that we come in contact with or which is known to man can be divided ultimately into particles known as atoms. These are the smallest segments into which a substance can be divided and still retain all its individual characteristics. Although atoms are so minute we are incapable of seeing

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them, still we know quite a bit about them. Chemists and physicists have discovered over a period of hundreds of years that there are something like 101 different kinds of atoms which, either singly or in combination, make up all the matter on this planet. The most familiar of these are hydrogen, oxygen, gold, silver, nickel, copper, iron, etc. Atoms can be further subdivided into smaller particles, but when we do this, they no longer retain their distinctive characteristics.

The Germanium Atom. Germanium is one of the elements most widely used in the manufacture of transistors. It consists of a central nucleus of 32 protons, each proton having a positive charge of electricity. Offsetting this are 32 negative electrons which rotate around the nucleus in relatively fixed orbits. On closer examination, it will be found that the orbits can be divided into fairly well-defined shells or energy levels. The level closest to the nucleus contains two electrons; the next level contains eight electrons, followed by a third level or shell of 18 electrons. Finally, there is, for germanium, a fourth level and here the remaining four electrons are found. These four electrons, situated in a shell which is not completely filled, govern the chemical activity of the germanium atom. For this reason, they are frequently given the name of valence electrons.

Germanium in the solid state possesses a crystalline structure in which a group of germanium atoms combine to form a repeated struc-

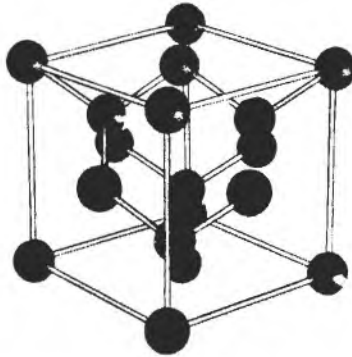


Fig. 1. Representation of the crystal lattice structure of germanium.

ture having a number of basic cubical lattices such as shown in Fig. 1. Each of the dark "balls" in the illustration represent the germanium atom; the rods between the balls represent the forces binding each atom to its neighbors.

A two-dimensional illustration of the manner in which the germanium atoms are bound to one another is given in Fig. 2. Focusing our attention on any one of the central atoms, we see that each of its four outer electrons (i.e., the valence electrons) is shared by four other germanium atoms. This gives the central atom a total of eight electrons

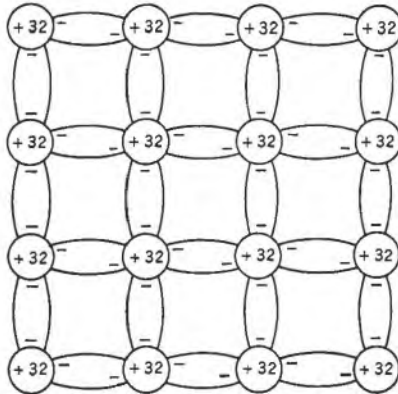


Fig. 2. Representation of electron-paired bonds in germanium. Note that only the valence electrons for each germanium atom are represented.

in its outermost ring; four of these electrons represent its own electrons, and the other four, electrons which it "borrows" from the surrounding atoms. Since eight electrons in a ring provide for a stable arrangement, the germanium crystal thus forms a stable structure.

What is true of the central atom is true of all its neighbors, each sharing its four outer electrons with four other germanium atoms. This, too, is shown in Fig. 2 for a limited number of atoms. All the valence electrons are tightly held together. Consequently, pure germanium is not a very good conductor of electricity. A good conductor would require an abundance of free electrons, and as we see, all electrons in germanium crystal are held fairly tightly because, in combination, they tend to complete the outer sub-ring of the germanium atoms.

That the substance is not a complete insulator, but rather a semiconductor, stems from the fact that thermal agitation, arising from the energy imparted to the electrons by the heat of its surroundings, causes an electron here and there to break away from its bond and wander through the crystal lattice structure in a more or less aimless manner.

Electrons and Holes. The bond from which an electron escapes is now left with a deficiency of one electron, and hence we should find

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here a positive charge of one. This electron deficiency has been given the rather descriptive name of "hole," as though a physical hole had actually been left by the removal of the electron.

We have been conditioned by our previous training to accept the fact that electrons are quite mobile and may be moved readily from point to point. Numerous tests have been performed in which this fact has been demonstrated, and in our own experience with electrical circuits we have never encountered any action which would cause us to think otherwise. Hence, when the statement is made, as it was above, that the freed electron wanders aimlessly through the crystal, every reader will accept it without question.

It is, however, also valid in this case to state that the hole left by the electron will also wander about within the crystal structure, and on this point we would run into a general raising of eyebrows. And yet, it has been conclusively demonstrated that holes do travel through germanium crystals. In fact, the concept of hole travel is basic to an understanding of transistor operation and hence warrants a more detailed description.

When a bound electron departs, the charge deficiency, or hole, that it leaves behind is confined to the valance ring of the atom. If, now, a nearby electron held in a convalent bond acquires enough energy to

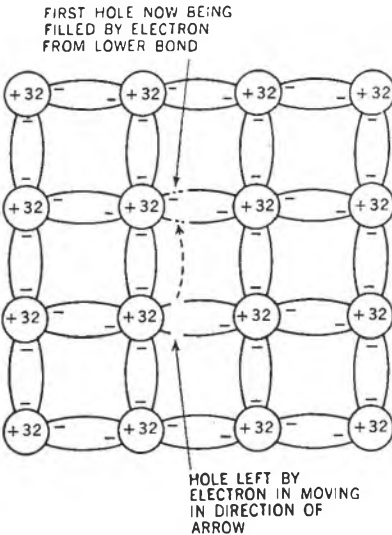


Fig. 3. Method by which holes travel through the germanium lattice structure.

leave its bond and jump into the waiting hole, then in essence what we have had is a shift in position of the positively charged hole from its first position to this new position (see Fig. 3). This same action can occur a number of times, with successive changes in hole position, so we can very well state that a hole drifts about in a random manner in exactly the same fashion as the electron which left the hole originally.

The foregoing discussion has dealt with a single electron and a single hole, but in actual crystals there would be many such pairs. And with many negative electrons and positive holes present, a considerable number of recombinations will be taking place all the time. By the same token, the energy (be it heat or light or an electric field) being supplied to the crystal will constantly be breaking other bonds. Eventually, a dynamic equilibrium will be reached in which the number of bonds being broken will equal the number being reformed.

If the energy supplied to the crystal is an electric field developed by the application of an electromotive force (emf) across the germanium crystal, then the motion of the electrons and the holes will be less random and more directed along lines determined by the voltage. Electrons will move toward the positive terminal of the battery, while the holes will drift toward the negative terminal of the battery.

N-Type Germanium. Externally applied heat and light may be used to produce free electrons and holes in a germanium crystal, but a much more efficient method of achieving the same result is to add exceedingly small amounts of selected impurities, generally to an extent no greater than 1 part in 10 million. One of the impurities frequently employed is arsenic. This enters the crystalline structure of the ger-

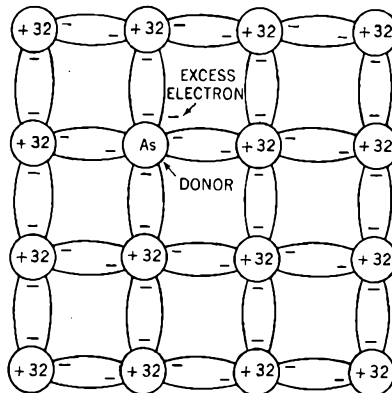


Fig. 4. The effect of an arsenic atom replacing a germanium atom.

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manium atoms at various points throughout the crystal lattice structure. A diagrammatic representation of this condition is shown in Fig. 4. Arsenic has five valence electrons, and four of these electrons enter into covalent bonds with four surrounding germanium atoms. This is in accordance with the structural arrangement in a germanium atom. The fifth electron is simply held in place by the positive attractive power of the arsenic nucleus. However, since the arsenic atom is sharing its other four electrons with four other germanium atoms, in essence it possesses the equivalent of eight electrons. Since all that the arsenic atom needs for a stable arrangement is eight electrons, the force with which the extra (i.e., the fifth) electron is held is fairly weak and the bond between this electron and the atom is easily broken. Thus, by the addition of minute quantities of arsenic to the germanium structure we have, in effect, provided the germanium with a source of free electrons. Substances like arsenic or antimony which serve as sources of electrons are called donor impurities. Furthermore, the germanium crystal containing these donor atoms is known as N-type germanium. The N, of course, refers to the fact that the electrical conduction through the crystal is done by electrons which possess a negative charge.

P-Type Germanium. It is also possible to add impurities which possess three, rather than five, electrons in their outer orbit. Boron, gallium, and indium are examples of such substances. As with the arsenic, each trivalent impurity atom will replace a germanium atom in the lattice structure (see Fig. 5). However, in this case, instead of having an excess of one electron, we now find ourselves with a deficiency of one electron. In order to complete the four electron pair bonds, the trivalent

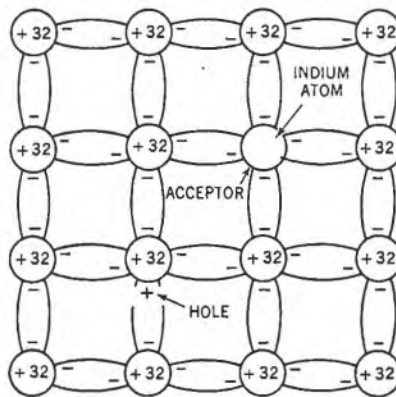


Fig. 5. A hole is produced when a trivalent impurity, such as indium, replaces a germanium atom.

atom robs an electron from a nearby germanium bond. The net result of this "robbery" is to leave a hole in the neighboring electron-pair band.

Thus, when the impurity added to the germanium crystal structure has only three valence electrons, a series of holes are produced. Under the pressure of an applied emf, electrons from other nearby bonds will be attracted to these holes, filling these gaps but creating a similar number of holes in their former bonds. Thus, we have the equivalent of a movement of holes through the crystalline structure, and conduction is said to take place by holes.

Trivalent impurities which create holes are known as acceptor impurities, and the germanium crystals which contain these substances are known as P-type germanium. Thus, by the careful selection of the impurity to be added, we can determine whether the germanium is of the N or P type. Both are employed in transistors, and it is important to understand the differences between them and how electrical conduction occurs through each.

It should be noted that there are a number of holes present in N-type germanium because of the normal breaking of bonds arising from the absorption of heat or light energy.* This is similar to the action in pure germanium. However, the electrons released by the arsenic impurity are, by far, the principal conductors of electricity in N-type germanium. By the same token, free electrons exist in P-type germanium, but again, it is the holes created by the electrical conduction that takes place here.

The impurities must be added in carefully controlled amounts, otherwise the germanium crystal structure is modified to such an extent that transistor action is not obtained.

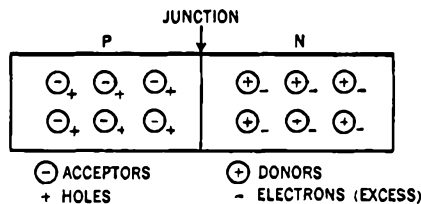


Fig. 6. A PN junction forming a familiar germanium diode.

PN Junctions. If we take a section of N-type germanium and a similar section of P-type germanium and join the two together, as shown in Fig. 6, we obtain a component which we know as a germanium diode.

*The holes in N-type germanium and the electrons in P-type germanium are called minority carriers.

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The N-type germanium is at the right, and the P-type at the left. The circles at the right with the positive sign represent the donor atoms. They possess a positive sign because their fifth electron has been removed, leaving the atom with a +1 charge. The free electron is indicated by the negative sign.

By the same reasoning, the acceptor atoms in the P-type germanium are represented by a circle with a negative sign, the latter due to the presence of the additional electron which was "robbed" from a neighboring electron-pair bond. The hole left by this electron is represented by a small plus sign.

When these two germanium sections are joined together, one might suppose that the excess electrons on the right would immediately cross the junction and combine with the excess holes on the left. This action, however, does not occur and the reason ascribed to this is explained as follows. As the electrons in the N-type germanium approach the junction point, they encounter the repelling force of the negatively charged acceptor atoms. It is this force which prevents them from crossing the junction. A few electrons may acquire enough thermal energy to overcome the repelling force and cross the junction, but this is true only of a relatively small number of electrons. The vast majority of electrons are kept on their side of the border.

In the same manner, the holes present in the P-type germanium try to cross the junction and are repelled by the positive charge of the donor atoms. Hence, they are forced to remain on their side of the junction also.

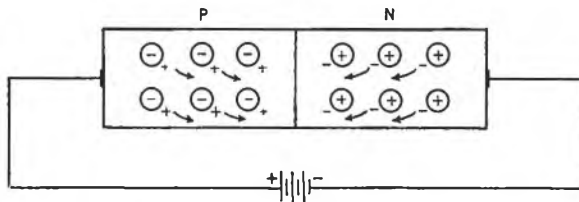


Fig. 7. The effect on the PN junction when forward bias is applied.

Current Flow. In order to produce a flow of current across the junction, we must neutralize the repelling forces that exist here. This can be done by applying an external potential across the ends of the two germanium crystals (see Fig. 7). The negative terminal of the battery connects to the N-type section, and the positive terminal of the battery goes to the P section. The free electrons in the N section are repelled by

the negative battery field and move toward the PN junction. At the same time, the positive holes in the P section are forced toward the junction by the repelling force of the positive battery field. If the battery is sufficiently strong, enough energy (i.e., push) will be imparted to these carriers to overcome the repelling forces at the junction and enable them to move across to the opposite side. Once the junction crossing is made, a number of electrons and holes will combine. For each hole that combines with an electron from the N-type germanium, an electron from an electron-pair bond in the crystal and near the positive terminal of the battery leaves the crystal and enters the positive terminal of the battery. This creates a new hole which, under the force of the applied emf, moves to the junction. For each electron that combines with a hole, an electron enters the crystal from the negative terminal of the battery. In this way, we maintain the continuity of current flow. Stoppage at any point immediately breaks the entire circuit, just as it does in any ordinary electric circuit. If this were not so, then electrons would pile up at some point, resulting in a gradually increasing charge or potential at that point. Since this does not occur, we must treat the circuit operation in the manner which has just been indicated.

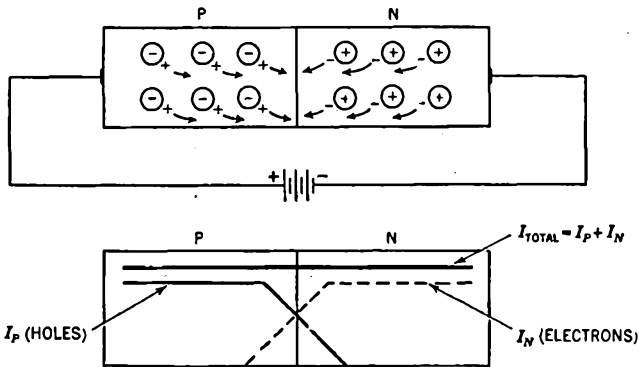


Fig. 8. The current flow in the N region is by electrons; in the P region, the current is carried by holes. In the vicinity of the junction, both types of carriers are present.

Note that current flow in the N region is by electrons; in the P region, the current is carried by holes (Fig. 8). As we approach the PN junction, we find both types of carriers. The over-all value of current, however, remains constant and is a function of the applied voltage.

As the external voltage is increased, it gradually overcomes the restraining forces present at the junction and the current rises. Once the

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restraining forces are completely overcome, the current rises sharply. If the current flow is permitted to reach too high a value, the heat generated will permanently damage the junction and the unit will no longer function in the manner described above.

In the preceding discussion, the diode was biased in its forward, or low-resistance, direction. If, now, we reverse the polarity of the applied voltage, we find that practically no current passes at all. The diode is biased in the reverse direction.

The reason for the current decrease is readily understood. With the negative battery terminal connected to the P-germanium section, the excess holes, with their positive charge, are attracted away from the junction (see Fig. 9). At the same time, the positive terminal of the battery at the N side attracts the excess electrons away from the junction.

To sum up, then, germanium diodes offer a relatively low-resistance when biased in the forward direction and a very high resistance when biased in the reverse direction.

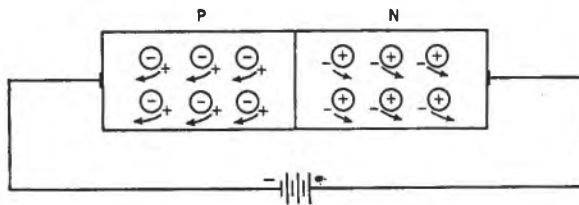


Fig. 9. When the battery connections are reversed, the electrons and holes are drawn away from the PN junction.

JUNCTION TRANSISTORS

Thus far, we have been considering the operation of germanium and the influence that certain added impurities have on its electrical characteristics. All this has been in the nature of preliminary groundwork for the important task ahead, that of understanding how germanium transistors operate. We are now ready to take this step, and we shall start with the NPN transistor, which is merely an extension of the PN junction diode just discussed.

NPN Transistors. An NPN junction transistor is formed by placing a narrow strip of P-type germanium between two relatively wide strips of N-type germanium. This is shown in Fig. 10a. Contact to each strip is made by means of a low-resistance plate, with connecting leads from the plates for external circuit attachment.*

The N-type crystal at the left is called the emitter, the central P-type strip is known as the base, and the right crystal is called the collector. Although these names have no particular significance as yet, they will tie in with the operation of the transistor.

As with the previous PN junction diode, the two end sections contain a number of free electrons, while the central P section possesses an excess of holes. There is no appreciable combination of electrons and holes at the two PN junctions for the same reasons that were indicated for the diode.

To employ this NPN transistor as an amplifier, we would bias the emitter and base sections in the forward, or low-resistance, direction.

*Some transistors, particularly those fabricated by the grown junction method, actually take this form physically. Most other junction transistors assume slightly different forms, although the sequence of emitter, base and collector remains unaltered. However, the transistor form shown in Fig. 10 lends itself quite well to the present discussion and so is being used.

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This is shown in Fig. 10a. At the same time we would bias the base and collector sections in the reverse, or high-resistance, direction (see Fig. 10b). Both bias voltages together are shown in Fig. 10c. Now let us see what happens within the transistor under these conditions.

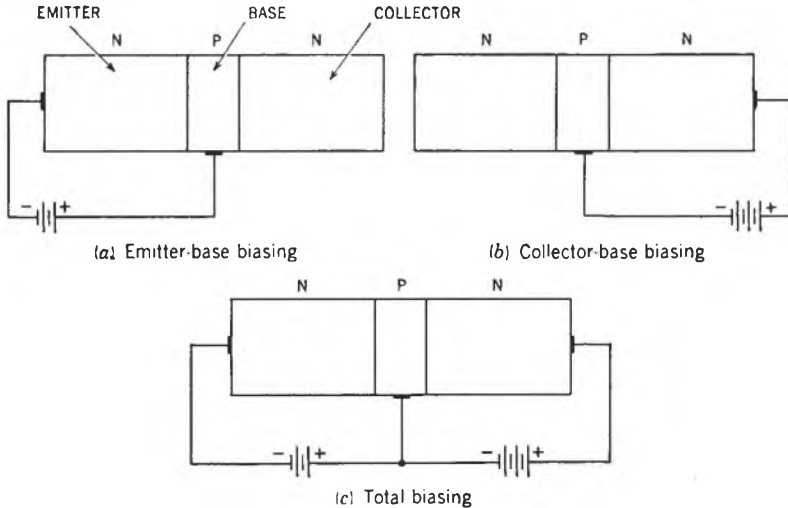


Fig. 10. The NPN transistor and the proper method of biasing it for use as an amplifier.

Since the emitter-base sections are biased in the forward direction, current will flow across their junction. Every time an electron from the emitter section crosses the junction and combines with a hole of the base section, an electron leaves the negative terminal of the battery and enters the emitter crystal. Since the battery cannot continue to supply electrons from the negative terminal without receiving an equivalent number at the positive terminal, then for each electron leaving the negative terminal, the positive side receives an electron from the base section. This loss of electrons in the base creates holes which then travel to the junction for eventual combination with an electron from the emitter.

If the center base section were made quite thick, then practically the entire current flow would occur in the manner just described and be confined entirely between emitter and base. There would be little current between base and collector because of the reverse biasing existing here.

However, the base strip is made exceedingly thin, and because of this, transistor amplifying action is achieved. For with the base thin, electrons leaving the emitter pass right through the base section and into

the collector region, where they see a positive attractive force that impels them on. Thus, they travel through the collector section and around the external circuit back to the emitter again, completing their path of travel.

At this point the reader may wonder why the emitter current flows through the collector when it was specifically stated that the collector was biased in the reverse, or high-resistance, direction. If we disregard the base for a moment and simply consider the path from the emitter to the collector internally and from the collector to the emitter externally, we see that the two bias batteries are connected series aiding. Thus, any emitter electrons that can pass through the base region without combining with the holes present here will find the attracting force of the collector battery urging them on through the collector section. The reverse biasing between collector and base does not affect the emitter electrons that pass through the base and reach the collector.

With the base strip made very thin, the number of combinations between emitter electrons and base holes will be quite small, probably no more than five percent of the total number of electrons leaving the emitter. The remaining 95 percent of the electrons will reach the collector strip and travel through it. Thus, while the number of electrons leaving the emitter is a function solely of the emitter-base voltage, the element which receives most of this current is the collector. The analogy here to vacuum-tube behavior is very marked. In a tube, the number of electrons leaving the cathode (i.e., the emitter) is governed by the grid-to-cathode voltage. However, it is the plate (i.e., collector) which receives practically all of these electrons. In a tube, the amount of current flowing is regulated by varying the grid-to-cathode voltage. In a transistor, the emitter-collector current is varied by changing the emitter-base voltage.

Note, too, that because the base current is very small, a change in emitter bias will have a far greater effect on emitter-collector current than it will on base current. This also is desirable, since it is the current flowing through the collector that reaches the output circuit. (By the same token, it is the current flowing through the plate circuit in a tube that is important).

Transistor Gain. We achieve a voltage gain in the transistor by virtue of the fact that the emitter-to-base resistance is low (because of the forward biasing between these two elements) whereas the collector-to-base resistance is high (because these elements are reverse biased). A typical value for the emitter-to-base resistance is about 500 ohms, and a typical value for the collector-to-base resistance is about 500,000

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ohms. The current that reaches the collector is 95 percent of the current leaving the emitter. If, now, we multiply the current gain (0.95) by the resistance gain $500,000/500$, we shall obtain the voltage gain of the collector circuit over the emitter circuit. Numerically, this is

$$\text{Voltage gain} = \text{current gain} \times \text{resistance gain} = \\ 0.95 \times \frac{500,000}{500} = 950$$

Thus, we see that while the current gain here is actually a loss, this is more than made up by the extent to which the collector resistance exceeds the emitter resistance. Furthermore, this overwhelming differential in resistance will also provide a power gain. This means that with a small amount of power in the input, or emitter-to-base, circuit, we can control a much larger amount of power in the output, or collector-to-base, circuit. Both of these characteristics are important; without them the transistor would have only limited application in electronics.

The voltage gain indicated above is that which would be obtained if the transistor operated into a very-high-impedance circuit. Actually, one of the problems which is encountered in cascaded transistor amplifiers is that of matching the relatively high output impedance of a prior stage with the low input impedance of the following stage.

From the foregoing discussion we can formulate two rules concerning this and *all* transistors.

- 1) The emitter is biased in the forward, or low-resistance, direction.*
- 2) The collector is biased in the reverse, or high-resistance, direction.

At this point, a note of caution regarding the application of reverse voltage to transistors. As we shall see later, the emitter bias voltage is quite small, on the order of 1 volt or less. The collector reverse voltage is generally much higher. If we should mistakenly connect the collector battery in the forward direction, the excessive current flowing through this section will develop enough heat to destroy the junctions and render the transistor worthless. Hence, always be certain the collector voltage polarity is correct *before* connections are made.

*There are occasions, as with vacuum tubes, when it is desirable to bias the transistor to cutoff. In the case of a vacuum tube, this is done by increasing the negative bias on the grid with respect to the cathode. For a transistor, cutoff is achieved by bringing the emitter-to-base bias to zero or even inserting a small amount of reverse biasing voltage. In the majority of applications, however, the statement indicated above is true.

Transistor Amplifier. We are now ready to connect this NPN transistor into an actual amplifier circuit with the signal input at one end and the load resistor at the other (see Fig. 11). The incoming signal is applied in series with the emitter-to-base bias, and the load resistor is inserted in series with the collector battery. When the signal voltage is

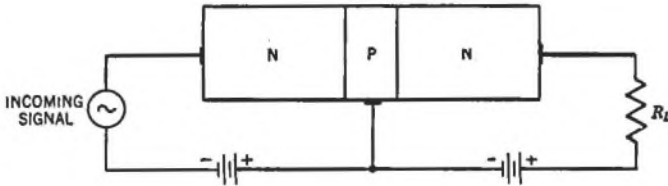


Fig. 11. The NPN transistor connected as an amplifier.

zero, the number of electrons leaving the emitter and entering the base region is determined solely by the forward bias on the emitter. When the signal goes negative, it adds to the forward bias, and causes more electrons to flow through the transistor. During the next half cycle, the signal goes positive, reducing the forward bias of the emitter and thereby reducing the number of electrons leaving the emitter and entering the base and, subsequently, the collector regions.

At the other end of the transistor, these current fluctuations produce corresponding voltage variations across R_L , the load resistor. When the input signal is negative and the current increases the top end of R_L becomes more negative. By the same reasoning, when the signal goes positive, current decreases and the top end of R_L becomes relatively more positive.

Thus, through this transistor, amplification is achieved without the normal 180° phase shift we are accustomed to in vacuum tubes. This is not always true of transistors, and in our subsequent study we shall come across instances when signal phase reversal does occur.

Another point to note here is that with this transistor, an increase in signal polarity (i.e., positive) causes the transistor current to decrease. This is in direct contrast to normal vacuum-tube amplifiers when the signal is applied to the grid. However, we also know that when the signal is applied to the cathode of a vacuum tube, a positive increase is equivalent to a more negative grid and the plate current decreases.

All this is mentioned in an attempt to illustrate that although transistors and vacuum tubes have many points in common, they also differ in many respects, and it is suggested that the reader learn to think of

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each in terms of itself. Later, we shall have occasion to make additional comparisons between these two devices.

PNP Transistors. In the formation of the initial transistor from a PN junction, we added a second N section to evolve an NPN transistor. We can approach the same problem by adding another P section to produce a PNP transistor (see Fig. 12). The emitter and collector sections

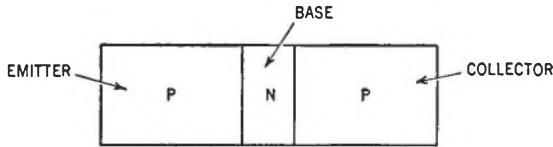


Fig. 12. A PNP transistor.

are formed now of P-type germanium, while the base section consists of N-type germanium. Since this is actually the reverse—as far as material structure is concerned—of the NPN transistor, we should expect differences in the mode of operation and in the polarity of the voltages applied to the emitter and collector. However, in spite of these differences, the emitter is still biased in the forward direction and the collector is biased in the reverse direction.

A typical bias setup with a PNP transistor is shown in Fig. 13. The positive side of the battery connects to the emitter, while the negative terminal of the battery goes to the base. The collector battery is attached in the reverse manner, with the negative terminal connecting to the collector plate and the positive terminal going to the base plate.

Holes are the current carriers in the emitter and collector sections; in the N-type base section, electrons are the principal carriers. With the

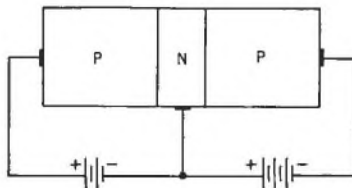


Fig. 13. Method of biasing PNP transistors.

emitter-bias battery connected as shown, the positive field of the battery repels the positive holes toward the base junction. At the same time, the negative battery terminal at the base drives the base electrons toward the same junction. When a hole and an electron combine at the junction, another electron from the emitter section enters the positive battery terminal. This creates a hole, which then starts traveling towards the PN junction. At the same instant, too, that the first hole and electron combine at the junction, another electron leaves the negative battery terminal and enters the base. In this way, current flows through the base-emitter circuit.

In the PNP transistor, the holes are carriers in the emitter section, and when they cross the junction into the base region, a number of them combine with the base electrons. However, over 95 percent of the holes do not combine with base electrons; rather, they pass through the base region and continue on to the collector. Here they meet a negative attractive force and move toward the collector terminal. When the terminal is reached, an electron from the battery combines with a hole and effectively neutralizes it. At the same instant, an electron leaves the emitter region and starts on its way around the outer circuit to the collector battery.

Note, then, that although holes are the current carriers in P-type germanium, current conduction through the connecting wires of the external circuit is carried on entirely by electrons. This fits in with the current conduction that we are familiar with.

The incoming signal and the load resistor occupy the same positions in a PNP transistor amplifier that they do in an NPN transistor amplifier (see Fig. 14). Only the polarity of the biasing voltage is reversed.

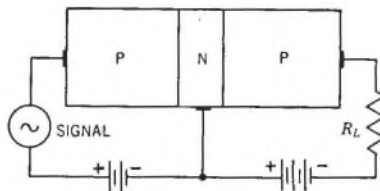


Fig. 14. A PNP transistor amplifier.

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Types of Transistors. NPN and PNP represent the basic construction of transistors. However, within this structure, a number of different transistor types have been developed, some of the more important of which are discussed below.

Alloy Junction Transistors. One of the most common transistors, for example, is the alloy junction type* developed by Radio Corporation of America. This transistor is formed by diffusing indium into germanium. A relatively thick wafer of N-type germanium is taken, and a small pit is drilled into it (see Fig. 15). Then indium is placed on

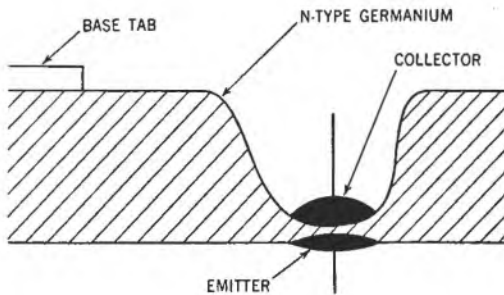


Fig. 15. Basic construction of an alloy junction transistor.

opposite faces of the germanium of this pit, and heat is applied. The temperature chosen is above the melting point of indium, but below the melting point of germanium. The indium alloys into the germanium until the two indium-doped regions are separated by the required distance. The result is a PNP transistor (indium is an acceptor atom). Connections to the indium-germanium alloy emitter and collector sections are made by wires soldered to the alloy. The other ends of these wires are then spot-welded to leads that make contact to the circuit in which the transistor is placed. For protection, the completed assembly is placed in a metal or plastic case and hermetically sealed against moisture (see Fig. 16).

The diffusion, or alloy, method is feasible for both PNP and NPN junction transistors. For an NPN assembly, P-type germanium would be used and a pentavalent element would be substituted for the indium.

Drift Transistor. The drift transistor was developed to overcome the high-frequency limitations of the alloy junction units. These limitations are related in part to the time it takes a carrier (hole or elec-

*These are also called fused junction transistors.

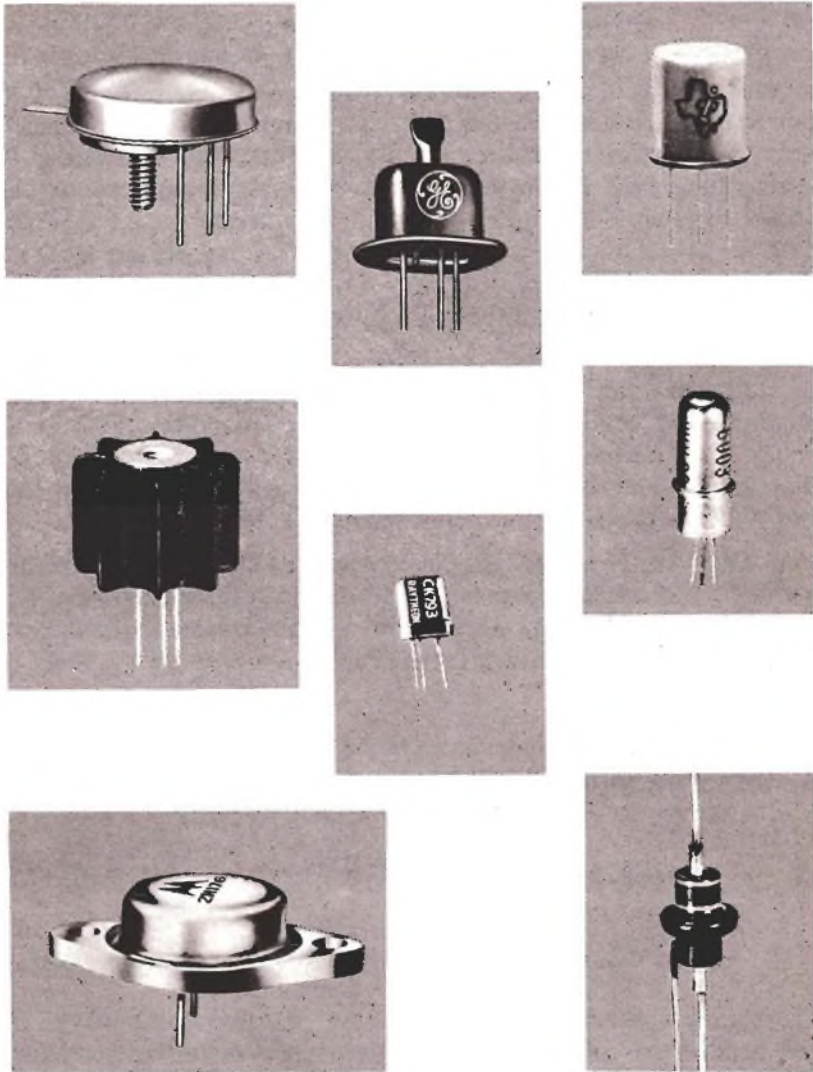


Fig. 16. Typical transistor housings.

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tron) to travel across the base region, in part to the internal collector capacitance, and in part to the input resistance of the transistor.

To speed up the movement of carriers through the base region, the impurities which, in the base of an alloy junction unit are uniformly distributed, are here (in the drift transistor) more highly concentrated near the emitter end of the base region. The result is a built-in electric accelerating field in the base. Holes (from a P-emitter) or electrons (from an N-emitter) entering the base now are subjected to this electric field and their travel time is shortened. The carriers no longer diffuse randomly to the collector as they do in the alloy junction transistor; rather, they drift toward the collector in a more direct path. Hence, the name of a drift transistor.

A drift transistor is constructed by taking a wafer of N-type germanium and exposing it, under controlled conditions, to an arsenic vapor. The arsenic impurity diffuses into the germanium in such a way that its concentration is greatest near the surface, gradually becoming less and less dense the deeper it moves into the germanium.

This skin of graded arsenic is removed from one side of the wafer and a P-type collector junction is alloyed into the etched side. A P-type emitter junction is then alloyed into the other face of the wafer where the graded arsenic is still present. The result, as shown in Figs. 17 and

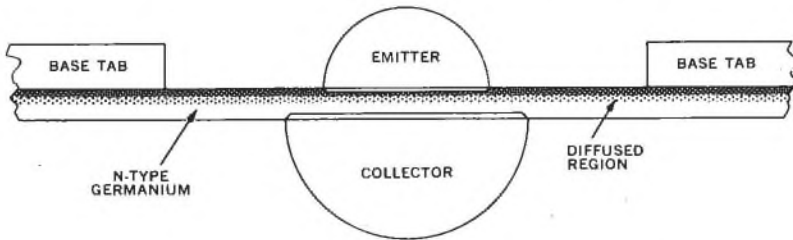


Fig. 17. Cross-sectional view of a drift-transistor structure. (Courtesy RCA).

18, is a transistor in which there is a high density of impurity in the base end nearest the emitter, with a steady decrease until the germanium becomes almost pure somewhat before the center of the base region. From here to the collector, the germanium remains fairly pure and hence possesses low conductivity. When the emitter and collector potentials are applied, an electric field is developed in the base which causes the injected carriers from the emitter to travel rapidly to the collector with little diffusion. Thus, transit-time is speeded-up and the frequency limit of the transistor is raised.

It will be recognized also that the high impurity concentration near the emitter end of the base reduces the resistance here. Further, the low conductivity of the base region near the collector acts to reduce the collector capacitance. Both of these effects help improve the high-frequency response of the unit.

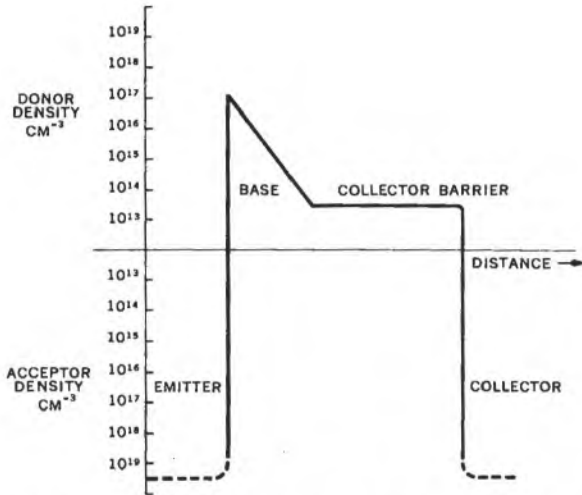


Fig. 18. The impurity distribution in a PNP drift transistor.

Other names for the drift transistor are graded-base and diffused-base transistors.

Tetrode Transistors. Another approach to high-frequency improvement in transistors is the tetrode transistor. This transistor is basically an NPN junction unit of the type already described.

However, a fourth electrode, labeled b_2 , is attached to the base layer at a point which is on the side opposite the original base connection b_1 (see Figs. 19 and 20). A potential is applied to this second base lead which is considerably higher than the normal emitter-to-base potential. The latter voltage is generally on the order of 0.1 volt. On the other hand, b_2 is given a potential of about -6 volts. This voltage is fixed and will not vary with the signal, since the latter still is applied between the emitter and base b_1 .

The presence of this large bias voltage at b_2 will modify the flow of current through the transistor. In the unit shown in Fig. 19, the emitter and collector sections are formed of N-type germanium and the base of P-type germanium. The application, then, of a relatively large

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negative potential to b_2 serves, in the base region under the influence of this voltage, to restrict the flow of electrons from the emitter to the collector sections.

It can be seen from Fig. 20 that the -6 volts is applied between b_2 and b_1 , or, actually, across the length of the base region. Since the base has an internal resistance, the voltage decreases uniformly from -6 volts at the top to 0 volt at the bottom. The voltage is negative enough at all points except near the bottom edge of the base to prevent

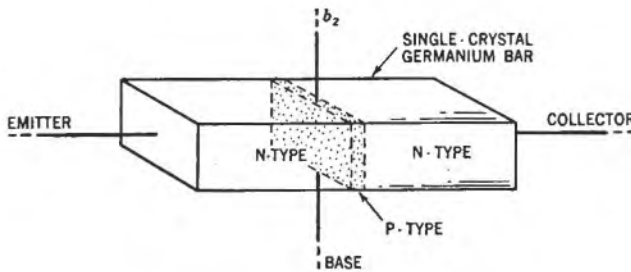


Fig. 19. A transistor tetrode.

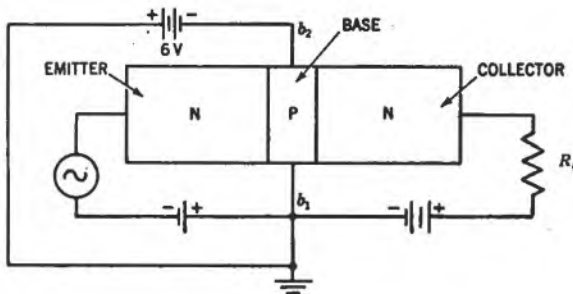


Fig. 20. The transistor tetrode with suitable d-c biasing voltages. The load resistor, R_L , develops the output signal.

any flow of electrons from the emitter across the base to the collector. At the bottom edge, the 0.1 volt forward bias between b_1 and the emitter will permit electrons to travel from emitter to collector.

Thus, the addition of connection b_2 and the application of a negative voltage here alter the flow lines in the conventional NPN transistor to the extent shown in Fig. 21. The ability of this modification

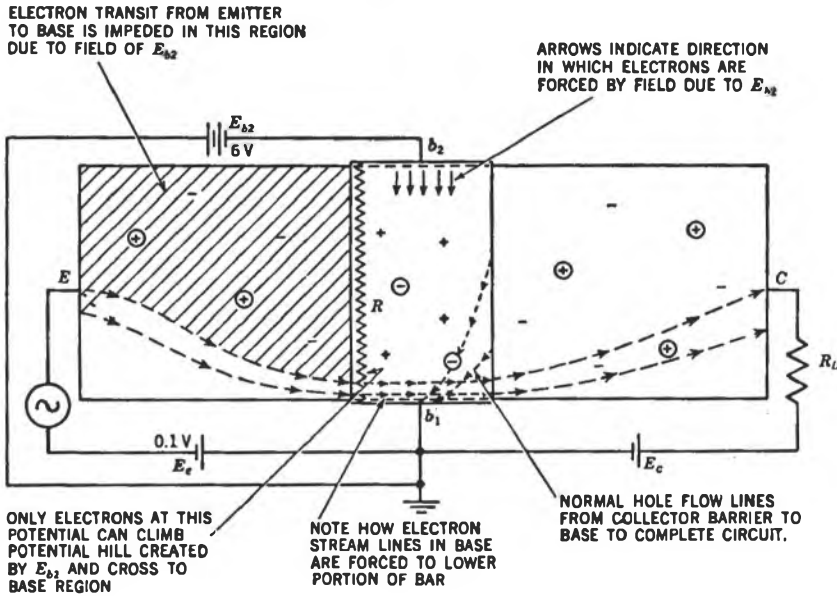


Fig. 21. The flow of carriers in a transistor tetrode. Note how little of the base section is actually used.

to improve the high-frequency operation of this transistor stems from two factors. First, the collector capacitance is reduced by decreasing the effective active area of the collector junction. This capacitance acts to shunt the signal around the output of the transistor and is analogous to the output capacitance of a vacuum tube. The smaller the capacitance, the higher the signal frequency at which its shunting effect becomes important. Second, the effective area of the base is reduced substantially, which means that the active base resistance is reduced. A low base resistance, we have previously seen, is conducive to improved high-frequency operation.

Surface Barrier Transistor. Another high-frequency transistor is the Philco surface-barrier transistor. In cross-sectional appearance,

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Fig. 22, this unit resembles junction transistors, although it is formed differently and functions somewhat differently. In all the junction transistors thus far described, two forms of germanium were employed, i.e., P and N germanium. In the surface-barrier transistor, only N germanium is used. Electrodes serving as the emitter and collector are plated electrolytically on opposite faces of a germanium wafer. A metal contact is then soldered to one end of the crystal and serves as the base electrode.

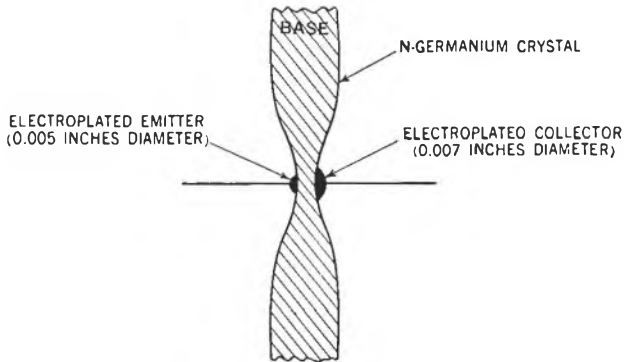


Fig. 22. Detail of surface-barrier transistor cross section.

With the surface-barrier transistor, video amplifiers of 5-mc bandwidths have been built and tuned amplifiers at 30 mc have shown stage gains of 15 db or more. For oscillator operation, considerably higher frequencies have been obtained. When the surface-barrier transistor is constructed using a diffusion process, frequencies of several hundred megacycles are readily possible with significant gains.

Power Transistors. Just as we have voltage and power vacuum-tube amplifiers, so we have voltage and power transistor amplifiers. An important consideration in the design of a power transistor is the ability to handle safely the power which is dissipated at the collector. To help remove this heat, power transistors are built with radiating fins (Fig. 23a) and in metal cases (Fig. 23b). Internal heat is transferred to the external metal case by metallic conduction with very little drop in temperature. The metal conducting surface may be soldered to any of the three transistor elements; in the power transistor of Fig. 23b, the outer metal cup is soldered to the collector.

A cross-sectional view of this power transistor is shown in Fig. 24. Note how the collector (item 5) is set flush against an inner surface of the metal housing. If the design of the circuit permits, the transistor is

mounted flush with the chassis, assuring the maximum dissipation of heat. In this case, items 7 and 11 of Fig. 24 would not be employed. However, if the collector must be electrically insulated from the chassis, there would be a small mica washer (item 7) on one side of the chassis and a nylon bushing (item 11) to insulate the stud and nut from the other side of the chassis.

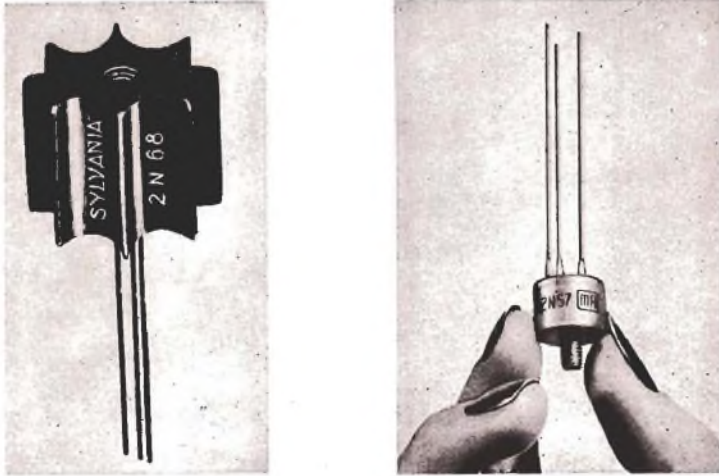


Fig. 23. (a) A power resistor with radiating fins to help remove heat. (Courtesy Sylvania Electric Products.)
 (b) A power transistor housed in a metallic container. (Courtesy Minneapolis-Honeywell Regulator Co.)

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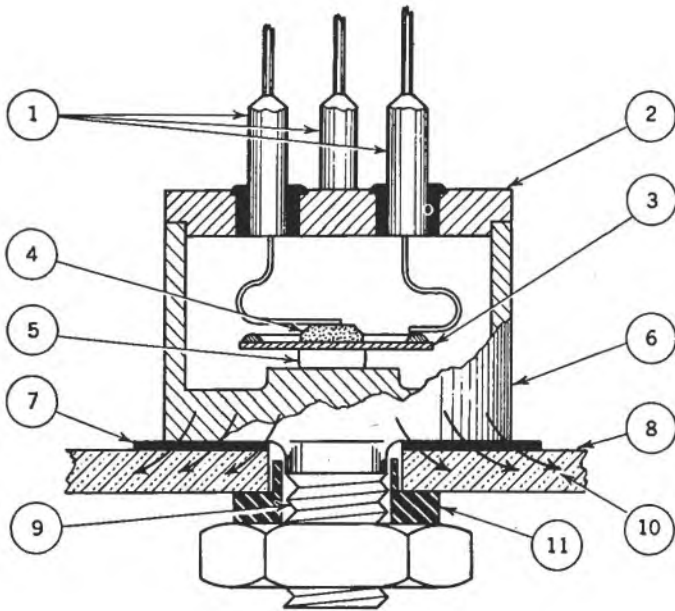


Fig. 24. A cross-sectional view of the power transistor shown in Fig. 23: (1) two-inch lead wires (base, collector, and emitter, respectively) for electrical connections; (2) metal top (with insulators for base and emitter leads), hermetically sealed for protection against contamination; (3) base (germanium crystal wafer with nickel reinforcing ring); (4) emitter (indium metal); (5) collector (indium metal); (6) metal case to provide durable enclosure for crystal assembly; (7) mica insulator to prevent power transistor from being grounded to chassis; (8) chassis (which usually serves as a heat sink); (9) mounting stud, integral part of metal case to provide solid attachment and facilitate good conduction for rapid heat dissipation to chassis; (10) arrows indicating path of direct heat flow; (11) plastic insulator bushing.

TRANSISTOR SYMBOLS

Circuit symbols for transistors are still somewhat in a state of flux, although the point has been reached where one will see fewer and fewer variations. The basic symbol for a transistor is shown in Fig. 25. The emitter element has an arrowhead, the base is a straight line, and the collector element is shaped like the emitter, but it possesses no arrowhead. This symbol is used for both point-contact and junction transistors and, like the tube symbol, may be placed in any position.

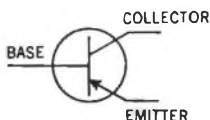


Fig. 25. The basic symbol for a transistor.

To distinguish between NPN and PNP transistors, the method shown in Fig. 26 is employed. If the emitter is a P-type germanium, the arrowhead is directed in toward the base. On the other hand, if N-type germanium is used for the emitter, the arrowhead points away from the base. This particular custom is not yet universally followed, so the reader is cautioned to check the applied bias polarities. These are the most positive indicators.

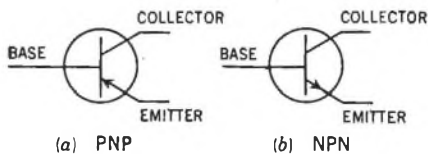


Fig. 26. To distinguish between PNP and NPN transistors, the method shown is frequently employed.

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Two minor variations that have been employed are shown in Fig. 27. Their use is not extensive, and actually they would not cause any confusion. In addition, there are other types of transistors and where their form differs significantly from the transistors discussed, other symbols are used.

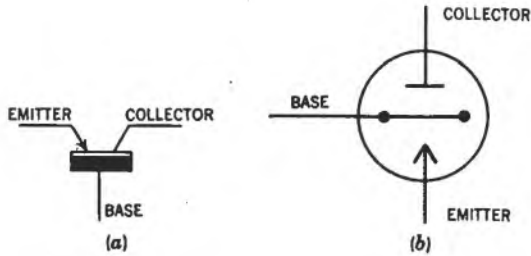


Fig. 27. Two additional symbols that have been employed for transistors.

BASIC TRANSISTOR AMPLIFIER CIRCUITS

All vacuum-tube amplifiers can be divided into three classifications: grounded cathode, grounded grid, and grounded plate. A similar division exists for transistor amplifiers: grounded emitter, grounded base, and grounded collector.

Classifying vacuum-type amplifiers in terms of grounded cathode, grounded grid, and grounded plate is a practice that has recently begun to gain favor among workers in the field. Consider, for example, the conventional amplifier circuit shown in Fig. 28a. The input signal is applied to the grid, while the output signal is taken from the plate. The cathode usually possesses a resistor in its circuit, but the resistor is bypassed in most applications by a capacitor that is frequently large enough to place the cathode at ground potential insofar as the signal is concerned. Under these conditions, the cathode need not be at ground potential with respect to a d-c voltage and, indeed, usually has some positive voltage on it because of the voltage drop across the cathode resistor. However, signal-wise, the cathode is at ground potential. This, then, is a grounded-cathode.

Note the situation does not change if the cathode is returned to some positive or negative d-c voltage, as in Fig. 28b, instead of to ground. In this instance, we have simply changed the reference point from one d-c voltage (zero) to another d-c voltage which may be higher than zero (i.e., positive) or lower than zero (i.e., negative). Amplifier operation, however, remains the same. Whatever the polarity of the d-c voltage chosen, this is still the point from which the other d-c voltages on the tube are measured.

The above designation remains the same even when a cathode bypass capacitor is not employed. This simply has the effect of introducing some inverse feedback. The signal input and output points are

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unaltered, and the cathode is still common to both input and output circuits.

The key word in the last sentence is the word "common." The more general definition of a grounded-cathode amplifier is one where the cathode is common to both input and output circuits. Hence, the

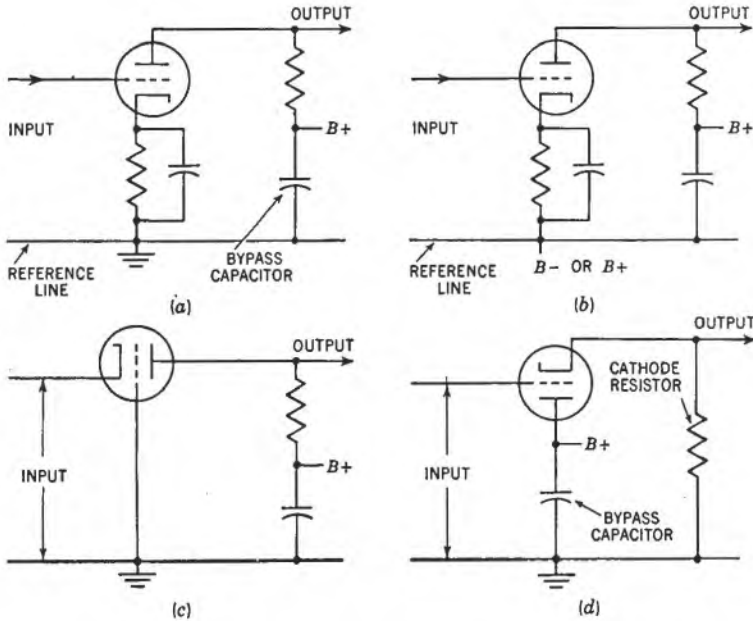


Fig. 28. (a) Grounded- or common-cathode amplifier. (b) Same amplifier with cathode returned to a d-c reference voltage instead of to ground. (c) Grounded- or common-grid amplifier where grid is common to both input and output circuits. (d) Grounded- or common-plate amplifier. If the last stage appears strange, turn it around and the familiar cathode follower will be immediately evident. The amplifiers have all been drawn in the manner shown to bring out the reason for their indicated designations.

name common cathode is interchangeable with grounded cathode, and both will be used throughout the book. The same applies to grounded-grid (or common-grid) and grounded-plate (or common-plate) amplifier.*

*The word ground, in nearly all its applications in electronics, should more frequently be considered in its general sense of being a reference point common to one or more circuits. The beginner in electronics is often led to believe that ground possesses special properties not found in other portions of the circuitry. Ground is best regarded as just another conductor which derives any special qualities it may have only by virtue of the fact that it is common to several circuits. The notation common-base, common-emitter, and common-collector amplifier is also widely used.

In a grounded-, or common-, grid amplifier (Fig. 28c) we place the grid at signal ground while the input signal is applied to the cathode and the output signal is obtained at the plate. Again, note that the grid may have some d-c voltage on it, for biasing purposes, without affecting the designation or operation of the stage.

The final arrangement, grounded- or common-plate, is shown in Fig. 28d. Here the plate is returned to signal ground, while the input signal is applied to the grid, and the output signal is obtained at the cathode. The best known name for this amplifier is cathode follower.

Grounded-Base Amplifier. It is convenient to start first with a grounded-base transistor amplifier. This is shown in Fig. 29a. The input signal is applied to the emitter, and the output signal is obtained at the

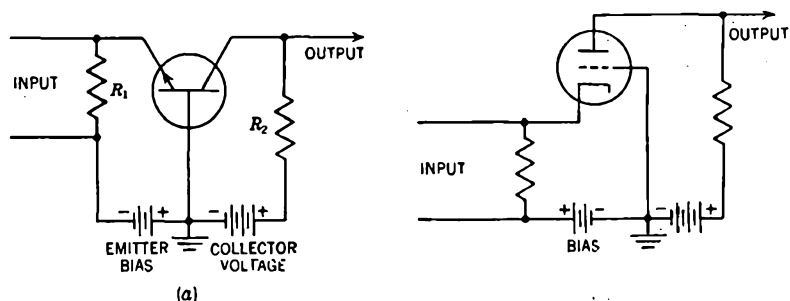


Fig. 29. A grounded-base transistor amplifier (a) and its analogous grounded-grid vacuum-tube amplifier (b). The polarity of the voltages used in the transistor circuit will be governed by the type of transistor (PNP or NPN) used. Here, an NPN transistor is shown.

collector. The equivalent vacuum-tube amplifier is shown in Fig. 29b. The grid, being equivalent to the base, is grounded. The signal is then fed to the cathode; the plate is the output circuit.

In a grounded-grid amplifier, the input and output signals possess the same polarity. In a grounded-base transistor amplifier, the same behavior is found. To illustrate this, the amplifier of Fig. 29a has been drawn using an NPN transistor and the battery polarities have been chosen accordingly. Assume, now, that the incoming signal is positive at this instant. This positive voltage will counteract some of the normal negative bias between emitter and base and serve to reduce the current flowing through the transistor. This, in turn, will reduce the voltage drop across R_2 , making the collector potential more positive. Thus, a positive-going input signal produces a positive-going output signal.

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During the negative half cycle of the input signal, the emitter will be driven more negative than it normally is with respect to the base. This will increase the flow of electrons (here) from emitter to collector and cause the negative voltage drop across R_2 to increase. This will drive the collector more negative. Again we see that the polarity of the output signal is similar to that of the input signal.

The input impedance of a grounded-base junction transistor amplifier is low, with values of 100 to 300 ohms being typical. The output impedance is quite high, being on the order of 500,000 ohms.

Grounded-Emitter Amplifier. The grounded-emitter amplifier (Fig. 30a) is the most popular of the three groups. The input signal is applied to the base, and the output signal is obtained at the collector. The equivalent vacuum-tube amplifier is shown in Fig. 30b, and the reader will immediately recognize this as the most common amplifier in use today.

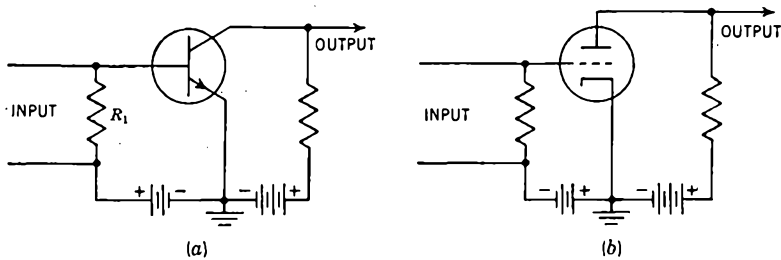


Fig. 30. A grounded-emitter amplifier (a) and its vacuum-tube counterpart (b). An NPN transistor is used in (a); for a PNP transistor, the battery polarities would be reversed.

It turns out, when the mathematics of grounded-emitter circuitry are analyzed, that this arrangement possesses a number of advantages for the junction transistor over the grounded-base approach. For one thing, the input impedance is higher, averaging between 700 and 1,000 ohms. Output impedance is lower than in the grounded-base connection and most frequently falls around 50,000 ohms or less. However, the voltage and power gains are considerably higher, being on the order of 500 or more for voltage gain and upward of 5,000 or more for power gain. Since it is these latter values with which we are most concerned, the popularity of the grounded-emitter arrangement becomes understandable.

An interesting feature of the grounded-emitter form of connection is the fact that a phase reversal occurs as the signal passes through the stage. In this it is similar to its vacuum-type prototype, the grounded-cathode amplifier.

The reason for the reversal can be understood by considering the amplifier shown in Fig. 30a. The base-emitter circuit is biased in the forward direction, with the negative side of the bias battery connecting to the emitter and the positive side of the battery to the base. (In this way, the negative battery terminal repels the excess electrons in the N-type emitter toward the PN junction while the positive battery potential drives the holes in the base to the same junction.) If, now, we apply a signal to the base, this is what will happen:

When the signal is negative, it will tend to reduce the bias potential applied between emitter and base. This means that the electrons in the emitter and the holes in the base will have less compulsion to overcome the inherent separating force at the junction and less current will flow. This, in turn, will reduce the collector current, providing less voltage drop across the load resistor. As a result, potential at the top end of R_2 will become positive.

During the positive half cycle of the signal, the total voltage in the emitter-base circuit will rise. This will increase the flow of current through the emitter, the collector and R_2 . The increased voltage drop across R_2 will make the top end of this resistor more negative. Thus, in grounded-emitter amplifiers, the output signal is 180° out of phase with the input signal.

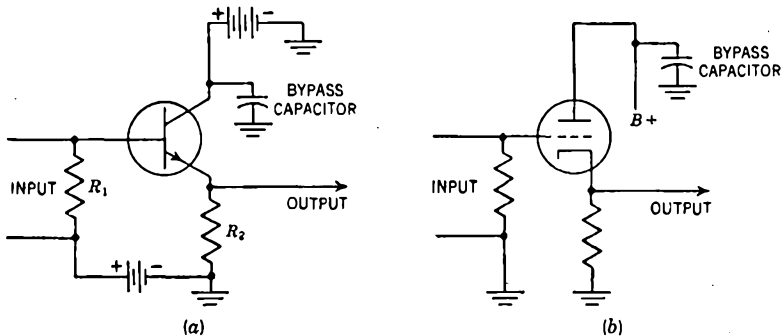


Fig. 31. A grounded-collector amplifier (a) and its vacuum-tube counterpart (b). The cathode resistor in (b) would have a fairly high value.

Grounded-Collector Amplifiers. The final transistor amplifier circuit arrangement is the grounded collector. This is shown schematically in Fig. 31 together with its vacuum-tube counterpart. Note that the plate of the vacuum tube is not d-c grounded, since this element still requires a positive potential (relative to the cathode) in order to attract

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electrons. However, the plate is at a-c ground by virtue of the large bypass capacitor, and that is actually what we are interested in.

The grounded-plate vacuum-tube amplifier will be recognized as the familiar cathode follower. It possesses a high input impedance between cathode and grid and a low output impedance. Voltage gain of this arrangement is always less than one. In the grounded-collector arrangement we find many of the same characteristics. Thus, the input impedance, base to collector, is very high because of the reverse biasing of the collector. Typical values range between 300,000 and 600,000 ohms. The output impedance, on the other hand, is low, frequently falling below 100 ohms. And to complete the analogy, the voltage gain of a grounded collector is always less than one. Thus, here we have the transistor equivalent of the vacuum-tube cathode follower.

Phase reversal of the signal does not occur in this stage. Any signal applied to input will appear at the output with the same phase. Junction grounded-collector circuits are stable, but point-contact stages have a negative output impedance. Again this characteristic might be desirable in an oscillator, but it would lead only to instability in an amplifier.

Note that no matter how a transistor is connected, the method of d-c biasing remains unaltered. The emitter is *always* biased in forward direction, while the collector is *always* biased in the reverse, or high-resistance, direction.

POWER AMPLIFIERS

Class A Power Amplifiers. Circuit arrangements of single-ended power amplifiers do not differ to any marked degree from corresponding voltage amplifiers. Figure 32 illustrates two class A power amplifiers designed to drive the loudspeaker of an audio amplifier (or a radio or television receiver). In one instance, two batteries are employed; in the

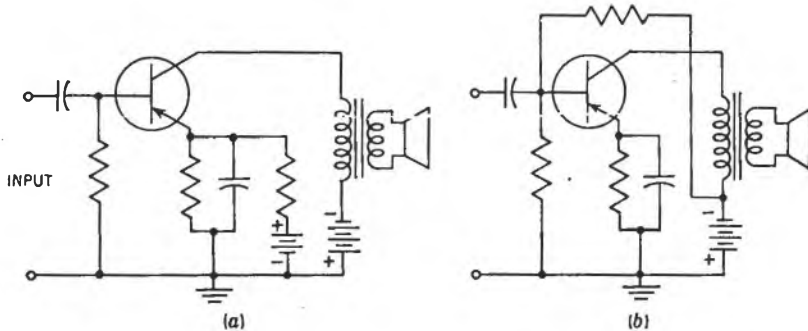


Fig. 32. Two class-A power amplifiers.

other, a single battery. The output transformer would be designed to match the impedance of the collector on one hand and the loudspeaker on the other. The amount of power that may be obtained from this arrangement will be governed by the size of the battery and the permissible dissipation in the transistor itself.

As in vacuum-tube practice, a single-ended power amplifier can be operated only class A.

Power amplifiers can also be operated in push-pull. A typical illustration of an audio amplifier using a single driver stage and a class A

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push-pull output stage is shown in Fig. 33. All transistors are operated with ground emitters, and transformer coupling is employed between the driver and output stages and between the output amplifiers and the loudspeaker. The resistance R_1 is variable and is adjusted for a total collector current of 8 ma.

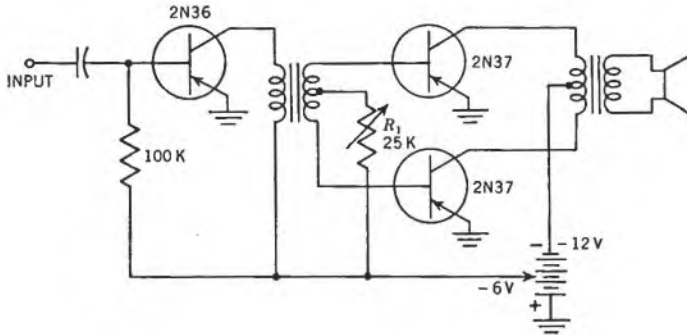


Fig. 33. An amplifier using a 2N36 driver and 2N37's in class-A push-pull. All these transistors are PNP units.

Push-pull amplifier operation results in the cancellation of second harmonics within the stage. For the same amount of distortion, then, a class A push-pull amplifier can be driven harder, providing greater output. It also means that we can obtain more than twice the output with push-pull operation than we can get using two similar transistors as single-ended amplifiers.

Class B Power Amplifiers. In class A push-pull operation, the average current that flows remains steady, whether or not a signal is being applied to the stage. More efficient operation can be achieved with class B operation, where each transistor is biased to cutoff. When no signal is applied, practically no current flows and no power is being dissipated.

The circuit of a class B push-pull amplifier is shown in Fig. 34. Three Sylvania type 2N68 power transistors are employed, the first one as a class A driver amplifier, the remaining two in a class B output stage. With 50 mw of audio input power, up to 5 watts can be obtained at the speaker, using only a single 12-volt battery. Efficiency of the class B stage here is close to 75 percent.

The reason for the high efficiency stems from the fact that with zero signal, the total class B collector current is only 1 ma. For maxi-

When no signal is present, the average current is 100 ma. In the presence of a signal, this current rises to 550 ma. In the preceding class A driver, the average current is 100 ma, signal or no signal.

Note that in the class B stage of Fig. 34, the emitter and base are connected together directly. This serves to reduce the collector current to the low value of 1 ma mentioned above. Actual collector current cutoff

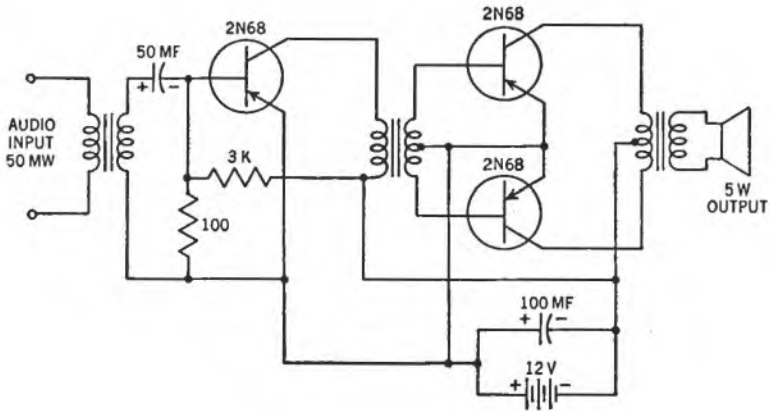


Fig. 34. A class-A driver stage with a class-B push-pull output.

is seldom sought because of the nonlinearity of the transistor characteristic at low signal levels. For any given transistor, there is some value of base bias which results in a good balance between distortion and efficiency, and it is at this point that the stage is operated.

RADIO- AND INTERMEDIATE-FREQUENCY AMPLIFIERS

In applying transistors to RF and IF amplifiers, careful consideration must be given to their input and output impedances. This, of course, is similar to audio-frequency application. The problem, however, takes on added importance at the higher frequencies because of the lower gain per stage obtainable.

Interstage Coupling Networks. The most common connection (for junction transistors) is the grounded emitter, and with this arrangement the input impedance is fairly low (on the order of 1,000 ohms or less) while the output impedance is in the neighborhood of 10,000 to 20,000 ohms. It is the purpose of the interstage coupling network not only to provide whatever frequency selectivity is desired but also to match these input and output impedances.

There are a number of interstage coupling networks possible, and the more important of these are shown in Fig. 35.* In the first group (Fig. 35A) the second amplifier is connected directly into the parallel-resonant circuit, either in series with the inductance or in series with the capacitance.

In the second group (Fig. 35B) the second stage is connected to the junction of two capacitors C_1 and C_2 , which resonate with the inductance. By properly proportioning the values of C_1 and C_2 , we can use the network to match the high output impedance of the first transistor to the much lower input impedance of the second transistor.

The third group (Fig. 35C) employs inductive coupling between stages. In the left illustration of Fig. 35C, the primary circuit is tuned,

*W. F. Chow, High-Frequency Transistor Amplifiers, ELECTRONICS, April, 1954.

offering a high impedance to the first transistor stage. The signal is then transferred to an untuned secondary containing fewer turns. This step-down action enables the low-impedance input of the second transistor to match the output of the first stage. In the second illustration of Fig. 35C, we obtain the same electrical action by dispensing with the second-

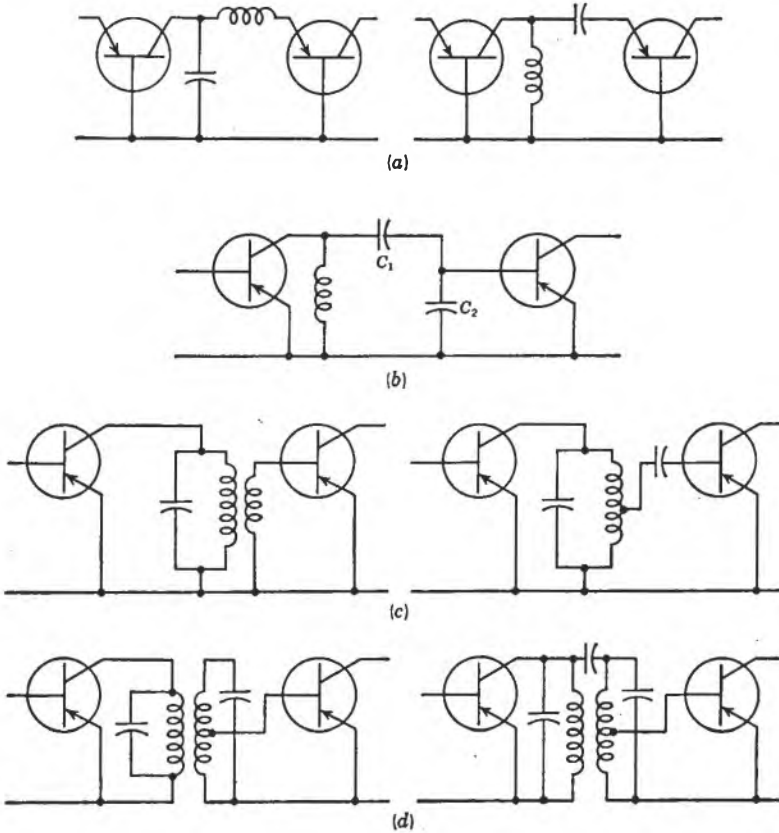


Fig. 35. Various methods of coupling transistor stages together.

ary winding and tapping directly into the primary inductance. In this arrangement, a coupling capacitor is needed to prevent the higher collector bias of the preceding transistor from reaching the base of the second unit.

In the final group of coupling networks (Fig. 35D) double tuning is employed. Again note how the second stage must be tapped down in order to achieve the proper impedance match.

UNDERSTANDING TRANSISTORS

Intermediate-Frequency Amplifiers. A two-stage IF system suitable for a broadcast receiver is shown in Fig. 36. The circuit uses two 2N482 high-frequency PNP transistors in a grounded-emitter configuration. Operating frequency is 455 kc, and the over-all power gain is at least 50 db (ratio of 100,000 to 1). The IF transformers have 155 total turns on the primary, tapped at 55 turns, with an 18-turn secondary. The coils are bifilar wound and enclosed in an adjustable ferrite cup. They are tuned by a fixed 125- μf capacitor across the primary.

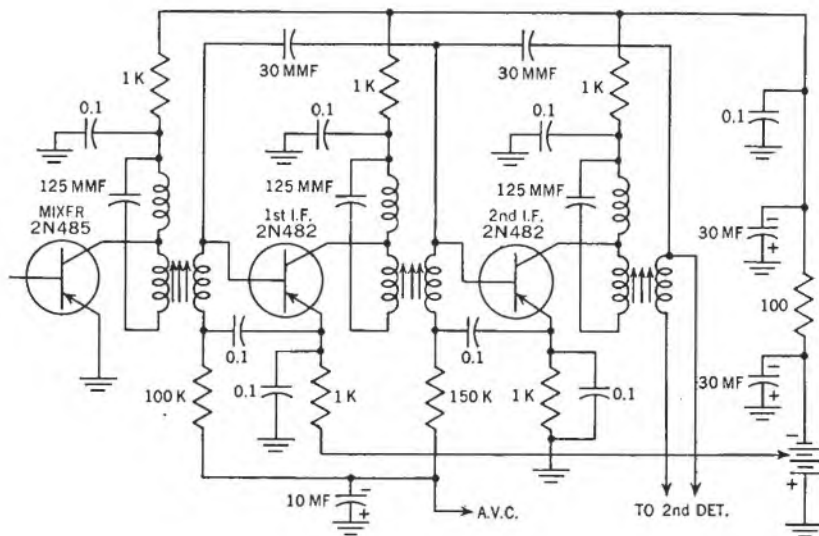


Fig. 36. A two-stage IF system operating at 455 kc.

Each emitter possesses a 1,000-ohm d-c stabilizing resistor. Alternating-current or signal degeneration is prevented by the use of 0.1- μf bypass capacitors across these resistors.

It will be noted that each IF stage is neutralized by connecting a 30- μf capacitor from the base of the following stage to the base of the preceding stage. (These two points are 180° out of phase because of the grounded-emitter arrangement.) Neutralization was deemed necessary because high-frequency transistors may become regenerative because of the value of the internal capacitances.

Radio-Frequency Amplifiers. The same considerations which govern the design of the IF amplifiers also hold true for RF amplification. However, because RF amplifiers operate at higher frequencies, we can lower gain.

The RF stage of a transistor radio is shown in Fig. 37. The input transformer T_1 is slug tuned, with its slug mechanically ganged to those of the converter and the local oscillator (not shown) coils. The base of X_1 is returned to the junction point of R_2 and R_3 , where the d-c potential is approximately 1.5 volts. A d-c stabilizing resistor R_4 is placed in

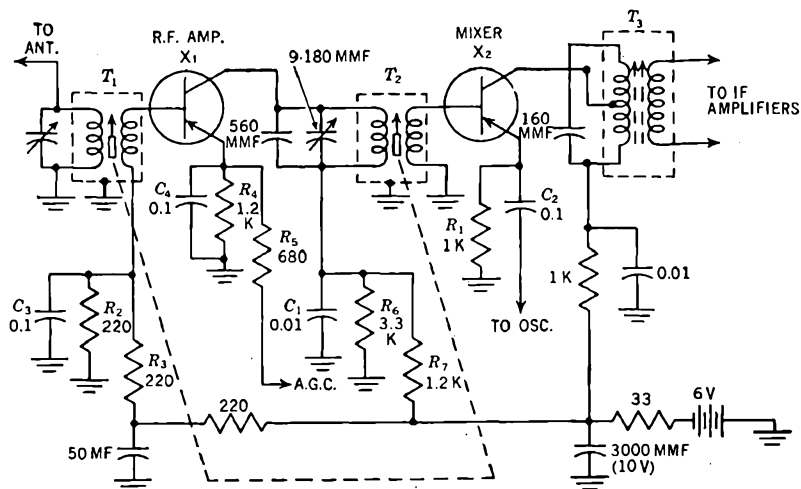


Fig. 37. The RF and mixer stages of a transistor radio receiver.

the emitter leg of X_1 to make the stage relatively insensitive to changes in ambient temperature. A small 680-ohm resistor R_5 brings an AGC voltage to the emitter. If no AGC control is desired, the connection between R_4 and R_5 can be severed. C_4 , across R_4 , serves to place the emitter at RF ground. C_3 , at the junction of R_2 and R_3 , serves also as a low-impedance path to ground for radio frequency.

The collector of X_1 connects to the primary of transformer T_2 and receives its d-c voltage from the junction of R_6 and R_7 . Collector voltage is 4.5 volts, and C_1 ensures that the RF signal will be shunted around the battery. Greater amplification could have been obtained from X_1 if the full 6 volts of the battery had been applied to the collector, but this would have tended to degrade the signal-to-noise ratio. Since the latter is particularly important in the RF stage, the lower collector voltage was employed.

Transformer T_2 couples the signal from the RF stage to the mixer. In the mid-frequency range of the broadcast band, the output impedance

UNDERSTANDING TRANSISTORS

of X_1 is 10,000 to 15,000 ohms and the mixer input impedance is about 500 ohms. These are the two impedances that must be matched by T_2 .

The RF signal is applied to the base of X_2 , while the locally generated oscillator signals is brought into the circuit by C_2 and developed across R_1 . The latter resistor, incidentally, also serves to provide bias stability in the same manner as R_4 in the RF amplifier stage. Approximately 0.4 volt rms of oscillator voltage is injected into the converter stage. The two signals mix in X_2 and the difference or IF signal is transferred to the IF amplifiers through transformer T_3 .

TRANSISTOR OSCILLATORS

Transistors will function as oscillators as readily as they will as amplifiers. For every vacuum-tube oscillator, there is a transistor counterpart. Furthermore, the circuit arrangement will generally be alike in both instances.

A simple audio-frequency transistor oscillator is shown in Fig. 38. The transfer of energy from the output (the collector) to the input (base) is achieved through transformer T_1 . The primary and secondary

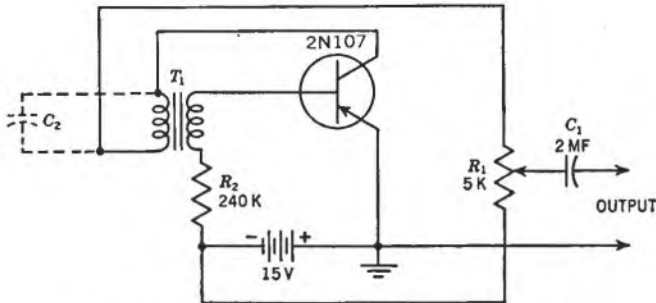


Fig. 38. A transistor audio-frequency oscillator.

sections are connected so that the field set up by the secondary winding establishes an induced voltage in the primary which acts to maintain oscillations in the circuit. An output control R_1 with an output coupling capacitor C_1 provide an output voltage. One battery is employed to bias both the base and collector circuits. R_2 is inserted in the base lead to limit the voltage between base and emitter to the proper value dictated by the transistor.

A widely-employed oscillator circuit is the multivibrator in which one transistor is cut off while the other one is conducting. The circuit

of a typical multivibrator is shown in Fig. 39. Each transistor is connected as a grounded-emitter amplifier in order to provide the necessary 180° phase reversal in each stage. For the values of the components shown, the repetition frequency is on the order of 2 kc. It is possible by altering these values to reach frequencies of several hundred kilocycles.

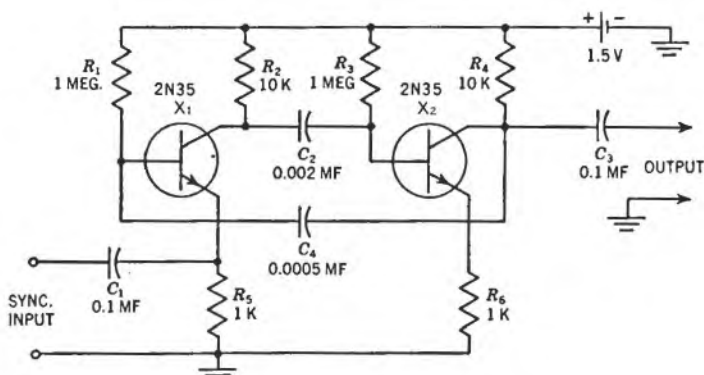


Fig. 39. A transistor multivibrator. (Courtesy Sylvania Electric.)

The battery voltage is 1.5 volts and the total current drain is 250 microamperes. Under these conditions, an open-circuit rectangular wave will be obtained having an amplitude of 1.4 volts peak-to-peak. Positive synchronization can be obtained by injecting a 5-volt rms signal at the sync input terminals.

Cutoff of a single stage is achieved in this multivibrator in exactly the same way that it is in the vacuum-tube multivibrator. For example, X_2 in Fig. 39 is cut off when the emitter-base voltage is such that the base is negative with respect to the emitter because the 2N35 transistor is an NPN unit. The negative potential acquired by the base for effective cutoff is developed across resistor R_3 . And X_2 remains cut off until the negative charge held by C_2 (and applied across R_3) has been reduced through discharge. For transistor X_1 , the controlling components are C_4 and R_1 .

If a sawtooth wave is desired across the output terminals instead of a rectangular wave, it can be obtained by connecting a capacitor from the collector of X_2 to ground.

An RF transistor oscillator using an LC tuned circuit is shown in Fig. 40. L_1 and L_2 are two tightly coupled coils which provide for

UNDERSTANDING TRANSISTORS

the transfer of energy between output and input circuits. L_3 is wound close to L_2 and the energy it absorbs is transferred to whatever output circuit is connected to the oscillator. Capacitor C_2 tunes L_2 and enables the generated frequency to be varied. R_1 serves to limit the emitter current to the correct value; C_1 across R_1 assists in the oscillating action.

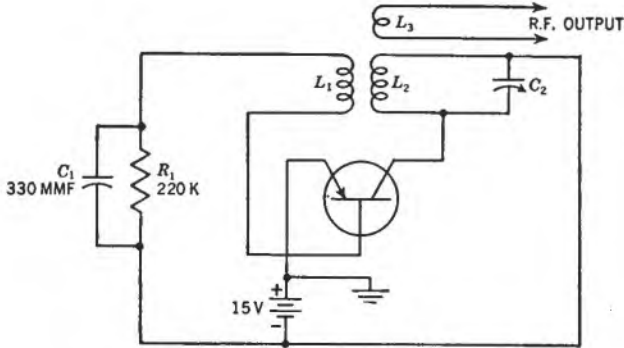


Fig. 40. An RF transistor oscillator.

Another oscillator which has been employed in a radio-broadcast receiver is shown in Fig. 41. If we ignore, for the moment, the turns on L_1 which extend above point A, and if we also disregard winding L_2 , then what we have here is a Hartley oscillator. The voltage which is developed between points B and C of L_1 represents the energy which is fed back to the base input circuit via coupling capacitor C_1 .

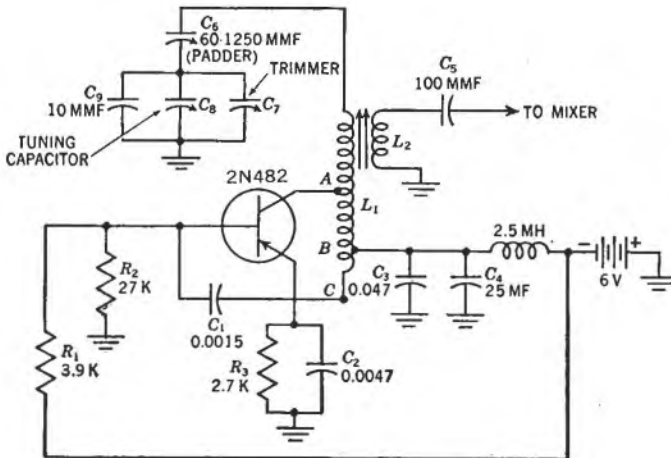


Fig. 41. An RF oscillator employed in a radio receiver.

The collector is tapped down on L_1 to decrease the effect of its (i.e., the collector) capacitance to provide a better impedance match between the transistor and the tuned circuit, and to improve frequency stability and tracking. (The last feature stems from the application of this oscillator in a radio receiver.) Tracking also explains the reason for the presence of C_6 (60 to 1,250 mmf) and C_9 (10 mmf). In this particular design three-point tracking between oscillator and mixer was obtained by using a slug in the oscillator coil, a padder capacitor C_6 and a gang capacitor trimmer C_7 . The slug takes care of the central portion of the band, the padder provides an adjustment at the low end of the band, and the trimmer is employed to make the high end of the tracking curve fall into line.

Energy from the oscillator is transferred into the mixer circuit (not shown here) by a combination of inductive and capacitive coupling. The initial transfer from L_1 and L_2 is inductive; the second transfer, from L_2 through C_5 to the mixer, is capacitive.

The necessary biasing voltage for the transistor collector is brought in through coil L_1 . A similar biasing voltage for the base is brought in via R_1 and R_2 . The resistor (R_3) in the emitter leg serves to limit the emitter current to a safe value. C_2 , across R_3 , assists in the oscillating action.

SILICON TRANSISTORS

The emphasis in the preceding discussion has been on germanium as the semiconductor material from which transistors were made. It is also possible to employ silicon for this purpose and this is indeed being done. Silicon is suitable for diode and transistor operation because its physical properties closely parallel those of germanium. Thus, silicon is a semiconductor with four valence electrons and, in the solid state, it will form a cubic crystal lattice in which the various atoms are held together by the same mechanism of shared bonds. It is possible to replace some of these atoms by impurities, of either the donor or acceptor variety, and form N-type or P-type silicon. By combining suitable P- and N-type sections of silicon, rectifier diodes or complete transistors can be fabricated.

OTHER SEMICONDUCTOR MATERIALS

Although germanium and silicon have received the greatest amount of research and almost exclusively dominate the commercial transistor field, considerable interest and investigation is being directed to other semiconducting materials. Among the more promising of the newer types are the intermetallic compounds. These differ chemically from such semiconductors as silicon or germanium in that they are formed with two pure elements in place of one. Thus, a germanium transistor starts with pure germanium and then has added to it appropriate impurities to form the requisite P and N regions. The same is true of silicon. In an intermetallic compound, the basic crystal structure consists of *two* different metallic elements, such as gallium and phosphorus. These together form gallium phosphide (GaP). Suitable impurities are then added to this compound to form the needed P and N regions.

In the introductory discussion on transistors, it was noted that germanium and silicon each has four valence electrons in its outer or chemically active ring. The crystalline structure is then formed by having the atoms share each other's outer electrons to form bonds. In the intermetallic compounds, one of the combining elements has three valence electrons per atom while the second element has five valence electrons per atom. Equal numbers of the two atoms are used and these also share each other's valence electrons to form a crystal structure. This structure exhibits many of the same properties as germanium and silicon.

We have seen that a fundamental electrical property of a semiconductor is the energy needed to free an electron from the bond formed between two atoms. In silicon, more energy is required to liberate electrons and this is a major reason why silicon can be employed at higher temperatures. With intermetallic compounds, by using dif-

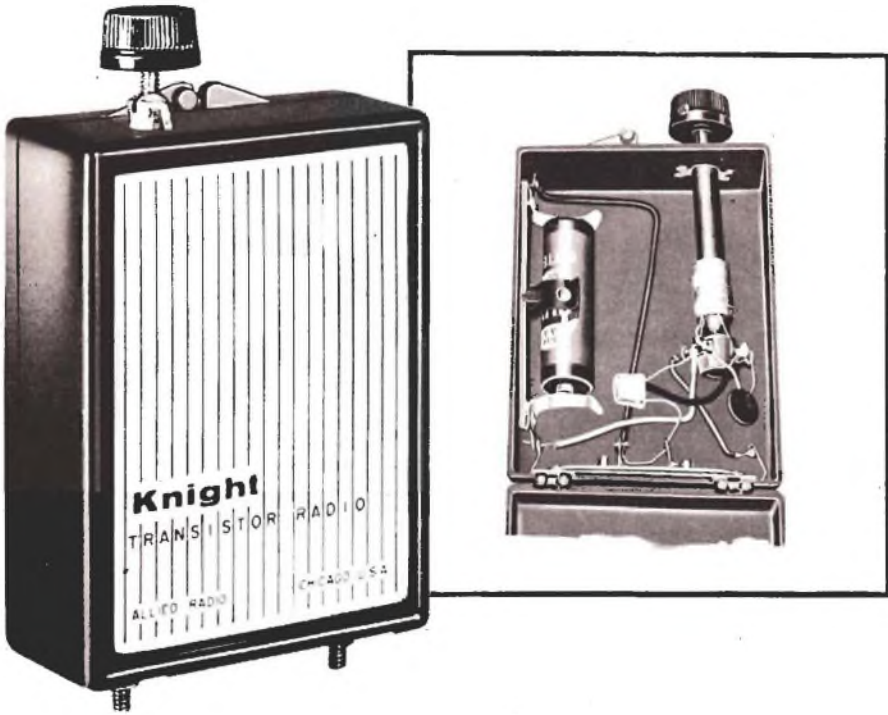
ferent combinations of three valence atoms and five valence atoms, we can achieve a very wide range of energy gaps.

The mobility of electrons and holes in semiconductors (i.e., the speed with which these particles or charges move through a crystal) can also be regulated over a fairly extensive range in intermetallic compounds. All these variations make it possible to construct transistors or semi-conductor diodes having a wide choice of such properties as current or power-handling capacity, frequency range and rectification ratio.

Some of the new compounds which are being studied extensively include gallium arsenide, gallium phosphide, indium phosphide, indium antimonide and indium arsenide. Gallium arsenide, as a semiconductor, can potentially combine the high temperature capacity of silicon (at present 150°C in practical devices) and the high frequency capabilities of germanium. Higher temperature capability will permit higher power applications and levels since the heat energy can be more effectively handled. Gallium phosphide, used in conjunction with gallium arsenide in a device, is expected to extend the upper temperature limit anticipated from gallium arsenide alone to above 500°C .

Indium phosphide, with an upper temperature limit of approximately 400°C , is considered as a possible "runner-up" to gallium arsenide. Indium antimonide and indium arsenide are being experimentally tested in galvano-magnetic devices where frequency and temperature do not play a primary role. Such semiconductors, as opposed to use in transistor or rectifier applications, have potential application in magnetometers, magnetic compasses without moving parts and gyrotors.

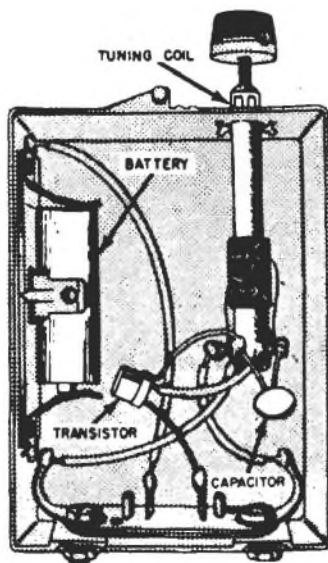
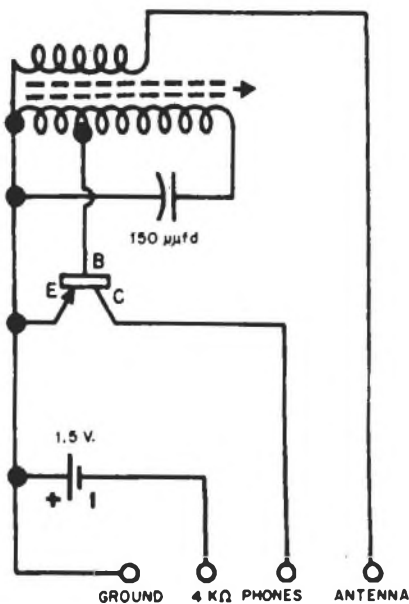
Many compounds are under investigation and undoubtedly some of these will be employed commercially. At the present time, fabrication of these substances presents major problems due to difficulty in trying to purify them to the degree necessary and then forming them into suitable transistors or diodes.



Knight-Kit Trans-Midge Transistor Radio Kit

The Knight-Kit Trans-Midge transistor radio is a 1-transistor circuit that is only slightly larger than a package of cigarettes. It uses a high-beta PNP transistor and, with a suitable outdoor antenna, will pull in local stations loud and clear.

In this circuit, incoming signals from the antenna are applied to the primary winding of a slug-tuned transformer. This signal voltage is stepped up by the secondary winding and applied between the base and emitter of the transistor. The base and emitter have no d-c voltage applied to them so that current will flow only when the base is negative with respect to the emitter. In essence, then, these two elements serve as a diode rectifier to detect the incoming RF signal. When current does flow, it is amplified by the transistor, producing an amplified signal in the collector or output circuit. This signal is then passed through a pair of headphones and made audible to the listener.



PICTORIAL DIAGRAM

A fixed 150-mmfd capacitor is shunted across the secondary winding of the tuning coil in order to have the range of this circuit fall within the broadcast band. The radio is turned on by plugging the headphones into the jack provided at the bottom of the case; this action completes the collector circuit. After the antenna and ground wires have been connected, the movable powdered iron core of the tuning coil is slowly moved in and out until a station is received. With this arrangement, several local stations should be heard at different positions of the core.

The proper type of headphone for this circuit is one that possesses an impedance of 4,000 ohms or more. Satisfactory reception may be obtained with a 3,000-ohm headphone if the incoming signals are strong.

The radio is turned off in the same way that it is turned on—by removing the headphone from its jack. This adds to the simplicity and economy of the circuit.

The Trans-Midge transistor radio kit, complete with transistor, high-impact plastic case, penlight cell and slug-tuned coil, is listed in the kit section of the Allied catalog.

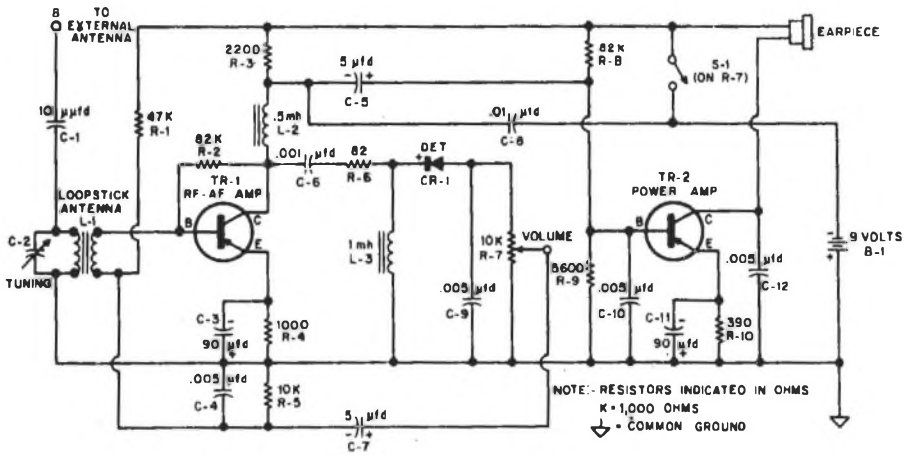


Knight-Kit 2-Transistor Pocket Radio

The Knight-Kit 2-transistor pocket radio uses a highly efficient circuit that actually does the work of 3 transistors. It works well from a built-in, high-gain ferrite core antenna, without an external antenna for local stations. If more sensitive operation is desired to cover a wider area or to pick up weaker stations, then an external antenna may be employed. Other important features of this pocket radio include the use of an air-dielectric variable capacitor for tuning and a printed circuit board on which all of the critical wiring has already been completed.

Operation of the 2-transistor pocket radio is as follows: Radio signals are picked up by the antenna system which is a combination of the loopstick antenna coil, L-1, and variable capacitor, C-2. Capacitor C-2 tunes with the loopstick to a particular station signal and this voltage is brought to the base of transistor TR-1 where it is amplified. L-2 is the load impedance for this RF amplifier. R-3, while it may appear to be part of the collector circuit, too, does not develop very much RF signal because C-8 bypasses to ground whatever RF signal does not appear across L-2. The RF signal across L-2 is coupled through C-6 and R-6 to CR-1 where it is detected and the audio modulation abstracted from it. The audio signal appears across R-7, the volume control, while C-9 bypasses the RF component of the detected signal back to ground.

From the volume control, the audio signal is fed back to the base of TR-1 by C-7 and R-5. Here, the signal is amplified with TR-1 now functioning as an audio amplifier. Load for TR-1 under these conditions is R-3; L-2 has negligible impedance at audio frequencies and its presence is scarcely felt. From R-3, the audio signal is coupled by



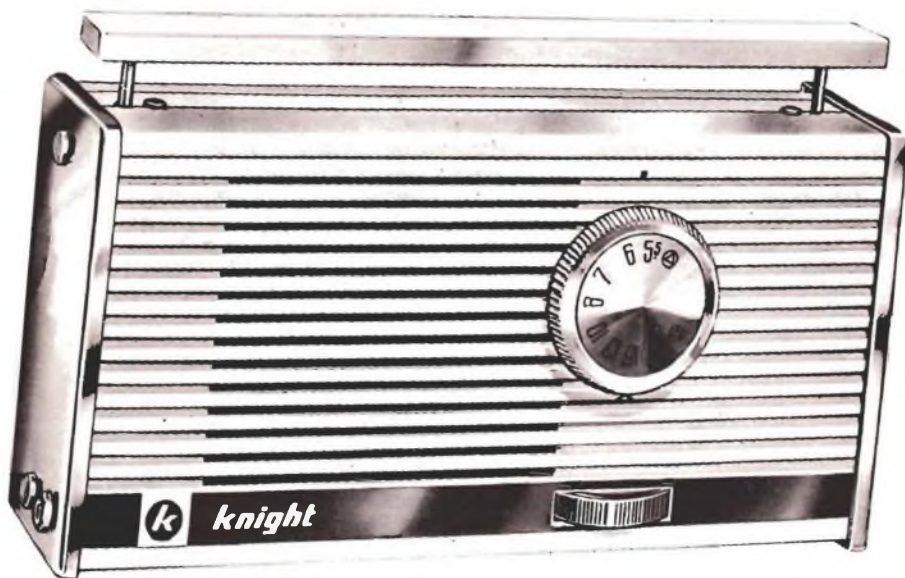
C-5 to the base of the power amplifier, TR-2. Here it is further amplified and then sent to the earphone where the sound is made audible.

Note, then, that TR-1 is functioning simultaneously as an RF and audio amplifier. This is possible because of the wide separation in signal frequencies and the fact that different load resistors are employed for each signal. The RF signal never "sees" R-3, the audio load resistor of TR-1, because of the presence of L-2 and C-8. These same RF signal currents never come in contact with R-5 because C-4 shunts this resistor. By the same token, L-2 and the secondary winding of L-1 appear as essentially straight pieces of wire to the audio frequencies and no measurable amount of audio voltage appears across either inductance. This action, known as reflexing, is an excellent way to make one amplifier do the job of two without interference to either signal. It does require, however, that the circuit be carefully designed and contain an adequate number of bypass capacitors. This has been done here.

Resistors R-8 and R-9 provide the proper d-c bias for TR-2 while R-1 and R-5 serve the same function for TR-1. R-2, between collector and base of TR-1, provides a small amount of feedback which acts to stabilize this critical stage. R-4 prevents changes in temperature from adversely affecting the operation of TR-1 while C-3, across this resistor, acts to keep the stage gain high. R-10 and C-11 in the emitter leg of TR-2 perform the same role.

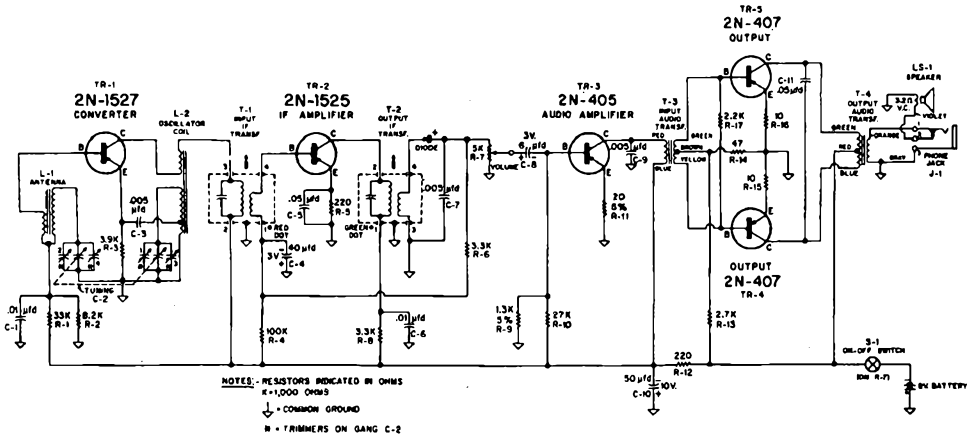
The 2-transistor pocket radio kit, complete with transistors, all parts, printed circuit board, earphone, and a plastic-impregnated tan carrying case, is listed in the kit section of the Allied catalog.

UNDERSTANDING TRANSISTORS



This compact, 5-transistor portable radio employs a superheterodyne circuit that gives sensitive, high-quality reception of the AM broadcast band. It is economical to use, requiring only a small 9-volt battery for months of operation. Among its many features are drift-field transistors for high gain combined with stability; a $3\frac{1}{2}$ " speaker, larger than is ordinarily used in transistor portables; a built-in, ferrite loopstick antenna; and an ear-phone jack for private listening.

In operation, the incoming signal is picked up by the loop antenna L-1 and fed to the converter stage through a tuned circuit formed by the antenna coil and one section of the ganged tuning capacitor C-2. At the same time, the converter is developing oscillations in the tuned circuit formed by L-2 and the other section of C-2. The component values in these tuned circuits are selected so that no matter what signal frequency C-2 is set to receive, the oscillator frequency will be 455 kc higher. The incoming signal mixes with the oscillator signal and produces the difference frequency, 455 kc. This 455 kc signal is fed into the intermediate frequency (IF) amplifier TR-2 through T-1, an IF transformer designed to pass 455 kc and reject all other frequencies.

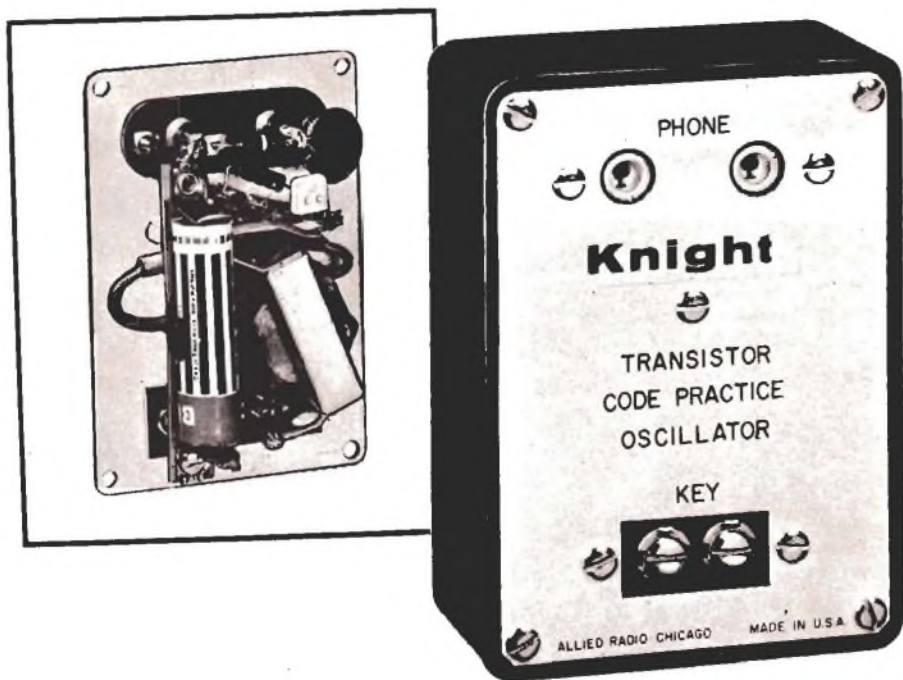


The IF stage is connected as a common-emitter amplifier, receiving the IF signal at its base, amplifying it, and then feeding it to the output IF transformer, T-2 (also sharply tuned to 455 kilocycles). From here, the signal goes to a crystal diode detector CR-1 where the audio signal is separated from the IF carrier. The audio signal is then further amplified by a Class-A amplifier, TR-3, and a Class-B power output stage. From here, the signal is applied to a 3½-inch loud-speaker. This particular mode of operation was selected for the final stage because it provides greater power output with less “no-signal” current drain.

The diode detector, CR-1, also provides a d-c voltage whose amplitude is directly proportional to the carrier of the received signal. This d-c voltage is fed back to the base of TR-2 through resistor R-6. When the signal is strong, the d-c voltage acts to lower the amplification of TR-2; when the signal is weak, the d-c control voltage causes the gain of TR-2 to rise. By this means, the level of the output sound is kept fairly steady at whatever level is selected by the volume control.

TR-1, TR-2, and TR-3 each has a resistor in its emitter leg to maintain the stability of each unit with changes in temperature.

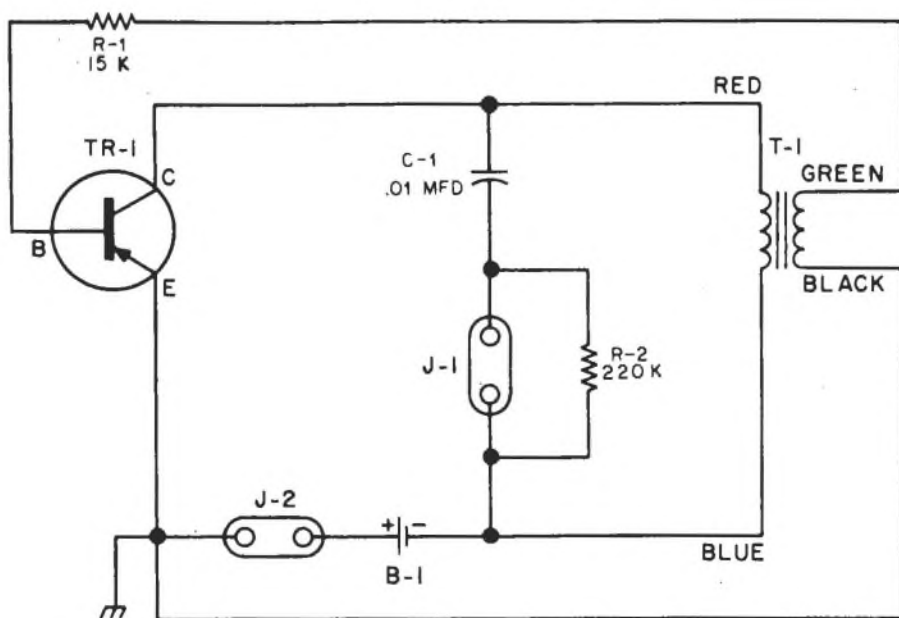
The Knight-Kit 5-transistor superhet radio kit, complete with printed circuit board, 3½-inch speaker, cabinet, wire, solder, all parts, and full instructions, is listed in the kit section of the Allied catalog.



Knight-Kit Transistor Code Practice Oscillator Kit

The Knight-Kit transistor code practice oscillator provides a low-cost instrument for aspiring Amateurs and short-wave listeners. The oscillator is completely portable, obtaining its operating power from a self-contained penlight cell. Circuit current drain is exceedingly low, enabling the unit to oscillate continuously for approximately 30 weeks on a single cell. Actually, of course, equipment of this type would seldom be called upon to provide such continuous operation and a much longer battery life can be expected.

The circuit of the code practice oscillator is quite simple. A PNP transistor, TR-1, is combined with a small audio transformer T-1 to form a low-frequency (500 cycle) oscillator. One winding of T-1 connects between the transistor collector and ground. The other winding, providing the feedback, is placed between the transistor base and ground. When power, from a small 1.5-volt cell, is applied, current starts flowing from emitter to collector and through the external circuit back to the emitter. This flow of current through the collector winding of T-1 induces a voltage in the base winding which acts to increase the collector current. This increase, in turn, provides more base voltage



which raises the collector current. The build-up continues until the collector current can no longer increase. At this point, no voltage is induced in the base winding, causing the base voltage to drop. The effect on the collector is also a decrease and this decreasing current, flowing through T-1, induces a voltage in the base winding with a polarity opposite to what it had before. The effect of this reverse voltage is to reduce the collector current even more, until eventually the collector current reaches a very low value. At this point, very little voltage is induced in the base circuit; this enables the collector current to increase again and the foregoing series of events repeats itself at the rate of 500 times a second.

If a pair of headphones are connected across terminals J-1 and a telegraph key across J-2, oscillations can be started and stopped. Any headphones having an impedance of 1,000 ohms or more may be used. If desired, two headphone sets, wired in series, may be used, enabling two people to listen at the same time.

The Knight-Kit transistorized code practice oscillator kit, with all parts, black bakelite case, anodized aluminum panel and easy-to-follow assembly instructions, is listed in the kit section of the Allied catalog. Headphones and key, available separately, are also listed.

UNDERSTANDING TRANSISTORS

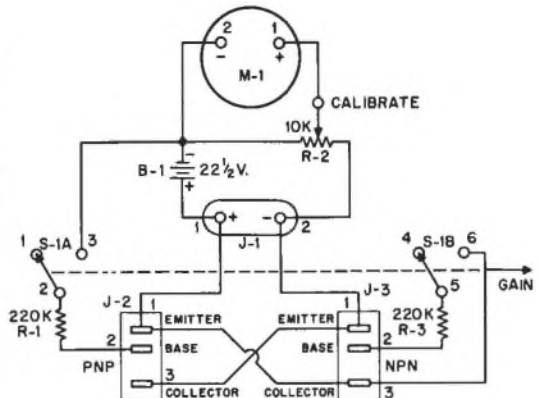


FIGURE 9. COMPLETE SCHEMATIC DIAGRAM

Knight-Kit Transistor and Diode Checker Kit

The Knight-Kit transistor and diode checker can be used to determine the operating condition of a wide variety of transistors, diodes, and rectifiers. This includes all germanium and silicon transistors, except power transistors and surface barrier transistors, germanium and silicon diodes and selenium rectifiers. For diodes and rectifiers, this instrument checks the forward and reverse current; for transistors, it checks the leakage-to-gain ratio.

Another important feature of the checker is that it enables you to listen to the noise generated by a transistor. By making use of this feature, it is readily possible to select low noise transistors for use in low level stages where noise can easily mean the difference between satisfactory or unsatisfactory operation.

The complete schematic diagram of the Knight-Kit transistor and diode checker is shown on the facing page. Diodes and rectifiers are tested by connecting them to two terminals of J-1. Transistors are tested by inserting them in the appropriate (PNP or NPN) socket.

When a selenium or copper oxide rectifier is to be checked, the negative terminal of the checker is connected to the positive post of the rectifier. The positive checker terminal connects to the negative

post of the rectifier. This biases the rectifier in the forward direction. The CALIBRATION control on the instrument is then adjusted until the meter needle is at the point marked 1. This establishes an arbitrary reference against which the next or reverse test can be compared.

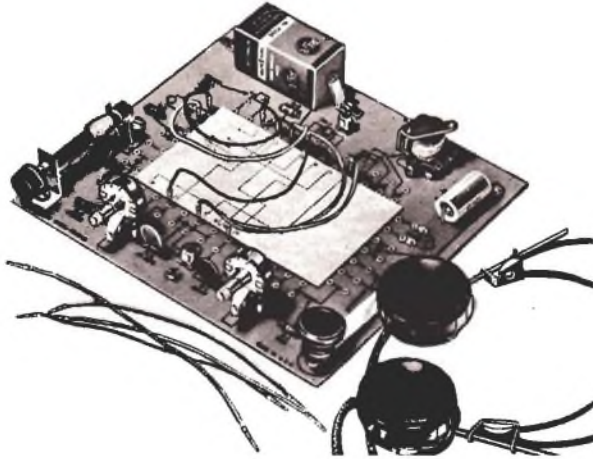
The connections to the rectifier are now reversed and the meter deflection noted. If the rectifier is good, only a small meter deflection will be obtained.

The checker can also test the forward voltage drop of selenium and copper oxide rectifiers. This is done in the following manner. The two test leads (from J-1) are shorted together and the CALIBRATION control adjusted until the meter reads full scale. This condition simulates zero forward resistance across J-1. Now, the diode or rectifier is connected to J-1 so that it is biased in the forward direction. Since the unit will have some resistance, the meter will read less than full scale. Rectifiers rated at 65 ma or less should read at least 90% of full scale. Rectifiers rated at more than 65 ma should read at least 95% of full scale. Rectifiers that do not meet these tests have too high an internal resistance and should not be used.

For transistor testing, the unit is placed in the appropriate socket. When switch S1A and S1B is in the position shown, the base lead is floating and the unit is being tested for leakage. The current that flows in the collector is a function of temperature, the resistivity of the germanium or silicon, and the applied voltage. Any contamination on the surface of the germanium or a short circuit in the device will be indicated by a high reading on the meter.

Closing switch S-1 applies voltage to the base through a 200,000-ohm resistor. The collector current of a good transistor will show an increase. The amount of increase is determined by the quality as well as the beta of the transistor. For a transistor to be useful, the current flow obtained in the GAIN position of S-1 should be equal to and preferably greater than the current obtained when the leakage is checked. The higher this ratio, the better the unit.

The Knight-Kit transistor and diode checker kit, complete with plastic case, transistor sockets, 22½-volt battery, a 0-1 ma meter movement, and an informative manual containing step-by-step instructions on construction and use, is listed in the kit section of the Allied catalog.



Knight-Kit 10-Circuit Transistor Lab Kit

This lab kit was designed to demonstrate the operation of a variety of transistor circuits ranging from a code practice oscillator to a 2-stage AM radio. One side of a printed circuit board is screen-printed to indicate where all components go. After the basic parts are soldered in place, the change from one circuit to the next is made by merely inserting plug-in leads into the proper jacks on the board; no additional soldering is necessary. Each different circuit is laid out on a separate guide card. To connect a desired circuit, simply place its guide card on the board and plug in the circuit leads where indicated.

Power for all of the transistor circuits is furnished by a 6-volt battery which is mounted directly on the printed-circuit board. This enables the lab kit to be operated wherever it is convenient to do so without regard to the availability of the a-c power outlet.

Listed below are the 10-circuits which can be built with the Knight-Kit 10-circuit lab kit.

1. Radio. This is a 2-stage receiver in which the first transistor serves as a detector and audio amplifier while the second transistor functions as an audio amplifier.

2. Audio Amplifier. A 2-stage audio amplifier that can provide a gain of 800. The output of any magnetic device (for example, a variable reluctance phono cartridge) can be amplified with this circuit.

3. Code Practice Oscillator. A high-gain 2-stage amplifier that oscillates because of feedback from the second stage to the base of the first stage.

4. Wireless Broadcaster. One transistor functions as a generator of alternating current. It converts the 6 volts of the d-c battery to a-c. The second transistor is operated as an audio amplifier and modulator. With this combination, an amplitude-modulated signal can be developed and broadcasted.

5. Photo-Electric Relay. Light, striking a photo-cell, generates a voltage which is amplified by two transistors to operate a relay.

6. Capacity Operated Relay. This circuit uses the electrical properties of the human hand to load down a Hartley oscillator. This action energizes a relay.

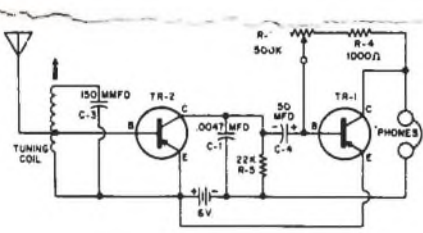
7. Voice Operated Relay. By talking into a phone, one transistor is made to conduct while the second transistor is cut off. This action de-energizes a relay located in the output circuit of the second transistor.

8. Electronic Switch. In this circuit, one transistor is cut off while the second stage is conducting heavily, energizing a relay. When the first stage is brought into conduction by completing its input circuit, the conduction of the second transistor is lowered, de-energizing a relay.

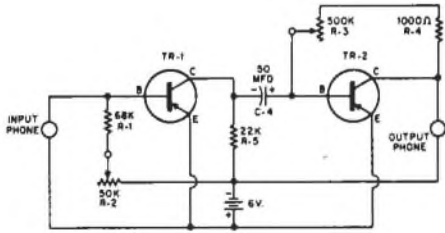
9. Timer. A 2-stage circuit in which the conduction time of one transistor is limited by a capacitor and a variable resistor. When this transistor is brought into conduction, energy is stored in the capacitor circuit is between 5 to 35 seconds. This energy is used to activate and de-activate a relay at a rate controlled by a potentiometer. If a light is connected to the input of the first transistor continually.

The transistor lab kit is listed in the kit section

Circuit Transistor Lab



BROADCAST RECEIVER



AUDIO AMPLIFIER

(See next page for 8 additional Transistor Lab Circuits)

UNDERSTANDING TRANSISTORS

