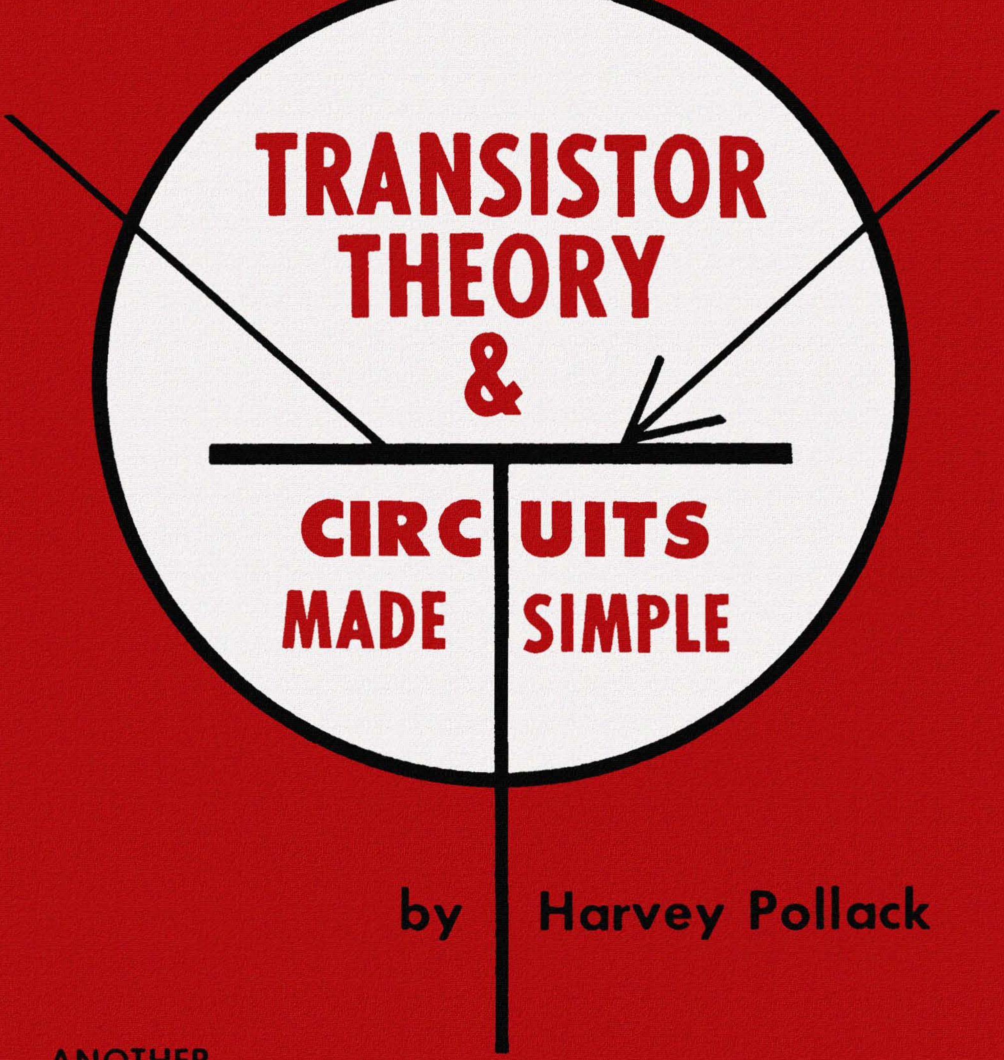

TRANSISTOR THEORY & CIRCUITS MADE SIMPLE

by Harvey Pollack

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by

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PREFACE

The transistor is, without question, the most startling offspring of our current technological age! After passing through its infancy and adolescence like the proverbial whirlwind, it has attained the stature of a full-fledged member of the electronics family in a phenomenally brief period of time. As the list of its practical applications continues to expand day after day, even the most die-hard proponents of the vacuum tube have begun to agree that tubes and transistors occupy comparable positions.

Most books dealing with the theory of transistor operation rest upon a highly involved mathematical structure. The equations are formidable, especially for the novice, and have tended to discourage many beginners from the start. For the technician, the engineering aid, the experimenter and the student, the burden imposed by rigorous mathematical treatment is entirely unnecessary. This is not to say that an occasional formula will not appear in this book, or that standard symbols will not be employed. Familiarity with fundamental symbols used to describe transistor characteristics is quite essential to prepare you to read other literature with comprehension. At the same time, however, mathematics will be conscientiously avoided when words will suffice.

In this book, you will first study a principle. Then you will see it applied in an actual circuit where all the parts are given values from devices that have been constructed and that are fully operative. Except where otherwise stated, you can build any device described herein with the assurance that it will work as described, provided you follow accepted constructional practices.

Thus, this book will serve you as a theory test of transistor principles and as a handbook of fully tested transistor circuits. As a matter of fact, we strongly recommend that you do some of the experiments as you read about them. Learning by doing is still the best method known for crystallizing ideas into facts.

Harvey Pollack

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CHAPTER 1

THE TRANSISTOR'S BACKGROUND

INTRODUCTION

There are many features that give the transistor its tremendous appeal. As tiny as your fingertip, it requires very little power to operate. It generates virtually no heat and yet, can perform the function of a vacuum tube in almost every circuit in which tubes have been used. A transistor can serve as a DC amplifier, an audio amplifier, an RF amplifier, an oscillator, a multivibrator, a blocking oscillator, a control device, or in any one of countless other applications to be discussed later.

In order to understand the operation of a transistor, we must start at the very beginning. The functioning of a transistor is a natural process involving certain forms of matter. Matter is composed of atoms and molecules which, in turn, are made of still smaller bits of fundamental material. To help us dig into the very first essentials of transistors, we must first investigate the structure of the matter which makes up our universe.

HOW ATOMS ARE BUILT

The microscope that will enable us to look into a single atom of copper or iron or carbon is yet to be devised. Still, we can come to well-founded conclusions concerning the nature of even invisible things if we analyze their VISIBLE behavior and apply to them certain physical laws we know to be true. During the last few decades, atoms have come in for extremely close scrutiny. We have learned that they all contain three fundamental particles (with the notable exception of hydrogen which contains only two): ELECTRONS, PROTONS and NEUTRONS. It is convenient to picture atoms as miniature solar systems in which electrons rotate in orbits around a central nucleus, like the planets revolve around the sun. The nucleus contains the protons and neutrons. Although this view is no longer considered rigorously correct, it does not introduce serious errors on a basic level and will be quite adequate for our purposes.

The only difference between an atom of helium and, say, an atom of sodium, is the NUMBER of these elementary particles they contain and their respective arrangements within the structure of the atom. Fig. 1-1 illustrates this fundamental concept.

It should be noted that these typical atoms are electrically neutral; that is, they contain an equal number of electrons, each carrying a negative charge of one unit, and protons, each carrying a pos-

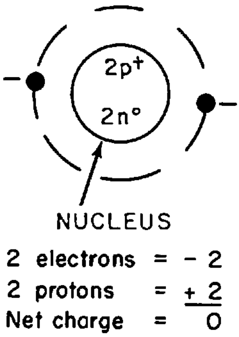

Fig. 1-1A. An atom of helium.

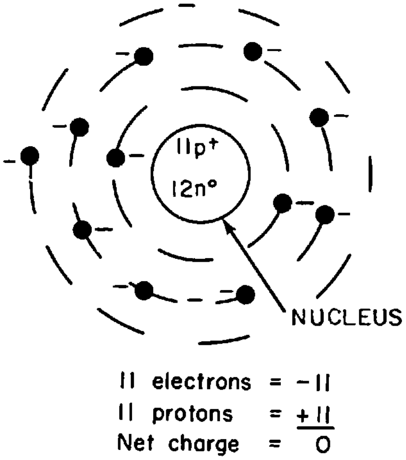

Fig. 1-1B. An atom of sodium.

itive charge of one unit. Neutrons, as the name implies, are neutral particles and carry no charge at all. Another important idea illustrated in Fig. 1-1 is that the whirling electrons do not circle the nucleus in the same orbit. They tend to segregate into rings or shells, each ring containing a very definite number of electrons for any given element. Helium, with a total of only two moving electrons, has a very simple structure in which both electrons are found in the same shell. Most of the atomic volume of sodium, however, is taken up by its eleven planetary electrons, arranged in three rings - two in the innermost ring, eight in the second and one in the outer ring.

A discussion of neutrons is not necessary in this explanation of the atom's electrical neutrality, since only electrons and protons need be considered in counting the total plus and minus charges. The existence of neutrons was originally introduced to explain how an atom like that of helium could have a MASS four times greater than that of hydrogen, when helium contains only twice the number of protons. This difference of mass could not be explained on the basis of helium's extra electron since these tiny negative particles are extremely light. (It takes almost 2,000 electrons to equal the mass of a single proton!) On the other hand, by assuming the existence of a neutral particle having a mass very nearly the same as a proton, scientists were able to explain both the chemical activity and the mass nature of all the known atoms. Since that time, there have been literally dozens of other bits of evidence which confirm the neutron's existence.

The motion of the electrons in their orbits occurs at very high speed. Their tendency to fly out of the atoms, like mud from a whirling wheel, is counterbalanced by electric, magnetic and gravitational forces. Hence, the atom is a more or less delicately stable system of interacting pulls and pushes. A normal atom remains stable and unchanged, just as long as it does not undergo damaging onslaught from the outside. It is easily possible, however, to change the character of almost any atomic structure by applying the right kinds of stresses.

ATOMS OF CONDUCTORS, INSULATORS AND SEMICONDUCTORS

All the forces that tend to hold an atom together operate most effectively over short distances. For this reason, the electrons in the inner rings of complex atoms are tightly bound to the nucleus and can be stripped away from the central body only with the greatest of difficulty. The electron or electrons in the outermost shells, however, are more loosely held in place since they are appreciably further away from the nucleus. These are the electrons which take part in chemical reactions; these are also the electrons that are the first to be dislodged under the action of cosmic rays, X-rays, or strong electric fields. These outermost electrons are called VALENCE ELECTRONS.

Suppose that the single sodium electron in the third ring suffers a collision with some other high-energy particle and is torn from the sodium atom. Due to the loss of a negative unit of charge, the atom has been altered in that it now has a net charge of one unit positive. (11 protons and 10 electrons). In this state, it is termed a POSITIVE ION. Less frequent, but nonetheless possible, is the formation of a NEGATIVE ION. This occurs when an otherwise neutral atom captures and holds one or more electrons from some outside source. Fig. 1-2 illustrates how an atom of aluminum might become a positive ion during a chemical reaction. Here the aluminum gives up all three of its valence electrons to change to a positive ion bearing a charge of +3.

In the solid state, most metals (like copper and silver) readily release their valence electrons. These released electrons, now referred to as FREE ELECTRONS, serve as current carriers. Thus, metals in general are CONDUCTORS of electricity. Non-metallic elements, such as sulphur and phosphorous, do not exhibit the ability to conduct electricity because their valence electrons are tightly held to the nucleus by sub-atomic forces; hence, they fall into the general classification of INSULATORS. Between these two categories lies a group of elements that exhibit both characteristics to some degree: the SEMICONDUCTORS, such as silicon, selenium and germanium. To compare their respective electrical conductivities, consider the figures given below: (The resistances apply to a segment of the material 1 cm. long and 1 sq. cm. in cross-sectional area).

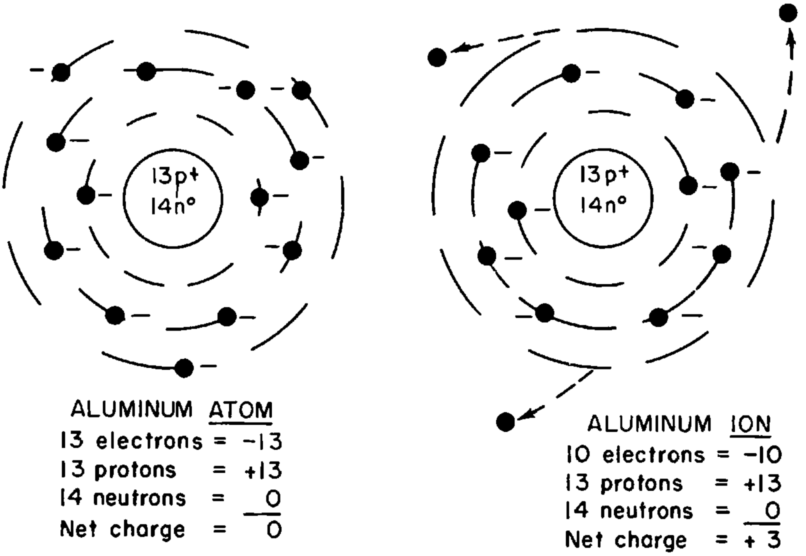

Fig. 1-2. An aluminum atom becomes an ion.

Copper ------ .0000017 ohm
Silver ------- .0000016 ohm
Nickel ------- .0000070 ohm
Transistor Germanium ------ 64 ohms
Pyrex Glass ------ 61, 000, 000, 000, 000 ohms

It is quite apparent that germanium, one of the popular transistor materials, is in a class by itself, in contrast with good conductors such as the "true" metals (copper, silver and nickel) or with standard insulators such as glass. As we shall see in a moment, PURE germanium has a much higher resistance than indicated in the table above and could be classed as an insulator. By adding certain impurities, the conductivity of germanium (or silicon) can be increased to the order of the value shown, and it is only in this state that it becomes useful as a transistor material.

THE ATOMS OF THE CARBON FAMILY

The common element carbon has four valence electrons, as shown in Fig. 1-3. This kind of structure is shared by other elements that fall into the same chemical family: silicon and germanium, particularly. One of the consequences of this four-electron structure is the formation of a kind of natural lattice in the crystalline states of these elements in which the valence electrons that are usually free to move become tightly bound to the nucleus of the atom. Carbon is chosen for discussion because it is familiar to you in two of its com-

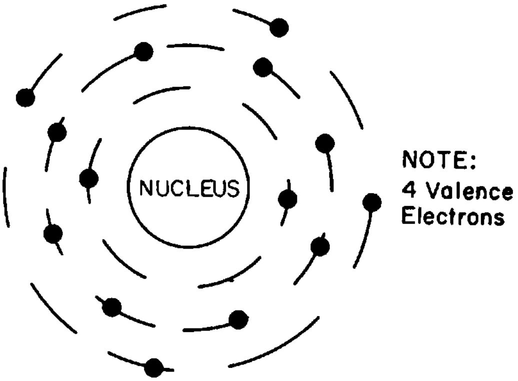

Fig. 1-3. A carbon atom.

mon forms -- as graphite (non-crystalline) and as diamond (crystalline). Carbon is an excellent conductor of electricity when in the non-crystalline graphite form; it is used in dry cells, microphones and electric-arc lamps. This means that its valence electrons are loosely held to the nucleus and can move freely to serve as current carriers. Yet, when carbon is in the crystalline or diamond state, it is an excellent insulator. Something has happened to the freedom of its valence electrons; no longer can they tear loose from their orbit, even under the action of a strong electric field. Modern chemical theory explains this by assuming that a new type of bond between atoms forms under these conditions. This bond holds electrons from adjacent valence rings to each other with greatly increased strength, substantially restricting their liberty to shift from place to place. This is known as the CO-VALENT BOND.

CO-VALENT BOND

Valence electrons are shared between atoms, the sharing process somehow increasing the electronic stability of the whole crystal to a very large degree. Co-valent bonding occurs in three dimensions with carbon atoms above, below, behind and in front of any other atom being considered. It is believed that the bonded atoms form the corners of a geometric figure known as a regular tetrahedron. This is pictured in Fig. 1-4. Since an attempt to diagram such a configuration involving many atoms would be difficult and confusing, co-valent bonding is generally represented on the printed page in only two dimensions, somewhat as illustrated in Fig. 1-5. This drawing shows a group of germanium atoms co-valently bonded in the pure state. Within the group, all the outer electrons are shared with other atoms so that none have any freedom to move about and

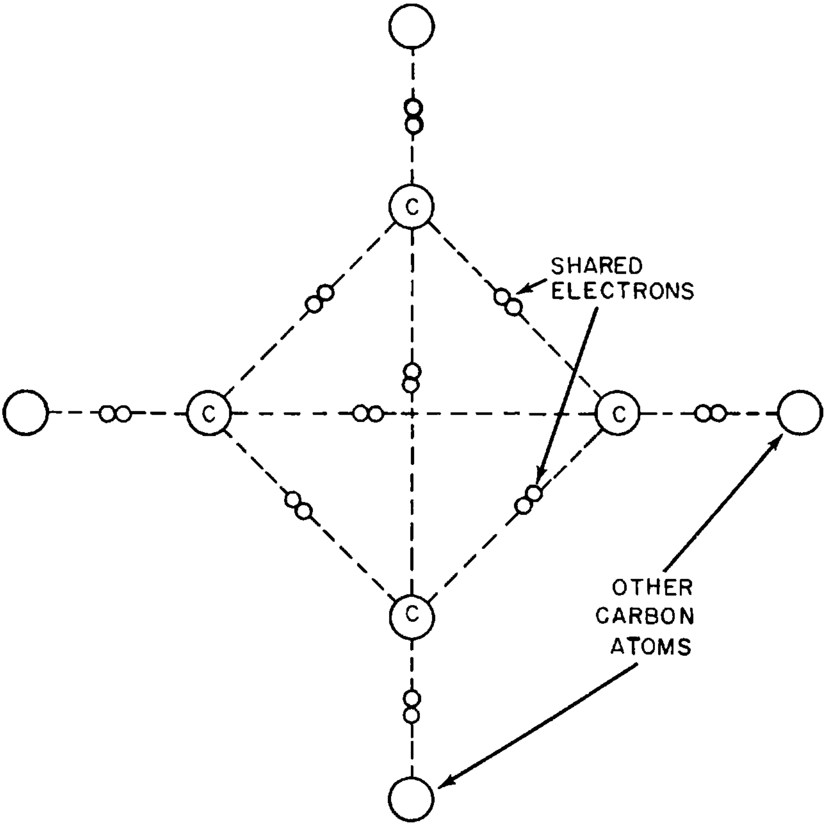

Fig. 1-4. Bonded atoms form a regular tetrahedron.

serve as current-carrying charges. Thus, pure germanium is not a semi-conductor at all; it is a nearly perfect insulator and can carry current only when excited by extremely high voltages. Obviously, then, pure germanium or pure silicon, which has a similar structure, cannot be used, without modification, in any electrical devices in which currents must flow.

EFFECT OF IMPURITIES ON SEMICONDUCTORS

The lattice-like structure of diamond, germanium crystals and silicon crystals in their pure form prohibits electron flow only because there are no free electrons present to carry an electric current. If we could reach into one of these crystals with a pair of submicroscopic forceps and carefully place a single electron in the body of the substance, the electron would move about at random quite freely. A more practical procedure, however, consists of adding a very tiny quantity of some impurity --- possibly only one part in

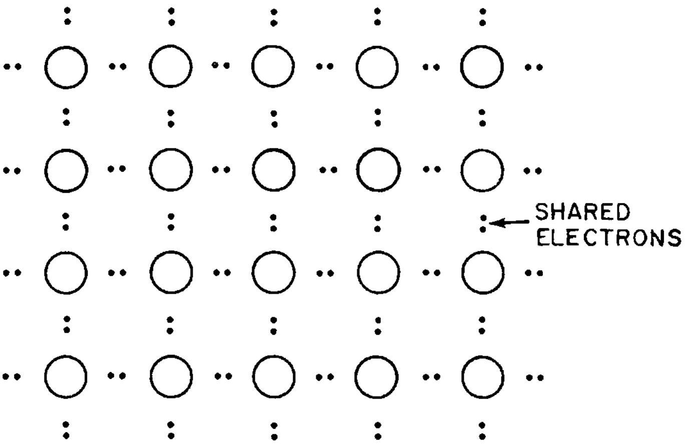

Fig. 1-5. Co-valent bonding in germanium.

10,000,000 --- which will be capable of disturbing the family ties of the semiconductor to the extent that some free electrons will make their appearance. Elements such as antimony, arsenic, phosphorus and bismuth that have five valence electrons, can be employed as the impurity.

Consider a single atom of arsenic in the midst of a group of germanium atoms. Arsenic has five valence electrons (for this reason, it is known as a PENTAVALENT element) and when it finds itself in the company of an overwhelming number of germanium atoms, it tends to behave just like its neighbors. That is, it uses four of its five electrons to form co-valent bonds with nearby germanium atoms to keep the lattice intact. But its extra electron forms no attachments. Being deprived of much of the original nuclear attraction by this displacement process, the electron is free to move about as a current carrier. If an emf. is now applied across the ends of the crystal, a small current flows, indicating that the resistance of the germanium has decreased tremendously. Even a small quantity of the pentavalent impurity yields a very large number of free electrons. Fig. 1-6 shows this mechanism in operation.

When the displaced electron from the arsenic impurity reaches the positive terminal, it leaves the crystal altogether. Since the crystal was electrically neutral to begin with, it will now be positively charged, having an electron deficiency. Thus, a substitute electron will enter the germanium crystal from the negative terminal of the battery to keep a continuous stream in motion as long as the emf. is applied. It is evident from this analysis that the arsenic's electrons are not "used up". That is, new supplies of the impurity

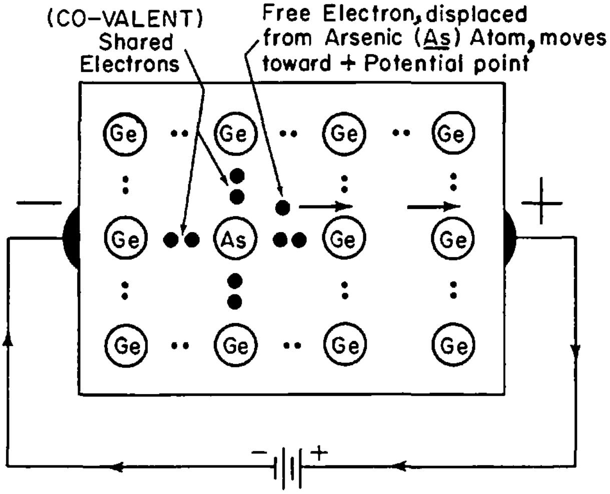

Fig. 1-6. An atom of arsenic in the midst of a group of germanium atoms. Note that all electrons are of the same size. Accentuated group around arsenic nucleus is merely for diagrammatic clarity.

do not have to be added to maintain the activity of the semiconductor.

For the reasons given in the foregoing discussion, pentavalent impurities, such as arsenic, are called DONOR impurities because they donate free electrons to the normally insulating lattice structure of the crystal. Let's keep this action in mind for a moment while we investigate the results of adding a different kind of impurity.

Certain elements are TRIVALENT. These have only three valence electrons in their outer shell; the elements in this family include boron (B), aluminum (Al), gallium (Ga), indium (In) and thallium (Tl). Some of these, notably indium and gallium, exhibit a very strong tendency to form co-valent bonds with other atoms, such as those of germanium. Thus, when an indium atom is added to a pure germanium crystal, it replaces the latter in the structure but MUST TAKE AN ELECTRON from another germanium atom in order to complete its four co-valent bonds. In doing so, one of the germanium bonds is disrupted and an electron is removed, leaving behind it a region of positive charge, equal in magnitude to the charge on the electron, but of opposite polarity. Such a disrupted area is termed a HOLE since it actually is an area where a particle ONCE resided and then was removed.

Fig. 1-7 illustrates the formation of a hole in a germanium crystal having an indium impurity. The HOLES ARE MOBILE since they move toward the negative terminal of the applied emf. Thus, a hole is nothing more than a disrupted co-valent bond and takes on the

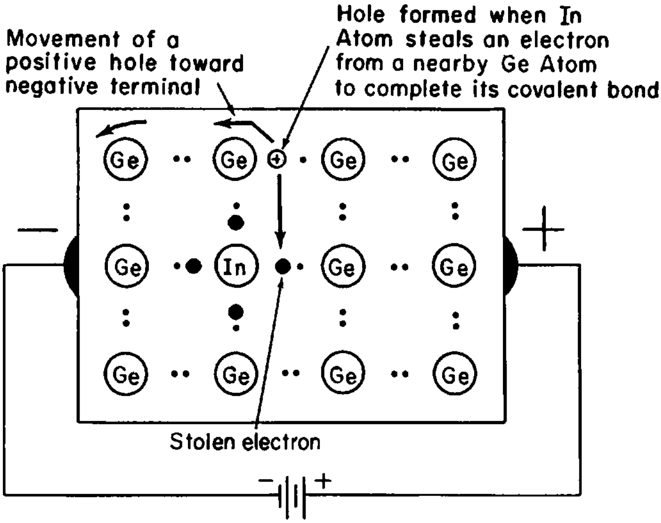

Fig. 1-7. An atom of indium in the midst of germanium atoms.

properties of a POSITIVELY CHARGED PARTICLE with a mobility comparable to that of an electron.

An impurity of the trivalent variety, such as arsenic, is called an ACCEPTOR since it accepts electrons from the germanium atom. As the hole formed by this electron "swapping" process moves toward the negative terminal, it behaves as a charged carrier, and when it arrives at the negative end, an electron immediately moves into the hole from the source of emf., causing cancellation of charge. The crystal may now be considered to have a net negative charge, since it has gained one electron. As a result, an electron leaves the crystal at the positive terminal due to electrostatic attraction, forming a new hole in this vicinity. The newly born hole then proceeds toward the negative end once again; hence, the movement of holes is a sustained process as long as the emf. is applied. It should be recognized that a flow of holes constitutes an electric current to exactly the same extent as a flow of electrons. The difference is one of polarity. This merely means that, relative to the external source and load circuits, A FLOW OF HOLES HAS EXACTLY THE SAME EFFECT AS A FLOW OF ELECTRONS - ONLY GOING IN THE OPPOSITE DIRECTION.

Early in the history of transistor development, germanium crystals to which donor impurities were added, were called N-type crystals because of the fact that conduction was carried on by moving negative charges. Similarly, germanium containing acceptor impurities was referred to as P-type transistor material since the charged carriers were positive holes. (Note that the "n" in donor and the "p" in acceptor can be used to help you remember which is which). These designations are still in use and have achieved the stature of fully accepted terms. We shall use them freely in this book.

RECTIFICATION AT AN N-P JUNCTION

Either P-type germanium or N-type germanium alone has no special properties. Reversing the polarity of the emf. applied to either type will merely reverse the direction of the current flowing through it. This must be so because there is nothing in the structure of the material which favors one direction of movement over the other. Although we shall not make extensive use of the fact, it might be wise to point out at this time that a small number of electrons that could serve as current carriers, co-exist in P-type germanium with a much greater number of holes; similarly, N-type material contains a very small quantity of holes mixed in with its abundance of free electrons. It is for this reason that you will occasionally encounter the terms "majority" and "minority" carriers in transistor literature. The majority carriers in N-type crystals are the electrons and the minority carriers are the holes; in P-type material, the reverse is true. For the time being, we shall be concerned only with the majority carriers.

If a wafer of each type of transistor germanium is joined to the other to form a JUNCTION, special properties then develop. A satisfactory N-P junction cannot be made merely by placing the wafers in contact. Delicate and tightly-controlled manufacturing processes are needed to perform this operation. Once the junction exists, however, the crystal then exhibits UNIDIRECTIONAL CONDUCTIVITY (conduction in one direction only) and may be used in circuits as a RECTIFIER.

Reference is made to Fig. 1-8 in discussing this action. An AC generator is connected to the ends of the two slices of germanium with the junction midway between. In A, the instantaneous polarity is such that the positive generator terminal is connected to the N-type material and the negative terminal to the P-type. The electric field thus produced has the effect of moving the electrons in the N-type germanium close to the positive side of the generator and the holes in the P-type nearer to the negative side of the generator. As the diagram indicates, virtually no current carriers can be found at or near the junction. An external current cannot flow under these circumstances because the carrier-free junction area behaves like an open circuit. With a definite voltage applied and little or no resulting current flowing, we must conclude that the N-P junction is now behaving as a very high resistance.

Consider now what happens when the instantaneous generator polarity reverses on the next half-cycle. Both the electrons in the N-type material and the holes in the P-type material are propelled

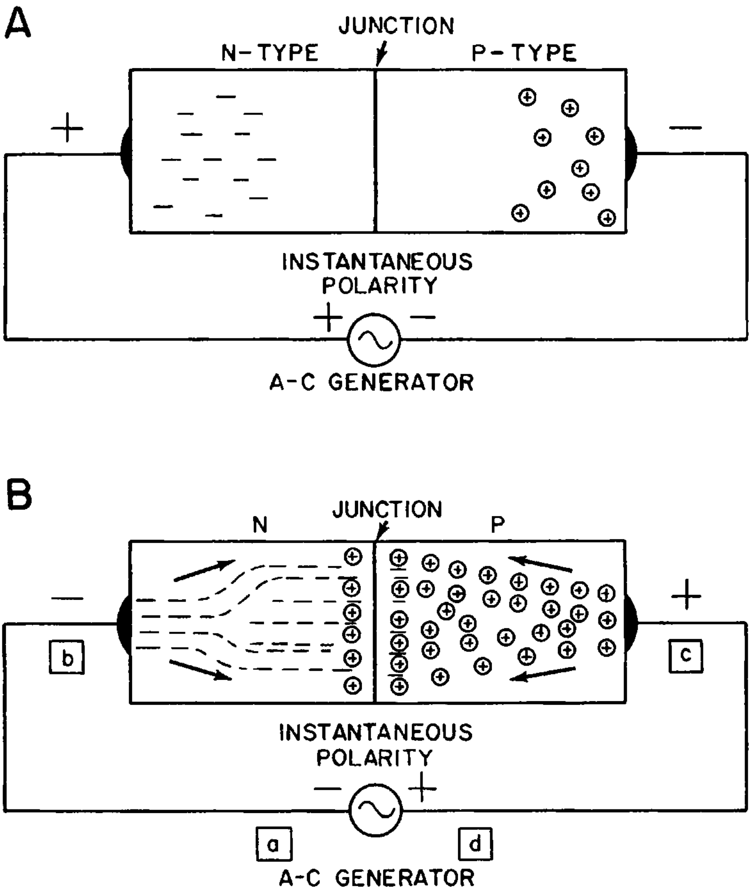

Fig. 1-8. Rectification at an N-P junction.

toward the junction by the electric forces. As they cross the barrier, they intermingle freely and neutralize each other so that the N-type section is now left with a deficiency of electrons and the P-type material with a deficiency of holes. This opens the way for new electrons to enter the N-type side from the generator connection, thereby producing a current in the wire from point a to point b. The P-type wafer, by the same reasoning, has a net negative charge due to its deficiency of holes. It therefore releases an electron to the positive generator wire, forming a new hole at the junction, as described in the previous paragraph. The electron moves through the wire to the positive terminal of the generator (path c to d), thus completing the electron current circuit. Meanwhile, the hole just formed at c moves toward the junction to sustain the process. Thus we see how a combination of P-type and N-type germanium can be used as a rectifier to convert AC to DC.

The current flow in the generator and its wires has been described entirely in terms of ELECTRON FLOW, although the passage of charges within the crystal involves both electrons and holes. Relative to the external circuit, nothing is to be gained by retaining the hole concept. This is a fortunate situation, particularly for the novice, because we may continue to think of the source of emf. and the load circuits as carrying only electrons, just as they do in circuits that do not involve transistors.

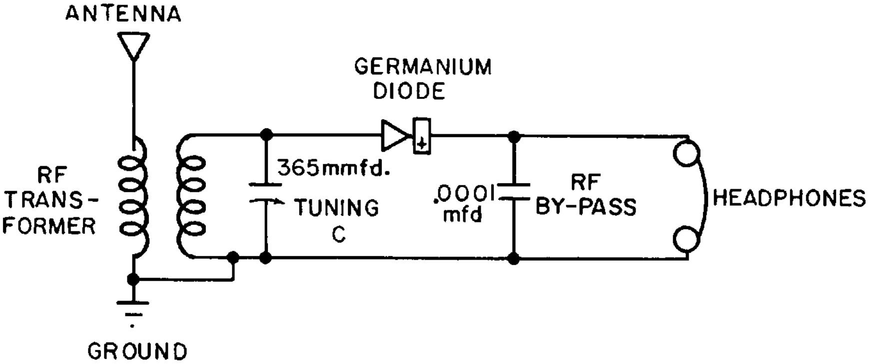

Fig. 1-9. A simple diode receiver.

Fig. 1-9 indicates how a germanium rectifier diode is connected to make use of its unidirectional conduction characteristic. In the arrangement shown, it serves as a detector in a simple, tubeless radio receiver. Diodes of this variety are found in all sorts of radio-frequency rectifier applications; their use is advantageous compared with rectifier tubes because they do not require a source of filament voltage nor any warm-up time as vacuum tubes do. The symbol for the germanium diode, shown in Fig. 1-9, is now widely accepted. The flat plate against which the point of the triangular arrowhead rests is the terminal on the diode that is marked either "+" or "K" and corresponds to the cathode of an equivalent rectifier tube. The electron flow occurs from the "+" or "K" terminal to the triangular section of the diode.

INVENTION OF THE TRANSISTOR

Credit for the discovery of the germanium rectifier in 1942 is generally attributed to Dr. S. Benzer of Purdue University. This, and other experimental rectifiers that followed it, were not junction-type units as we have been describing them. Rectification was accomplished by a point-contact method to be described shortly. Very little publicity was given the germanium diode at that time, due to wartime security, but in 1944 Dr. Benzer described it in an article entitled "The High Voltage Germanium Rectifier" published in The National Defense Research Council.

A group of scientists, under the directorship of Dr. William Shockley of the Bell Telephone Laboratories, began work on preparation methods for germanium rectifier crystals shortly after Dr. Benzer's discovery was announced. During the course of their work, some unexpected phenomena were observed, phenomena which pointed the way to other divergent lines of research. About three years later, the research team had progressed far enough with their work to add a third "element" to the germanium assembly, thus bringing into existence the first transistor (TRANSFER RESISTOR). Public disclosure of this discovery was made in the form of a patent filed in June, 1948.

Again, three years elapsed before any major innovations were reported; in 1951, the first junction transistor was announced. Thus, the history of today's transistor had its inception a relatively short time ago, as time is measured in scientific progress.

Although the name of Dr. William Shockley is, by far, the most prominent one in transistor literature, this does not imply that the present state of development of this device is due to the efforts of one man or a few men. Between 1948 and the present time, a large number of conferences and symposia conducted by organizations such as the IRE and the AIEE (Institute of Radio Engineers and American Institute of Electrical Engineers, respectively), brought to light many of the more important developments and processes currently utilized in manufacturing transistors.

The tetrode transistor, a modification of the basic unit which permits operation at frequencies substantially higher than previously thought possible, was made public in August, 1952, by Dr. R. L. Wallace, Jr. of the Bell Telephone Laboratories. By the end of the same year, transistorized hearing aids appeared in the consumer market!

The amazing pace of transistor development continues today. When a scientist or engineer mentions a specific transistor limitation, he usually qualifies it by adding "at present". He knows that the word "impossible" is indeed a rash term to apply to science and to say that something is impossible is to see it made possible next week, next month, or next year!

CHAPTER 2

HOW TRANSISTORS WORK

FORWARD AND REVERSE BIAS

The diode action of an N-P junction, as discussed in Chapter 1, was based upon the application of an AC potential to two pieces of transistor germanium, one with an N-type of impurity and the other with a P-type of impurity. In discussing true transistor behavior, it is often helpful to think in terms of directional RESISTANCE and what is referred to as transistor BIAS.

If an N-P junction is connected to a source of DC rather than AC, the presence or absence of an appreciable current flow depends upon the polarity of the applied voltage, as in the case of rectification. If the polarity is such that little or no current flows (- of the source connected to the P-type germanium and + of the source connected to the N-type material), we say that the junction is BIASED IN THE REVERSE DIRECTION. When connected this way, the source of emf. encounters a HIGH RESISTANCE. In contrast with this, the application of the source potential in the direction which gives rise to a sizable current is said to represent a condition of FORWARD BIAS or low resistance.

These concepts are introduced at this point because they facilitate the explanations to come. Refer to the diagrams illustrating diode action in Chapter 1 to be sure these ideas are clear. Fig. 2-1 illustrates the same principles in a more concise form.

STRUCTURE OF THE JUNCTION TRANSISTOR

A transistor differs from the semiconductor diode in that it consists of three sections rather than two. In a sense, it resembles a

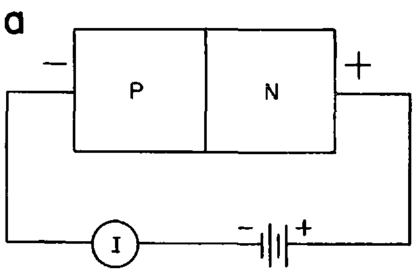

Fig. 2-1a. Condition of reverse bias or high resistance. The current (I) is very low.

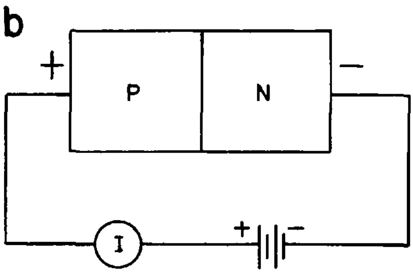

Fig. 2-1b. Condition of forward bias or low resistance. The current (I) is high.

sandwich in which one type of transistor material is held firmly between two slices of the other type of transistor material. Fig. 2-2 shows the two types of "sandwiches" now in common use. If the middle section is a P-type semiconductor, the transistor is called an N-P-N type for obvious reasons; similarly, a P-N-P transistor contains N-type semiconductor between two sections of P-type material.

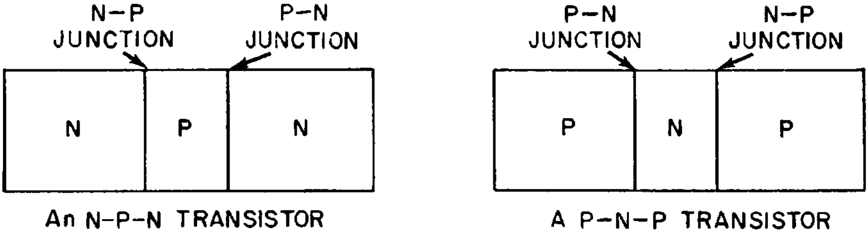

Fig. 2-2. Two types of basic transistors.

A satisfactory junction cannot be made by simply placing P-type and N-type materials in contact with each other, since the free interchange of holes and electrons does not easily occur under these conditions. The manufacturing methods are delicate and precisely controlled with definite variations in practice, even between manufacturers using the same process.

Probably the most straightforward method of making transistors uses the DIFFUSION PROCESS. Starting with a thin wafer of N-type semiconductor material, an acceptor impurity such as gallium or indium is placed in contact with the semiconductor surface and heated in an oven. The indium or gallium melts and diffuses into the surface of the semiconductor, penetrating deeper and deeper during the interval that heat is applied. (See Fig. 2-3). At the end of the diffusion process, the portion of the semiconductor into which a relatively tiny number of acceptor atoms have penetrated becomes P-type material, while the central portion of the wafer remains unaffected N-type semiconductor, so that the finished product is, therefore, a P-N-P transistor. Note from the diagrams that the P-material is formed simultaneously on both surfaces of the original N-semiconductor wafer. As you will see, it is important that the unaffected N-type semiconductor in the middle of the sandwich remains a very thin slice. Unless this is carefully controlled, transistor action is not readily obtained.

N-P-N transistors, on the other hand, are not generally fabricated by the diffusion process. An entirely different method, called the "grown-junction" process, is used in the manufacture of N-P-N units. More recently, both P-N-P and N-P-N transistors of excellent quality and performance have been manufactured by a method

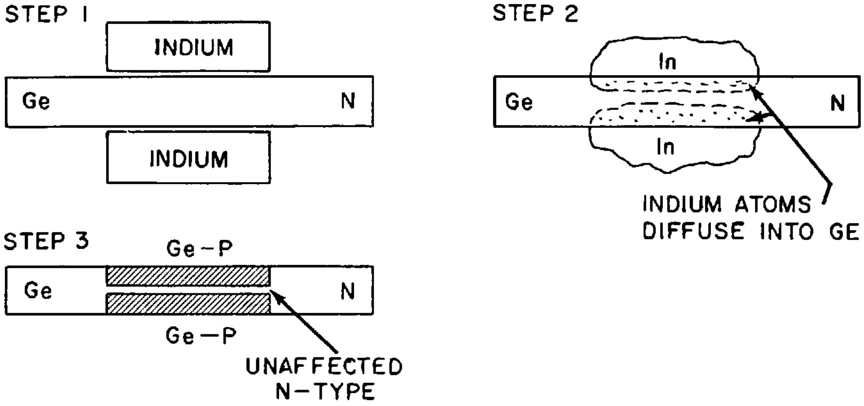

Fig. 2-3. Making P-N-P transistors by the diffusion process.

generally called the "rate-grown" process. For detailed information relating to these processes, it is recommended that you refer to the more advanced specialized periodicals. *

SETTING UP A TRANSISTOR AMPLIFIER

For simplicity of reference, we have labeled the parts of the transistor (N-P-N type in Fig. 2-4), E (for emitter); B (for base) and C (for collector). We have connected two separate batteries to the unit, as shown, and have placed a current reading instrument -- a microammeter or milliammeter, as the case may be -- in series with the outgoing battery leads.

As the first important step in understanding the effects that underlie transistor amplification, consider that parts E and B together form one germanium diode since E is N-type germanium and B is P-type germanium. In a similar manner, consider parts B and C as forming a second germanium diode. Thus, part B is common to the two diode sections.

Second, examine the battery polarities to determine whether forward or reverse bias is being used on the two sections. Evidently, the E-B diode is biased in the forward direction (see Fig. 2-1b) and a current will flow from the negative side of the battery, through the E section to the B section, through the meter Ie and back to the positive end of the battery. The B-C diode section, however, has REVERSE BIAS applied to it and therefore, exhibits a high resistance.

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* Teal, Sparks, and Buehler: "Growth of PN Junctions", Phys. Rev. Vol. 81, p. 637.

* Hall, "PN Junctions by Rate Growth Variations", Phys. Rev. Vol. 88, p. 139.

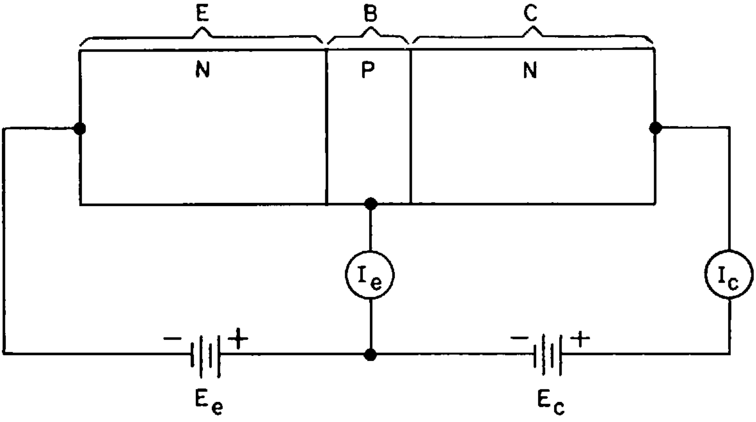


Fig. 2-4. Bias voltages in an N-P-N transistor.

Therefore, the current Ic would be very small. But the above reasoning completely ignores the very important fact that part B is COMMON TO BOTH DIODES. And, as we shall see in a moment, it is this sharing of section B that makes amplification possible!

You will recall that the P-type material forming the center section of the N-P-N transistor is made extremely thin. On the other hand, when we discussed the junction diode in Chapter 1, the assumption was made that both halves of the diode (the N-type half and the P-type half) were equal in size. This also assumed that the number of available electrons in the N section and the number of holes in the P section were approximately the same. Under these conditions, there were an equal number of majority carriers in each of the two halves to support the explanation of the diode's operation.

Here the case is quite different: the P-section is extremely thin and does not contain nearly as great a total number of holes as each of the N-sections have electrons. As electrons move into the B region across the E-B junction, they encounter very few holes with which they can combine. Since few holes are neutralized, the negative charge produced in the P-type material is quite small. Therefore, the number of free electrons available to return to battery Ee is also correspondingly small. Electrons that enter B from E are now subject to the forces produced by two electric fields: (1) the field produced by battery Ee and (2) the field produced by batteries Ee and Ec connected in series aiding. Since battery Ec is generally of a larger voltage than Ee and, furthermore, since the two batteries in series give rise to a much stronger electric field than Ee alone, most of the electrons follow the electric lines produced by the stronger field, with relatively few taking the path offered by the weaker field. Hence, since little recombination takes place between the electrons that enter B from E, most of these electrons diffuse across the B-C junction, travel through section C and return through Ec to the positive end of battery Ec. In Fig. 2-5, this comparative motion of electrons has been illustrated pictorially.

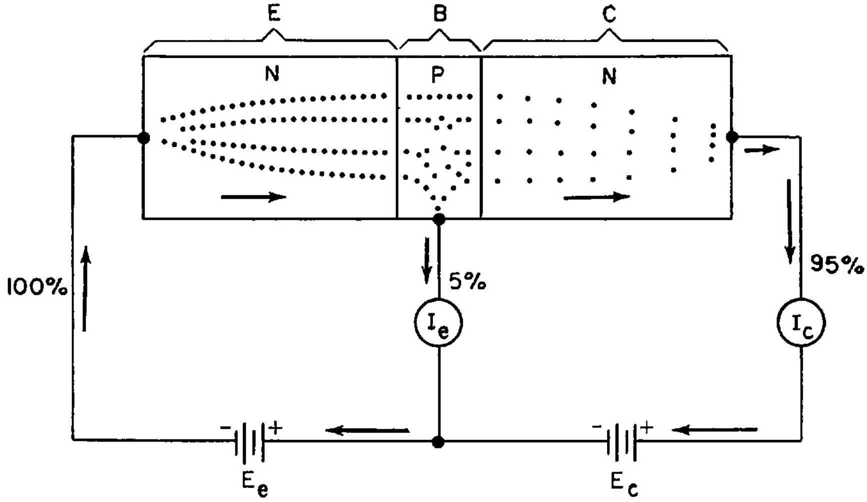


Fig. 2-5. Electron flow in a junction transistor.

Thus, sections E, B and C may be considered as a series-group across both batteries in series-aiding, as explained above. The bias produced by battery Ec, we have said, is REVERSE BIAS, resulting in a HIGH RESISTANCE across the B-C junction, a fact that would seem to imply that large currents could not flow through section C. This might be true if the circuit contained only B and C and battery Ec. But now that we can visualize the series-aiding connection of the two batteries and the series-connected semiconductors E, B and C, it can be appreciated that any electrons that do find their way through B, will be impelled through C by the action of the combined battery voltages.

About 5% of the electrons that leave battery Ee and enter section E, return to Ee through the meter Ie. The other 95% proceed on through B, into C and return to the batteries through meter Ic. On the other hand, the voltage which governs the electron flow into E from Ee is that of battery Ee.

All of the foregoing leads to this conclusion: THE VOLTAGE BETWEEN E AND B CONTROLS THE TOTAL ELECTRON FLOW, BUT ELEMENT B DOES NOT COLLECT THESE ELECTRONS; MOST OF THE ELECTRONS CONTINUE TO MOVE ON INTO ELEMENT C. For those who know vacuum tubes, this should have a very familiar ring. In the case of tubes, the number of electrons that leave the cathode is controlled by the cathode to grid voltage, but the grid does not itself collect these electrons; most of the electrons continue to move on to the plate of the tube. The parallelism is apparent. In fact, it has been carried right over to the nomenclature of the transistor sections.

Section E is called the EMITTER because (in the N-P-N transistor) the electrons enter the transistor here, just as they do from the CATHODE of a tube.

Section B is called the BASE and because it acts as a controlling element on the entering electrons, is comparable to the GRID of a tube. Using the name "grid" for this element would not fit the physical picture at all, hence the title "base" was chosen.

Section C is called the COLLECTOR because, like the PLATE of a vacuum tube, it receives the "emitted" electrons and returns them to the circuit.

Our discussion thus far has been based upon an N-P-N transistor, only because the average reader is more accustomed to reasoning in terms of excess electrons and electron flow, rather than the movement of holes. The explanation of the behavior of a P-N-P transistor is entirely parallel, except that the majority carriers in the body of the semiconductor are holes rather than electrons. Because the carrier charge is reversed, the battery polarities must be reversed. Otherwise, the over-all performance for each is nearly identical. The bias polarities for correct operation for both types are shown in Fig. 2-6.

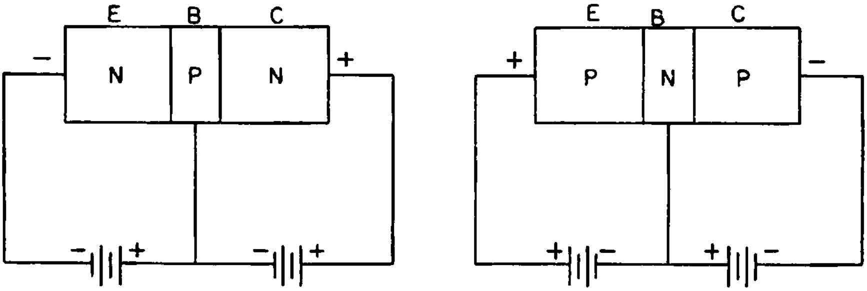


Fig. 2-6. Bias polarities for N-P-N and P-N-P transistors.

Although transistors are rugged devices from the point of view of vibration and shock, they are affected by high temperatures. It is because of temperature effects that a REVERSAL OF BIAS POLARITIES CAN DESTROY A TRANSISTOR. The heat generated by the excessive collector current at the B-C junction, due to the application of forward rather than reverse bias in this circuit, is responsible for this danger.

HOW A TRANSISTOR AMPLIFIES

The voltage amplification or voltage gain of a vacuum tube is defined as the ratio of the signal voltage developed across the load to the signal voltage applied to the input terminals of the tube. Exactly the same definition is used for the voltage amplification of a transistor. It is somewhat easier, however, to make an analysis of transistor amplification by considering what takes place across the load resistor or other load impedance when a small change of DC voltage is applied across the input circuit. We might, therefore, set up the equipment shown in Fig. 2-7. Resistor Ri, in the emitter-base circuit, permits us to vary the potential applied between these two elements. The output voltage Eo is equal to the collector current, multiplied by the resistance Ro.

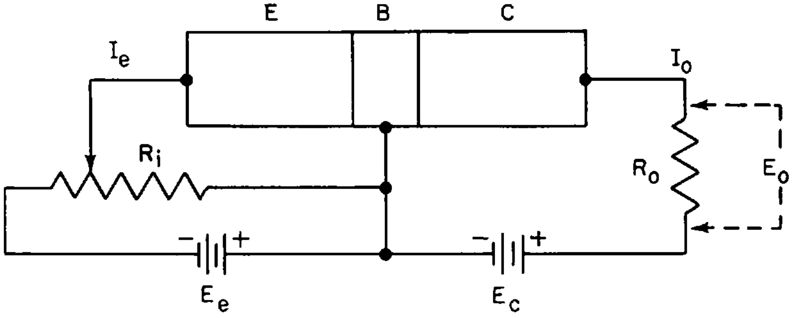


Fig. 2-7. Circuit for studying transistor amplification.

Let us now look at some representative values of emitter-to-base and collector-to-base resistance. Since the emitter is biased in a forward direction, its resistance is low; a typical value for an N-P-N transistor is approximately 350 ohms. The collector-to-base resistance is high due to the reverse bias applied by Ec. This may be in the order of 350,000 ohms for the same transistor.

Due to the combinations and recombinations of electrons and holes in the base region, the variations in the collector current Io are always less than the corresponding variations in the emitter current Ie. This results from the fact that 5% of the electrons that form part of the emitter-base current stream never arrive at the collector at all. In order for the collector change or variation to be equal to the emitter change, ALL the incoming electrons from Ee would have to take part in the collector variations. This represents a CURRENT LOSS or, stated in another way, a CURRENT GAIN of less than 1. In transistor terminology, current gain is referred to as ALPHA (α) and takes on a value in the vicinity of .95 for most transistors. (See Fig. 2-5).

To counter this, however, we have the very substantial difference in input and output resistances -- 350 ohms to 350,000 ohms. Since a voltage drop is always proportional to resistance, the higher output resistance indicates the possibility of a higher voltage across the output circuit. If there were no current loss or current gain, the voltage gain due to the higher resistance alone would be 350,000 / 350 or about 1,000 times. Since there is a current loss of about 5%, the voltage gain is reduced by the same percentage. That is, the total theoretical voltage gain is about 1,000 minus 5% of 1,000 or:

$$\text{voltage gain} = 1000 - (0.05 \times 1000) = 950$$

We must emphasize that this voltage gain is entirely theoretical. It could be obtained only if Ro were of infinite value, an impossible condition, of course. Even with reasonable values of Ro, however, the voltage gain still compares favorably with a standard triode tube. It is not uncommon to find transistor circuits which yield actual voltage gains that exceed 20 or 30 times.

In summary: Even though a junction transistor has an alpha or current gain of less than 1, this deficiency is more than compensated for by the extremely great ratio of collector to emitter resistance which permits, therefore, a much greater "resistance gain" than there is a current loss. Resistance gain, in this sense, means the ratio of output to input resistance which, in turn, determines the ratio of output to input voltage.

POWER GAIN IN JUNCTION TRANSISTORS

In any type of amplifier, we are always concerned with the relationship between the CHANGE of power output and the amount of change required in the input circuit to produce this variation of output. Where actual power output is measured in terms of watts, POWER GAIN tells us how much input is required to control a given power output and is expressed as a ratio without units. Since power may be defined as: $P = I^2R$

then power gain, or the ratio of output power to input power, may be expressed as:

$$\frac{Po}{Pi} = \frac{Io^2Ro}{Ii^2Ri} = \left(\frac{Io}{Ii}\right)^2 \times \frac{Ro}{Ri}$$

In the formula shown above, P represents the power in watts; I is the current in amperes; Ro is the output resistance and Ri is the input resistance.

Since $\frac{Io}{Ii}$ is equal to current gain and $\frac{Ro}{Ri}$ is equal to resistance gain, we can restate the formula as follows:

Power Gain = (current gain)^2 x (resistance gain)

$$\text{or P.G.} = \alpha^2 \times \frac{Rcb}{Reb}$$

where: is current gain, Reb is the emitter-to-base resistance and Rcb is collector-to-base resistance.

To find the theoretical power gain of the typical transistor discussed in the previous paragraph, we might substitute the known values in this equation and obtain:

$$\text{P.G.} = (0.95)^2 \times \frac{350,000}{350} = .90 \times 1,000 = 900$$

In actual practice, it is entirely possible to realize power gains greater than 400. This means that relatively large power outputs are controllable by small power inputs and that junction transistors compare very favorably with vacuum tubes in this respect.

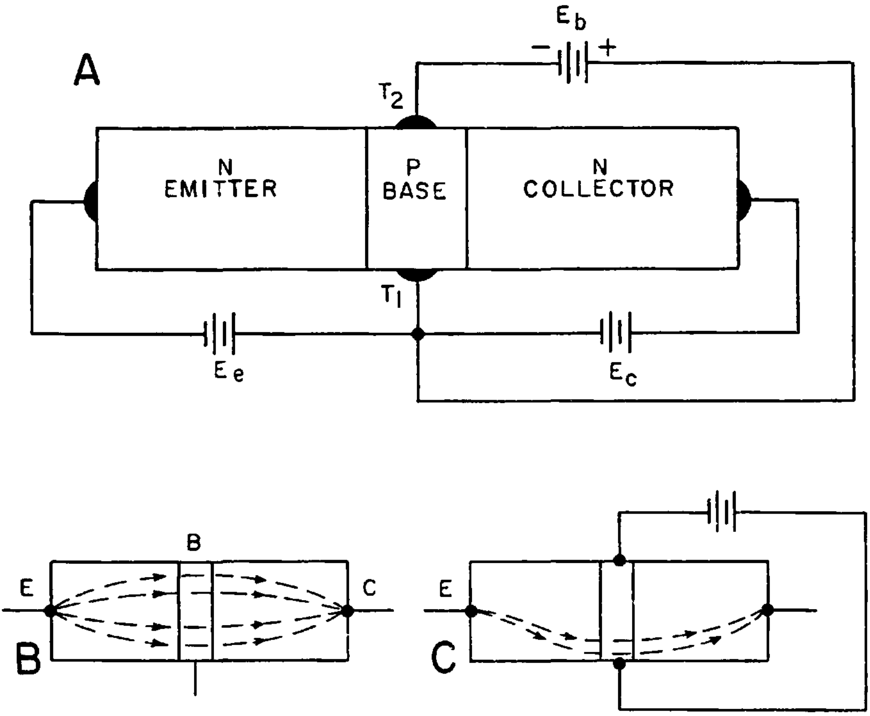
TRANSISTOR PROGRESS

The diffusion process for fabricating P-N-P junction transistors has been described in some detail; the grown junction method used to manufacture N-P-N types has also been mentioned. New processes are constantly under test to improve the performance of junction transistors.

One of the outstanding transistor developments is the SURFACE-BARRIER TRANSISTOR in which the surface peculiarities of a single wafer of N-type germanium are utilized to produce transistor action. Pseudo P-type behavior is obtained at the transistor surface by exciting electrons in the valance rings to the point where they leave their atoms, leaving holes behind. The required excitation is thermally produced by natural heat reaching the transistor from its environment. Surface-barrier transistors are being used in video amplifiers having a bandwidth of at least 5 Mc., in 30 to 40 Mc. RF amplifiers and in oscillators which operate reliably up to almost 100 Mc.

A further extension of the frequency range of transistors has been realized by adding a fourth terminal to an N-P-N junction transistor, as shown in Fig. 2-8A. Because of the four connections, this unit has come to be called a TETRODE TRANSISTOR. The assembly resembles a conventional N-P-N junction transistor; the essential difference is the presence of bias battery Eb connected to the second of the base terminals T2.

Although a rigorous explanation of the tetrode action is complex, no serious error is committed by imagining that the strong electrostatic field within the base section, from top to bottom, forces the



ELECTRON FLOW LINES IN NORMAL N-P-N TRANSISTOR

CONFINED FLOW LINES IN TETRODE TRANSISTOR

Fig. 2-8. A tetrode transistor.

flow lines of electrons to confine themselves to the lowermost section of the composite slab. In other words, electrons traveling from emitter to collector can no longer pass through all parts of the junction; the electrostatic field originating at T2 drives them downward so that the electron stream is much narrower and more confined. (See Fig. 2-8C).

This flow-line modification has two important effects, both of which operate to widen the useful frequency range of the transistor. The first is that the collector-to-base capacitance is decreased, reducing the shunting effect of the transistor on the load resistance. As in a vacuum tube, capacitive shunting by the amplifying device works to the detriment of high frequency response, by by-passing these frequencies around the output load. The second effect is that the BASE RESISTANCE of the transistor is reduced. As we shall show later when this transistor characteristic is discussed, a reduction of base resistance encourages improved high-frequency voltage gain.

One additional difference in structure is that the central P region of these units is made much thinner than the equivalent section in a standard N-P-N transistor. This permits the current carriers to move across the junctions in less time (the equivalent of shorter transit time in vacuum tubes). With a reduction in transit time, there is an improvement in high-frequency operation.

The contrast between the high-frequency behavior of a standard N-P-N transistor, connected first as a "triode" and then as a "tetrode", is clearly shown in the curves of Fig. 2-9. The initial current gain of the triode transistor is unquestionably superior to that of the tetrode at frequencies in the lower portion of the frequency range, but the alpha drop-off of the tetrode is much more gradual as Curve B in Fig. 2-9 illustrates. Up to about 25 or 30 megacycles, the triode unit performs as well or better than the tetrode; beyond this frequency, the performance of the tetrode is unquestionably superior.

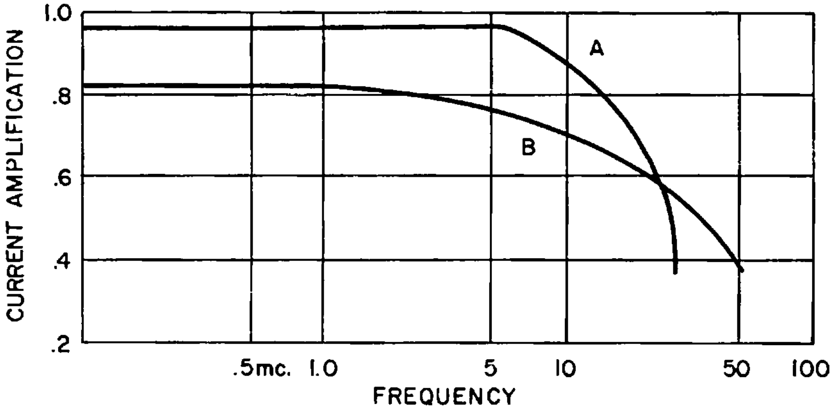


Fig. 2-9. Comparison of current amplification (α) for tetrode transistor connected as a triode (A) and as a tetrode (B).

Other additions to the transistor family, such as the PN Hook, PNIN and NPIN transistors, PNPN types, double emitter assemblies, thyratron transistors, field-effect units and silicon transistors are additional developments in the field of semiconductors. The triode, though, is still the most widely used and for this reason, the major emphasis will be placed on basic N-P-N and P-N-P assemblies in the remainder of this book. A thorough comprehension of these forms will enable the reader to carry his research into the more advanced types at his leisure.

THE P-N-P TRANSISTOR

Our discussion has emphasized N-P-N units since such transistor types more closely resemble vacuum-tube triodes than do P-N-P transistors.

If you will examine the P-N-P transistor shown earlier in Fig. 2-6, you will see that the collector is connected to the negative terminal of the reverse bias battery, while the emitter is connected to the positive terminal of the forward bias battery. If you will compare the diagram of the P-N-P unit with that of the N-P-N unit shown at the left in Fig. 2-6, you will see that the battery connections are exactly opposite. Since we have transposed the battery connections, the current will flow in the opposite direction.

In the P-N-P transistor, current flow starts at the negative terminal of the reverse bias battery. From here it goes to the collector, through the base, through the emitter and into the positive terminal of the forward bias battery. A small amount of current, known as base current, flows down from the base and back to the reverse battery. Thus, the main current flow in the P-N-P transistor, is from the collector to the emitter. Since the collector is the current source, it corresponds to the cathode of a tube, while the emitter can be compared to the plate.

In a vacuum tube, electron current can move only from cathode to plate. We have greater flexibility with transistors for we have two types - the N-P-N in which current moves from emitter to collector, and the P-N-P in which current flows from collector to emitter.

THE FIELD-EFFECT TRANSISTOR

One of the disadvantages of the ordinary triode transistor is its inability to function well at high frequencies. The shunting effect of a transistor, not too serious at lower frequencies, becomes a serious problem when megacycle frequencies must be handled. The field-effect transistor, originally known as the unipolar transistor, but now more popularly referred to as a FET, is an example of a transistor specifically designed to work at high frequencies. It is used in the front ends of FM receivers and TV sets.

In the construction of a FET, we start with the basic part which is a section of N-type semiconductor material, connected across a DC voltage source. This is shown in Fig. 2-10. Because of the way in which the battery is connected, the direction of current flow is from the negative terminal, through the section of N-type semiconductor, and then on to the positive terminal. The semiconductor is referred to as the body, with the left end of the semiconductor called the source and the right end the drain. There is no restriction on current flow and the electron current utilizes the full volume of semiconductor material.

The next step in the construction of a FET is to surround the body of N-type semiconductor with a wraparound or jacket of P-type

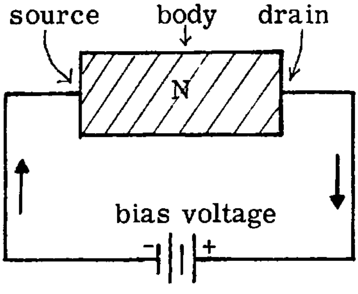


Fig. 2-10. Preliminary construction of a FET.

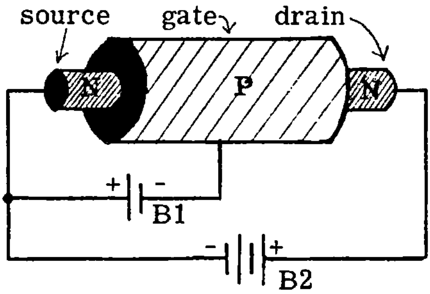


Fig. 2-11. The basic Field Effect Transistor.

semiconductor, as shown in Fig. 2-11. In addition, we have also connected a battery from the P-type semiconductor (known as the gate) to the source end of the N-type semiconductor. This battery supplies an electric field (hence the name, field-effect) which extends across the N-type body. Note the similarity of this concept to that of a vacuum tube triode in which a control grid is inserted between cathode and plate. The voltage on the control grid supplies an electrostatic field between control grid and cathode. However, in the tube, the control grid is directly in the path of current flow. It is for this reason that the control grid is made of an open mesh of widely spaced wires. It therefore presents minimum interference with current flow, while permitting complete current control. In the case of the FET, there is no physical interference with the movement of electrons from the source to the drain. In comparing the FET with a vacuum tube, the source, the gate and the drain correspond to the cathode, the control grid and the plate, respectively.

In Fig. 2-11, you can see that the gate is reverse biased with respect to the source, much as a control grid would be biased negatively with respect to its cathode. As the reverse biasing is increased, the flow of electron current from the source to the drain decreases. On the other hand, if the reverse biasing voltage is lowered, the current through the body of the FET increases.

Fig. 2-12 shows a method of connecting the input and output of a FET. The input signal is injected in series with the gate circuit. The output is taken from the drain circuit across the load resistor.

Earlier we showed you the similarity existing between a triode tube and an N-P-N transistor. The FET, however, has a much closer resemblance. Any prior study of the triode vacuum tube will enable you to easily grasp the general idea of the FET. However, while the FET is most often compared to a triode, its characteristic curve is much more like that of a pentode.

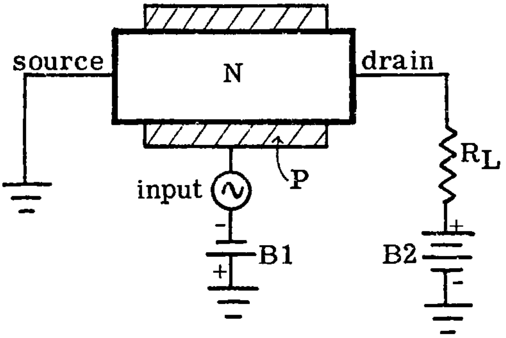


Fig. 2-12. FET circuit.

TRANSISTOR TYPES

Although we have described just a few transistors, such as the junction type, the surface barrier and the FET, there are many other transistor types. Most of them use names that describe their method of manufacture, while others, developed for special purposes, are little known. Thus, you may come across transistors described as the alloy-diffused transistor, the double-base junction, the evaporation-fused, the micro-alloy diffused base, the fusion alloy junction transistor, the silicon fusion alloy junction transistor, the intrinsic transistor, the tandem transistor, the multi-headed transistor, the silicon mesa transistor, etc. Even the FET, described earlier, is available in different varieties, such as the MOSFET and the IGFET.

CHAPTER 3

TRANSISTOR CHARACTERISTICS

PHYSICAL CHARACTERISTICS

The mention of the word "transistor" often calls to mind an image of a tiny bit of metal or plastic used to replace an electron tube in a radio receiver or some similar device. While this physical characteristic has had the greatest impact on the average consumer, it should be remembered that it is only one of many characteristics and that the small size introduces some disadvantages, as well as advantages.

A typical modern transistor designed to replace a tube in the intermediate-frequency amplifier section of a radio receiver measures 0.345 inches in height and 0.345 inches in diameter. Thus, the space occupied by such a transistor is a small fraction of that required by an electron tube that has the same function. One consequence of this kind of miniaturization is the reduction of power-handling ability. The transistor mentioned above can safely handle only .065 watts (65 mw.), while the corresponding tube can dissipate considerably more power than this. Where no more than very small power need be handled in the particular circuit application, however, the transistor offers more convenience and adaptability.

All important commercial transistors are now hermetically sealed against the effects of humidity, air currents and dust, so these factors do not present problems. Many manufacturers house their finished units in glass and metal enclosures, some of which are specifically designed for use with printed circuits. Some transistors are epoxy sealed. Hermetic sealing is important to long life. In sealing a transistor, it is imperative that no "poisonous" gases or volatile materials be trapped in the transistor enclosure. For this reason, many of the larger manufacturers use a process known as "weld-sealing", requiring no destructive fluxes in the seal-off procedure.

Storage and operating temperatures are always specified by the manufacturer. Since transistors are much more heat sensitive than the materials in electron tubes, the specified maximum and minimum temperatures should not be exceeded. A typical storage and operating temperature range is from -55°C to 85°C for a germanium transistor. Silicon transistors have, in general, a greater range of operation and a higher temperature storage limit. For example, a typical high-frequency silicon transistor may be operated at any temperature between -65°C and 150°C and may be stored at temperatures up to 200°C. Since the last figure given is 100% higher than the boiling point of distilled water, it can be seen that substantial progress has been made in transistor design and fabrication.

The power dissipation rating of most transistors is given in terms of the power that can be handled at the collector junction. For instance, a typical N-P-N transistor can dissipate 65 milliwatts at 25°C. However, the sensitivity is such that this transistor's rating must be reduced for higher temperatures. Thus, the manufacturer specifies for this transistor, a derating factor of 1.1 mw. per degree C increase. Should the temperature climb to 30°C, the dissipation rating drops 1.1 mw. x 5 or 5.5 mw. This transistor, therefore, can handle only 59.5 mw. at this temperature. The dissipation rating also depends in large measure on the transistor's surroundings and mounting method. In free air, a power transistor may be able to dissipate approximately 2.5 watts; in contact with a good "heat sink", such as a heavy metal plate or chassis, the safe dissipation rating may rise to 4 watts or more.

TRANSISTOR LEAD ARRANGEMENTS

Several standard "basing" or lead arrangement methods are now in use. Some of them are:

(1) COLOR CODING: A colored dot is painted on one side of the transistor case. The leads are numbered, starting with "1" nearest the dot. (Fig. 3-1A). Lead #1 is the collector, #2 is the base and #3 is the emitter.

(2) LEAD SPACING: The wire leads are spaced unequally, two of the three wires being more closely-spaced. (Fig. 3-1B). The wire lead that is farthest from the closely-spaced pair is the collector, the center wire is the base lead and the remaining one is the emitter lead.

(3) TRIANGLE-CORNER POSITIONING: Some transistors have three wire leads which emerge from the housing at the corners of an isosceles triangle. The minimum spacing between leads is about 0.15 inches, which allows direct insertion in printed circuit boards. An indexing tab is provided on the transistor body for easy location and insertion in the socket holes. (Fig. 3-1C).

Transistors require more care in installation than do vacuum tubes since the leads are made of wire rather than sturdy metallic cylinders. When a transistor is soldered directly to a terminal, the soldering iron must not be permitted to remain on the connection for too long a period of time. Many manufacturers also recommend that the wire lead be gripped in the jaws of a pair of long-nose or similar pliers, between the transistor body and the point of connection. The metal mass of the pliers helps to conduct the heat of the soldering iron away from the sensitive elements of the transistor.

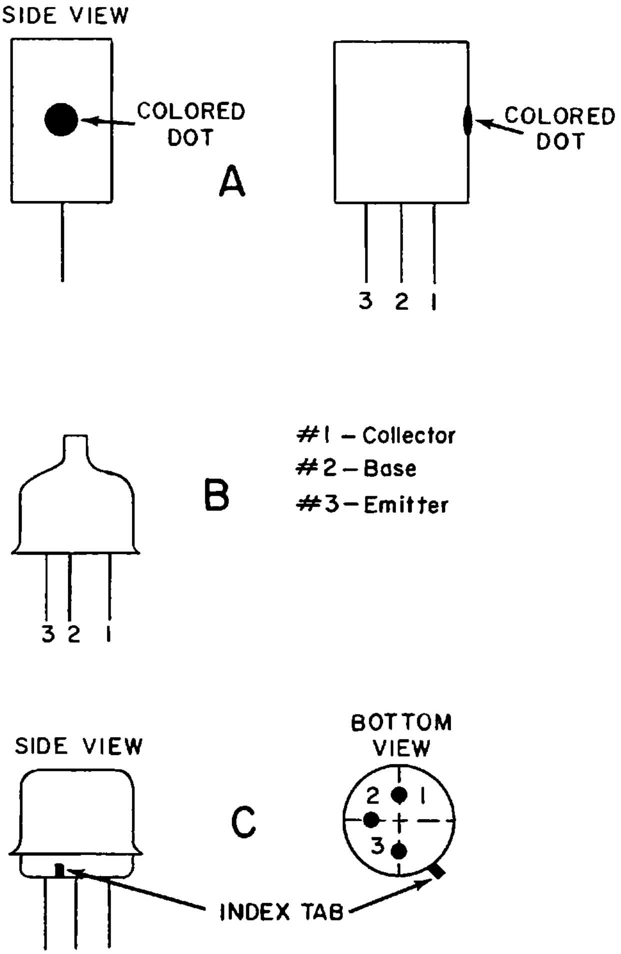


Fig. 3-1. Common basing connections of transistors.

INTRODUCTION TO ELECTRICAL CHARACTERISTICS

There is still a serious lack of uniformity from one manufacturer to another in the matter of choice of electrical characteristics listed on their specification sheets. Fortunately, the items which particularly concern us in developing an understanding of the theory and application of transistors, are given by most manufacturers. These are the quantities that will be explained and discussed in this chapter.

Tabulation of transistor characteristics is usually divided into three parts:

(1) Absolute maximum characteristics. These generally refer to voltages, currents and temperatures which must not be exceeded

under any circumstances.

(2) Average characteristics. This listing generally includes voltages, currents, impedances, temperatures, frequencies, capacitances, gain factors and noise factors which may be anticipated in properly designed equipment.

(3) Typical operation. Many of the quantities tabulated under this heading are repetitions of those found under Average Characteristics; others indicate changes or modifications that must be made in previously listed characteristics for special circuit conditions.

In addition to tabulations, most manufacturers also provide performance curves similar to those that appear in tube manuals.

To properly define and clarify the important terms, each characteristic will be discussed separately, relating it, where necessary, to other important transistor specifications. Unless otherwise stated, we shall be referring at all times to JUNCTION TRANSISTORS.

Before proceeding with a discussion of characteristics, however, it is advisable to mention one or two other important matters. First, there is the question of transistor symbols. Vacuum tube symbology is quite standard at the present time - after all, tubes

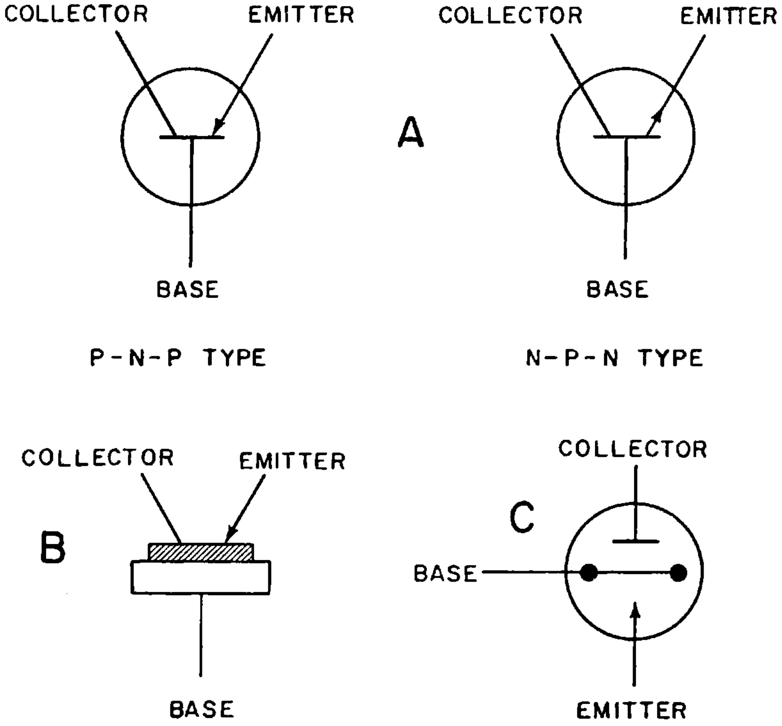


Fig. 3-2. Transistor symbols.
(Those shown at the top are more commonly used).

have had better than 50 years in which to acquire standardization. Certain specific transistor symbols have, by now, developed a following of their own, but standardization is still in the future. Symbols that you will still encounter in the literature are illustrated in Fig. 3-2. They are shown in the order of frequency of occurrence, with the most often-used symbols given first.

Second, there is the matter of transistor circuitry. In all of the explanatory diagrams showing circuit connections to transistors used in Chapter 2, the base of the transistor was shown as the COMMON element. That is, THE BASE FORMED A PART OF BOTH THE COLLECTOR AND EMITTER CIRCUITS. This is quite similar to the situation encountered in vacuum tube circuits, in which the cathode is common to both the grid and plate circuits. (Fig. 3-3). In both cases, the currents in the input and output circuits both flow through the common element.

As you will see, however, it is perfectly possible to make either the emitter or the collector the common element. When either of these is done, the behavior of the transistor alters radically. Hence, it is the usual practice to present figures concerning the performance of the transistor in all three basic connections, unless the unit is designed for specific application in only one of these circuits. Transistor circuitry using common base, common emitter and common collector arrangements, will be discussed in forthcoming chapters.

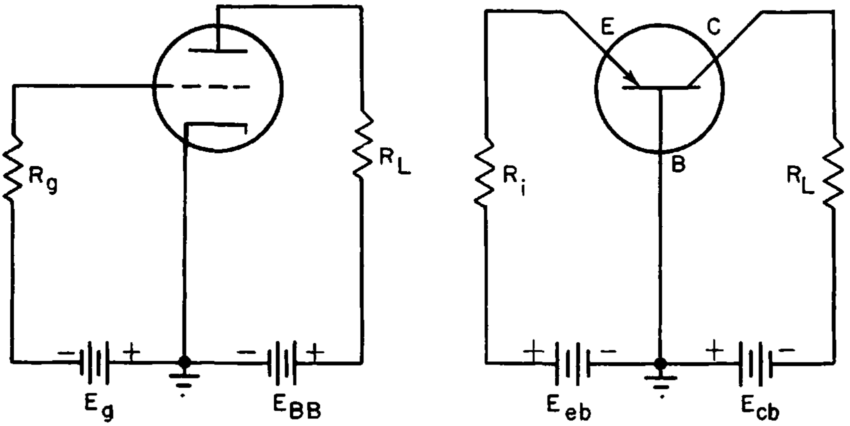
ABSOLUTE MAXIMUM RATINGS

COLLECTOR VOLTAGE Ec

The collector voltage is defined as the DC potential applied between the collector and the base. If no load resistor is present, then Ec is equal to the voltage of the collector battery (Ecb in Fig. 3-3). With a load resistor in the circuit and collector current flowing, then Ec is the actual potential between the collector and base terminals. In this event, the collector voltage is equal to the battery potential, minus the voltage drop across RL. Typical maximum collector voltage ratings range from a few volts to 80 volts or more. For P-N-P transistors, the collector voltage is given as a negative value (e.g. Ecb = -20 volts) to indicate that the battery polarity is such as to make the collector negative with respect to the base.

COLLECTOR CURRENT (Ic)

The collector current, most often stated in milliamperes, is the current flowing into or out of the collector terminal, either to or from the collector battery. Collector current may be measured by inserting a milliammeter between the battery terminal and the load resistor. A typical maximum collector current value might be given



E_g = bias battery
E_{BB} = plate battery
R_g = grid resistor
R_L = load resistor

E_{eb} = emitter - base battery
E_{cb} = collector - base battery
R_i = input resistor
R_L = load resistor

Fig. 3-3. The meaning of common base connection. (We are not comparing the behavior of a transistor in a common base connection with a vacuum tube. We are merely comparing circuits to illustrate the meaning of a "Common" electrode.)

as 20 milliamperes for a transistor using 15 volts of collector potential. As the permissible collector voltage rises, there is an accompanying rise in the current rating. A junction transistor rated at Ecb = 45 volts can pass a current of approximately 40 to 50 milliamperes without overheating.

COLLECTOR DISSIPATION (Pc)

Collector dissipation stated in milliwatts (or watts for power transistors) represents the maximum power that the collector junction can withstand without overheating. This rating is generally given for some specific ambient temperature such as 25°C. Very small transistors can dissipate small magnitudes of power, in the order of only 40 to 50 milliwatts; power transistors are larger in size, with consequent improvements in collector dissipation ratings.

JUNCTION TEMPERATURE (Tj)

The junction temperature is defined as the maximum temperature that can be permitted within a transistor junction (N to P or P to N) without causing instability or transistor destruction. The junction temperature is always associated with the heat dissipation qualities of the transistor. That is, junction temperature depends not only upon the voltages and currents in the collector circuit, but also on the provisions made to remove heat by conduction, convection and radiation. Germanium transistors are usually rated at a maximum Tj of 100°C or below; silicon transistors may be run at considerably higher temperatures.

AMBIENT TEMPERATURE

Ambient temperature (Ta) is the temperature of the air in the immediate vicinity of the transistor whose characteristics are being checked. Some manufacturers specify the maximum ambient temperature, as well as the maximum junction temperature. A common maximum ambient temperature is in the order of 50°C.

AVERAGE CHARACTERISTICS

The average characteristics of a transistor specify the anticipated behavior of the unit in a circuit of conventional design, as well as the element voltages and frequencies to be used. To make it more convenient for logical explanation, we shall list the average characteristics of a typical junction transistor. The significance of each of these terms will be described in detail.

TABLE 3-1
P-N-P JUNCTION TRANSISTOR

Voltage Characteristics
(common base, Tj = 30°C, f = 270 Hz)

Collector voltage	Ecb	-5.0 volts
Emitter current	Ie	1.0 ma.
Output impedance	Zo	1.0 megohm
Input impedance	Zi	40.0 ohms
Current amplification	α	0.92
Collector cutoff current	Ico	10.0 microamperes
Output capacitance	Co	40 mmfd.
Frequency cutoff	fco	1 Mc.
Noise figure	NF	22 db
Power gain	PG	28 db (for 1000 Hz small signal)

COLLECTOR VOLTAGE (Ecb)

This particular transistor is rated at a MAXIMUM collector voltage of -45 volts, but in typical low power applications as a voltage amplifier, for example, the manufacturer suggests only -5.0 volts for continuous operation.

EMITTER CURRENT (Ie)

Here again, although the maximum emitter current for this unit is given as 50 ma, a current of only 1.0 ma is characteristic in low power operation.

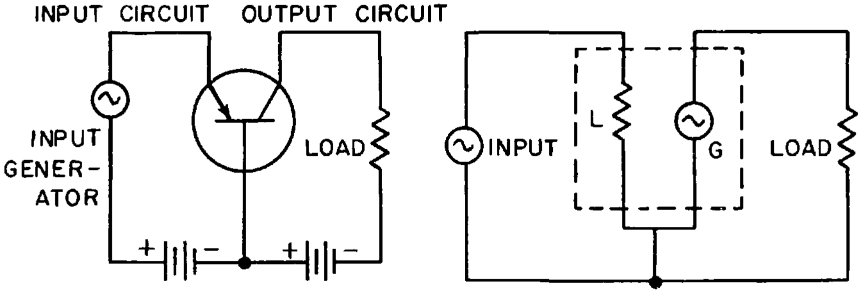


Fig. 3-4. A transistor's impedance.

OUTPUT IMPEDANCE (Zo)

A transistor, like a tube, may be considered as consisting of two distinct parts: an input section and an output section. See Fig. 3-4. To the input generator, the transistor's input circuit behaves as a LOAD. Relative to the load into which the transistor works, the transistor's output circuit appears as a generator. As shown in the figure, the input circuit of the transistor appears as a load, L, of a very definite resistance measurable in ohms; similarly, the LOAD, looking back into the output circuit of the transistor, "sees" a certain "generator" resistance (or impedance when dealing with AC). It is this apparent "generator" resistance (or impedance) that is referred to as Zo. As is evident from the average characteristics, the output impedance is quite high -- 1,000,000 ohms. As we have seen in Chapter 2, an output impedance of this magnitude permits a large voltage gain, even when there is a current loss from input to output.

INPUT IMPEDANCE (Zi)

The input impedance is the opposition presented by the input circuit of the transistor to the signal source. (Both Zo and Zi for the transistor under consideration are measured at a frequency of 270 Hz, as stated in the legend at the top of the table). Unlike a vacuum tube, the transistor in the common base connection has a very low input impedance. This low impedance, however, considered in conjunction with the high output impedance, is the factor that gives the transistor its large resistance (or impedance) gain. That is, the resistance gain is Zo/Zi = 1,000,000/40 = 25,000. This, in turn, gives us a large voltage gain.

CURRENT AMPLIFICATION (α)

Like all junction transistors, this transistor has a current am-

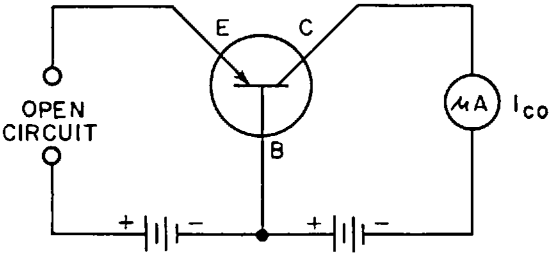


Fig. 3-5. Circuit for measuring I_{CO}.

plification of less than unity --- 0.92.

COLLECTOR CUTOFF CURRENT (Ico)

This is sometimes referred to as collector SATURATION CURRENT. It is defined as the current that flows in a reverse-biased collector circuit when the emitter-base circuit is open or disconnected (Fig. 3-5). As we know, the collector is always reverse-biased so that Ico may be thought of as the "idling" collector current. This current is very small, as it should be; the only reason for its existence is the action of heat energy on the molecules of the semiconductor. As a result of external ambient temperature effects, the molecules of the transistor material move randomly at some definite velocity. This causes some carriers to diffuse across the collector junction, thereby giving rise to a small electric current. The current causes a rise of temperature inside the transistor which, in turn, produces more diffused carriers and more collector current. Offhand, this appears to be a dangerously cumulative effect which might cause Ico to continue to rise until the transistor is destroyed. Indeed, just such an action often does occur. If the transistor is operated well within its ratings, however, and the ambient temperature is not allowed to rise above the manufacturer's recommended value, Ico will stabilize at some safe figure -- such as 10 microamperes in our example. This stabilized current assumes such a magnitude as to just raise the temperature high enough for heat dissipation to balance heat generation in the body of the transistor.

Ico IS STRONGLY DEPENDENT ON THE SURROUNDING TEMPERATURE and this temperature should always remain under control. One positive sign of a defective transistor is instability of Ico; that is, when there is an inclination of Ico to climb slowly of its own accord, you may be quite certain that the transistor has been damaged or was defective in manufacture.

OUTPUT CAPACITANCE (Co)

The output capacitance of a transistor, like its vacuum tube equivalent, represents the capacitance that shunts the load. This factor becomes more important as the frequency rises, for the capacitive reactance shunting the load drops lower and lower with ascending frequency. Thus, the output capacitance is one of the characteristics that sets a high frequency limit on the satisfactory performance of the transistor as an amplifier.

FREQUENCY CUTOFF (fco)

The current amplification for the transistor under discussion is given as 0.92. As the heading of the listing indicates, alpha was obtained at a frequency of 270 Hz for the input signal. Alpha begins to diminish as the frequency is raised, an effect due partially to the output capacitance Co and partially to the so-called transit time required for the movement of the carriers in the transistor. Transistor engineers have agreed that the frequency at which alpha drops to .707 of its low-frequency value (in this case, the value 0.92 at 270 Hz) should be called the cutoff frequency. This does not mean that a transistor will not operate at frequencies above its cutoff value; it simply indicates the frequency at which the transistor's performance is "down" by a significant amount. In our example, the current amplification of 0.92 at 270 Hz drops to 0.92 x .707, or 0.65, when the operating frequency is raised to 1,000,000 Hz.

NOISE FIGURE (NF)

The noise figure is a measure of the noise produced by the combination of a transistor and its associated components. We can also consider the noise figure to be the ratio of the signal-to-noise ratio at the output of a transistor amplifier to the signal-to-noise ratio at the input to the amplifier. The noise figure is measured in decibels.

The decibel (db) is a unit for expressing a power ratio, and is given by the following expression:

$$\text{db} = 10 \log \frac{P_2}{P_1}$$

The decibel has no other significance. It is merely a method of comparing a certain power (P_2) with another power (P_1). The original reason for employing logarithms in the definition of the decibel was that by this means, relative sound powers, as heard by the human ear, were more logically described. The ear has a logarithmic response. The ratio of "loudnesses" expressed by decibels is closer to what we actually hear than an arithmetic ratio would be. For our purposes, it will be sufficient to compare the noise figures of transistors with those of equivalent vacuum tubes. A noise figure of 12 db for a transistor is considerably higher than that of a good vacuum tube under similar conditions. There has been much recent progress made in reducing transistor noise. By careful choice of associated components and circuits, it is now possible to build transistor amplifiers and radio receivers with noise levels no greater than those of circuits using the best vacuum tubes.

POWER GAIN (PG)

The meaning of power gain has already been discussed. Note, however, that the PG of our sample transistor is given in db. A power gain of 28 db is equivalent to an output-power to input-power ratio of approximately 630 to 1. This can easily be checked with the aid of the db formula in the above paragraph.

The reader who has studied catalogs or other transistor listings may have observed other transistor characteristics that have not been discussed in this chapter. For example, many manufacturers list the BASE CURRENT GAIN of their transistor products, the so-called "beta" (B) factor. An understanding of beta must await further study of transistor circuits and configurations to be covered in the forthcoming chapter.

CHAPTER 4

AMPLIFICATION WITH TRANSISTORS

The strongest point of similarity between transistors and vacuum tubes is that they can perform identical functions in such circuits as amplifiers and oscillators. Here the similarity ends. Not only are their structures totally different, but their mode of operation and the functioning of their component parts diverge widely from each other. A transistor cannot be substituted directly for a tube in any circuit.

It is a mistake to try to fit vacuum tube ideas into transistor theory to any great extent. Although some of the amplifier and oscillator CIRCUITS are analogous in configuration, the role that the transistor plays should be approached as a brand new concept, rather than as a modification of an old one. In this way, there will be less to be unlearned. For those already familiar with vacuum tube circuits, certain points of similarity in circuit connections will become immediately apparent. For those who have not worked with vacuum tubes to any large degree, analogies would have little or no value anyway.

There are three basic CONFIGURATIONS for connecting the elements of a transistor amplifier into the associated circuit: COMMON BASE, COMMON EMITTER and COMMON COLLECTOR. "Common" is sometimes replaced by the word "grounded" in describing these fundamental configurations. In many arrangements having an element common to two or more individual circuits, the common element is also at the system reference potential or "ground" potential. In this usage, "ground" does not imply an actual earthed contact, but rather connection to a terminal whose voltage is used as a reference for all the other voltages in the system. (Refer to Fig. 3-3 in the previous chapter for further clarification of this point).

COMMON-BASE CONNECTION

The common-base arrangement was discussed in detail in Chapter 3 in connection with transistor characteristics. From Table 3-1 of Average Characteristics for a P-N-P junction transistor, given earlier in Chapter 3, the behavior of a common or grounded-base transistor can be summarized as follows: (The same characteristics would apply to an N-P-N transistor of corresponding structure).

(a) High output impedance.
(b) Very low input impedance.
(c) Current amplification (alpha) always less than one.

(d) Output capacitance rather high.

(e) Reasonably high power and voltage gains.

The common-base connection does not cause a phase inversion of input to output signal as a vacuum tube amplifier does; and a single battery -- rather than two separate batteries, as shown in Fig. 3-3 -- can be used in this circuit.

Let us consider the matter of tube phase inversion first. Fig. 4-1A presents a basic vacuum tube amplifier circuit. At the instant under consideration, a negative half-cycle of the input signal is being applied across Rg, making the grid negative with respect to the cathode of the tube. A negative-going grid reduces the plate current of the tube. Before application of the signal, a steady DC voltage drop appears across RL so that the plate voltage of the tube is appreciably less than the terminal voltage of the plate battery. As the plate current diminishes, however, the drop across RL also diminishes, making the plate voltage more positive with respect to com-

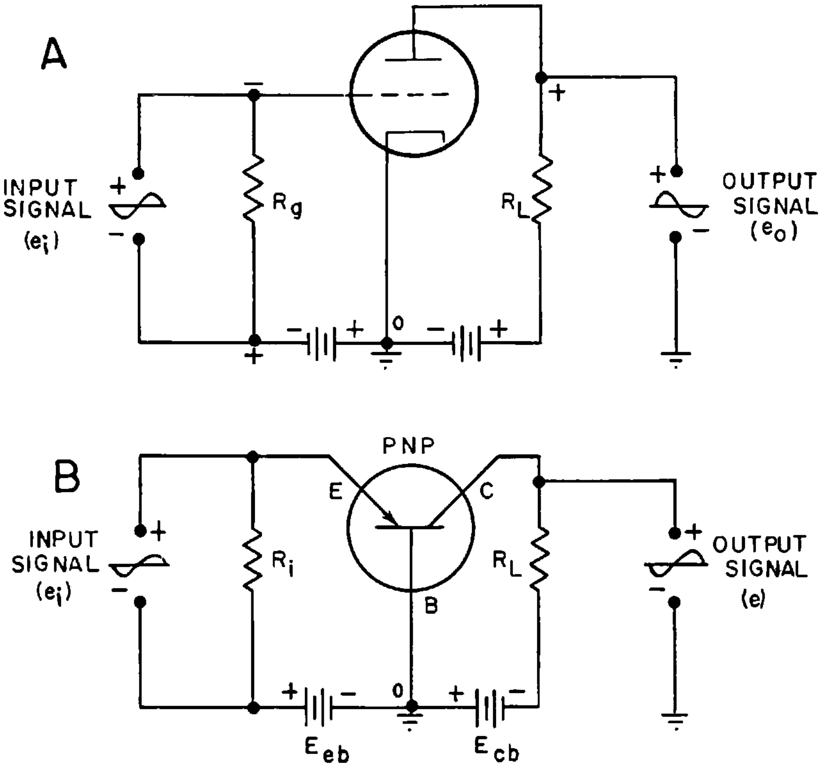


Fig. 4-1. Phase relationships between input and output voltages for: vacuum tubes (A) and common base transistor (B).

mon ground than it was before. Thus, at the instant that ei reaches full negative amplitude, eo reaches peak positive amplitude. (ei = input signal voltage, eo = output signal voltage). The same action occurs in reverse when ei goes through its positive half-cycle. Thus, eo is always out of phase with ei by 180°. This is what is meant by PHASE INVERSION.

In the common-base transistor circuit of Fig. 4-1B, the P-N-P unit, as you will recall, is biased in the forward direction (low resistance) by the battery Eeb and in the reverse direction (high resistance) by Ecb. Applying a negative-going half-cycle across Ri is similar to inserting a small cancelling voltage at this instant in series with Ecb, causing the emitter-base current to decrease. A reduction of emitter-base current leads to a corresponding decrease of collector-base current; hence, the voltage drop across RL becomes smaller and the collector terminal becomes more NEGATIVE (with respect to the base) than it was previously. Hence, the collector -- which is the upper terminal for the output voltage eo -- goes negative at the same instant that the input signal goes negative. The input and output signals are, therefore, in phase. This, of course, is a condition of zero phase inversion. Knowledge as to whether phase inversion does or does not occur is very useful in designing and building transistor amplifiers.

Fig. 4-2 illustrates the evolution of the basic common-base amplifier circuit of Fig. 4-1 into a one-battery, common-ground circuit. B differs from A only in that the batteries have been moved around into the vertical legs of the drawing to permit one terminal of the input, one terminal of the output and the base of the transistor to be joined directly to ground. This is standard practice - to maintain a common ground between input and output for hum reduction and stability. An N-P-N unit has been selected for discussion. With an N-P-N unit, the emitter bias battery Eeb is connected so that its negative terminal goes to the emitter and its positive terminal to the base, to provide the desired forward bias. The collector battery Ecb is inserted in such a manner so as to make the collector positive with respect to the base.

Referring to Fig. 4-2C, the emitter battery Eeb has been omitted while a new component (Rb) now appears in the circuit. (The capacitor Cb should be ignored for the moment). Rb does away with the need for the emitter battery for the following reason: a small amount of collector current (Ico) flows in the collector-base circuit, as indicated by the arrows, and produces a voltage drop across Rb in the direction shown. This fall of potential makes the base more positive than the emitter since the latter is connected to the lower part of the resistor Rb through Ri. This establishes a voltage difference between the base and the emitter, having the same polarity

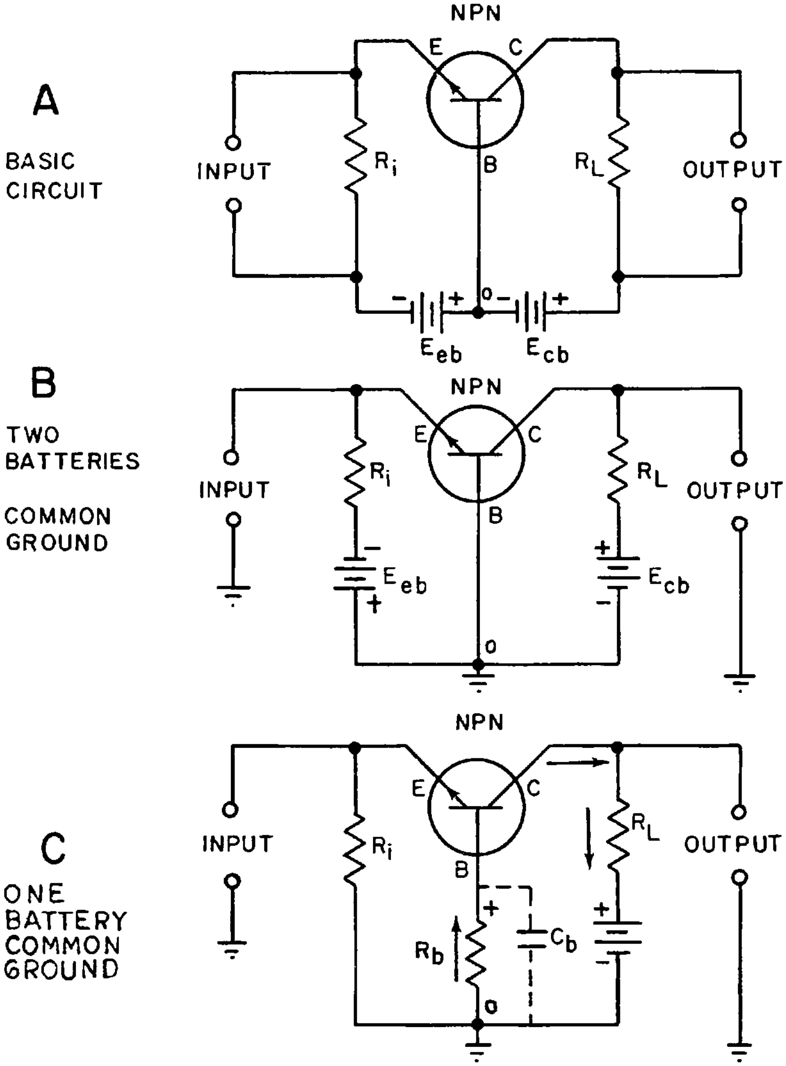


Fig. 4-2. The evolution of a one-battery, common ground transistor amplifier.

as that formerly produced by Eeb. The magnitude of this bias potential is determined primarily by the resistance of Rb which, in turn, depends upon the desired voltage conditions given by the manufacturer for the particular transistor.

If an AC voltage, such as that obtained from a microphone or some preceding stage, is now applied across the input terminals, alternating currents will flow in both emitter and collector circuits in accordance with the input signal. Since the voltage drop across Rb is intended to replace or simulate a bias BATTERY, it must continue to be a pure DC voltage, despite the presence of an AC signal in the transistor elements. To maintain the bias potential fixed and invariable, a capacitor (Cb) may be connected across Rb to carry the AC component of the current around the resistor. Cb, therefore, prevents DEGENERATION or loss of gain due to the insertion of Rb into the circuit.

The similarity between Rb in Fig. 4-2 and a cathode resistor used for tubes is apparent. In the early days of radio, a battery, known as a "C" battery was used to supply bias. The cathode resistor replaced the "C" battery, just as Rb in Fig. 4-2 has replaced the forward bias battery.

VOLTAGE POLARITY

In tube circuits, the DC voltage applied to the plate is invariably positive. The control grid is made negative with respect to the cathode, or, stated differently, the cathode is made positive with respect to the control grid.

However, we have two basic types of transistors, N-P-N and P-N-P, and so a direct comparison between the DC voltages applied to a transistor and those put on tube elements isn't suitable. For a P-N-P transistor, the DC voltage polarities are:

Emitter	positive
Base	negative
Collector	negative

In the abbreviation, P-N-P, the first letter refers to the emitter, the second letter to the base and the final letter to the collector.

For an N-P-N unit, the polarities are exactly opposite. Thus:

Emitter	negative
Base	positive
Collector	positive

If we take the emitter as the reference point, then for a P-N-P transistor, the base and the collector are negative with respect to the emitter. For a N-P-N unit, the base and collector are positive with respect to the emitter.

There are various ways of obtaining forward and reverse biasing voltages from a single battery. The circuit in Fig. 4-2 shows just one of them.

In Fig. 4-3 we have an N-P-N transistor circuit making use of just one battery, B1, to supply both forward and reverse bias. In an N-P-N circuit, we must make the emitter negative and, as you can see, we have done so by connecting the emitter directly to the minus terminal of B1. In an N-P-N circuit, both base and collector must be positive with respect to the emitter. In Fig. 4-3, both of these transistor elements are wired to the positive terminal of the battery through resistors R1 and R2. The positive voltages put on the base

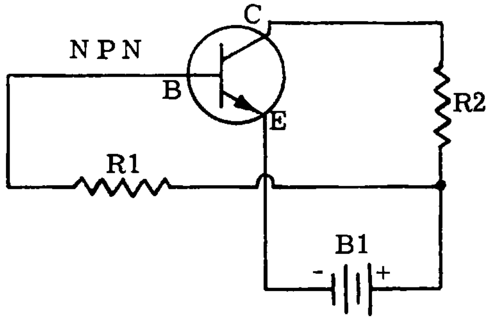


Fig. 4-3. A method of obtaining biases from a single battery.

and the collector will be determined by the values of R1 and R2 and the amount of current flowing through these two resistors.

Fig. 4-4 shows still another single battery arrangement. Resistors R1, R2 and R3 are in series. This series combination is shunted directly across bias battery B1 and so these three resistors form a voltage divider. The emitter of the N-P-N transistor is wired directly to the negative terminal of B1. The collector receives its positive voltage through R3. There is also positive voltage with respect to the emitter at the junction of R1 and R2. Thus, the base also receives a positive voltage.

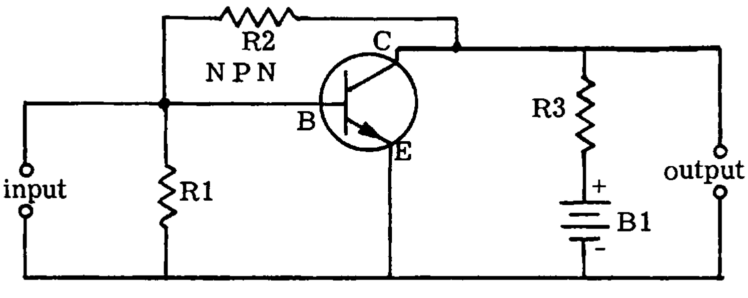


Fig. 4-4. Bias voltages obtained by use of voltage divider.

Although both the base and collector are biased positively, this does not mean they receive the same amount of voltage. The positive voltage on the collector is much higher than that on the base.

Fig. 4-5 presents a practical common-base audio amplifier, using a single battery. This single stage amplifier is shown with matching transformers in the input and output circuits to establish the correct impedance relationships between the driving source, the transistor and the output load. The low input impedance characteristic of the common-base connection is matched by a transformer having 30 ohms as its secondary impedance, while the high output

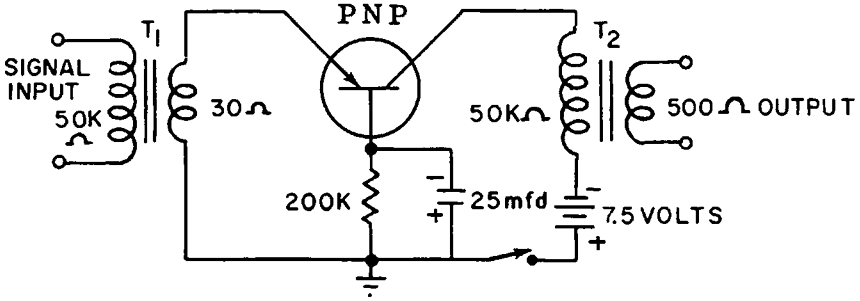


Fig. 4-5. A practical common-base audio amplifier.

impedance of the transistor works into a 50, 000 ohm primary on the output transformer. The power output of this circuit is approximately 1.5 milliwatts and the power gain of the order of 25 db. Such an amplifier would do nicely as an interstage unit between a radio detector and a 500 ohm transmission line, to a pair of headphones or the input circuit of a tape recorder.

COMMON-EMITTER CONNECTION

Thus far we have discussed transistor amplifiers only in terms of the common-base connection and have presented transistor characteristics as they apply to this particular configuration. Fig. 4-6A is a repetition of a previous diagram in which an N-P-N transistor is shown with its voltage sources and current measuring instruments to distinguish between emitter current (Ie), base current (Ib), and collector current (Ic). In the discussion of the fundamental common-base arrangement, it was pointed out that the base-current was due to a small number of re-combinations of holes and electrons and that, due to the thin cross-section of the base material, most of the current carriers from the emitter proceeded into the collector circuit to produce Ic. Essentially, then, the base current is the DIFFERENCE BETWEEN THE EMITTER CURRENT AND THE COLLECTOR CURRENT. Base current is invariably much smaller in magnitude than either emitter or collector current for this reason. This relationship of element currents yields the definition of current amplification in the common base connection:

$$^{*}\text{ Current amplification} = \alpha = \frac{\Delta Ic}{\Delta Ie}$$

where ΔIc is the change in collector current due to some small change in emitter current (ΔIe).

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*Note: The concept of alpha in Chapter 2 was based upon fundamental considerations of transistor behavior. This definition sets up a ratio of "output current" to "input current" which is a true measure of amplification.

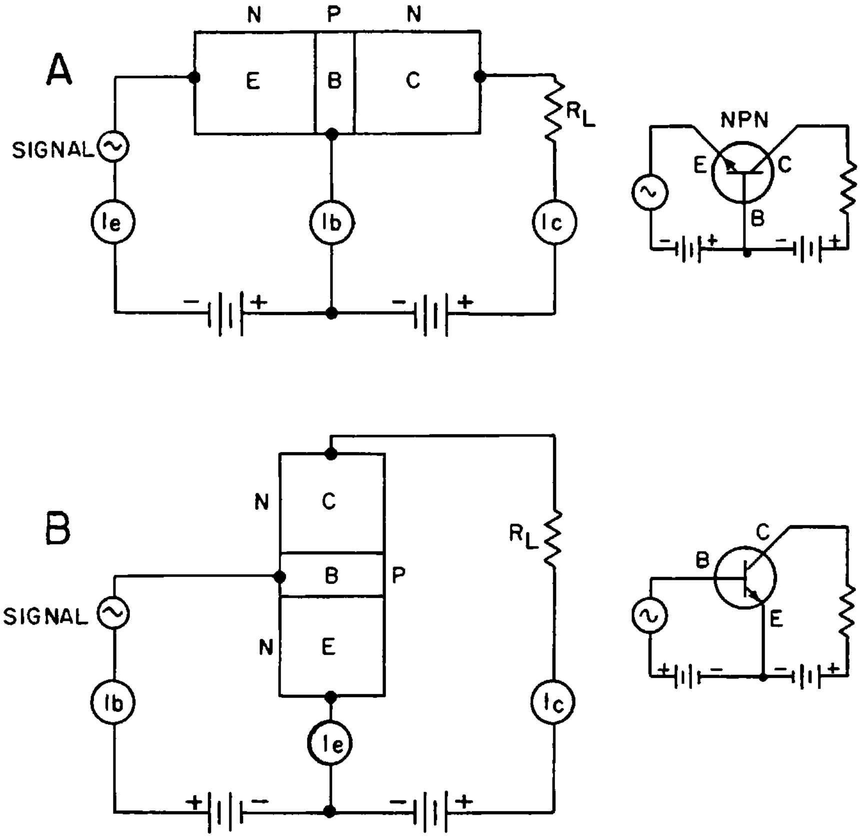


Fig. 4-6. Common-base and common-emitter circuits.

It will be recalled that alpha can never reach or exceed unity because the base current always subtracts some current from that flowing between the emitter and collector. Our sample transistor of the previous chapter, for example, has a current gain of 0.92.

As we have previously stated, a transistor may be connected into a circuit so that its emitter is common to both the base and collector paths. This circuit is shown in Fig. 4-6B, in both pictorial and schematic form, for convenient comparison. An N-P-N type is illustrated in this figure and it should be noted that THE SAME BATTERY POLARITY IS USED FOR THE COMMON-EMITTER CONNECTION AS FOR THE COMMON-BASE ARRANGEMENT: the base is still positive with respect to the emitter, and the emitter is negative with respect to the collector. (For a P-N-P transistor, these polarities would be reversed). The fact that a different element this time -- the emitter -- has been made common to the other two circuits does not alter the following fundamental facts:

(1) For a given transistor type, changing the common element does not affect the battery polarity. The emitter-base circuit is still biased in the forward (low resistance) direction and the collector circuit is polarized in the reverse (high resistance) direction.

(2) The base current Ib is still the difference between the emitter current Ie and the collector current Ic, and hence, is small in magnitude.

(3) The ratio of collector to emitter current does not depend upon the configuration; that is, this ratio stays the same whether the base or the emitter is common.

The really significant difference between the two arrangements is that the applied signal in the common-emitter configuration of Fig. 4-6B is used to vary the BASE CURRENT RATHER THAN THE EMITTER CURRENT. This means that we are interested in the ratio of ΔIc to ΔIb in this case, rather than ΔIc to ΔIe as we were when considering the current gain of the common-base connection. We can therefore see that the gain of any device is actually a comparison between the size of a certain output variation and the size of the input variation that caused it. For the common-emitter circuit, we can vary the base current Ib by means of the signal and observe how Ic varies. We can then substitute these values in the following formula:

$$\text{Common emitter current gain} = \frac{\Delta \text{Ic}}{\Delta \text{Ib}}$$

It will be recalled, however, that $\alpha = \Delta \text{Ic} / \Delta \text{Ie}$ and that this ratio does not change just because we have changed the common element. (See (3) in previous paragraph). Hence, we are forced to the conclusion that α is the current gain ONLY IN THE COMMON-BASE CONFIGURATION AND THAT THE CURRENT GAIN EXPRESSED BY THE RATIO OF ΔIc TO ΔIb IS A DIFFERENT FACTOR THAT IS NOT NECESSARILY EQUAL TO α. This current gain is expressed as beta (B) by virtually all manufacturers and engineers.

As it turns out, beta for junction transistors is GENERALLY MORE THAN 1, ranging as high as 60 or better for many commercial types. We might have anticipated a current gain of this magnitude from the consideration given in (2) of the previous paragraph. Since the base current is VERY SMALL, it would be reasonable to expect a much larger change in collector current as a result of a small variation in Ib caused by a signal input.

COMMON-EMITTER CHARACTERISTICS

One of the best ways to arrive at a clear picture of the performance of any amplifier is to study its characteristic curves. In the common emitter circuit, the collector current Ic depends upon (a) the collector voltage and (b) the controlling base current. When the collector current that flows for various base currents is plotted

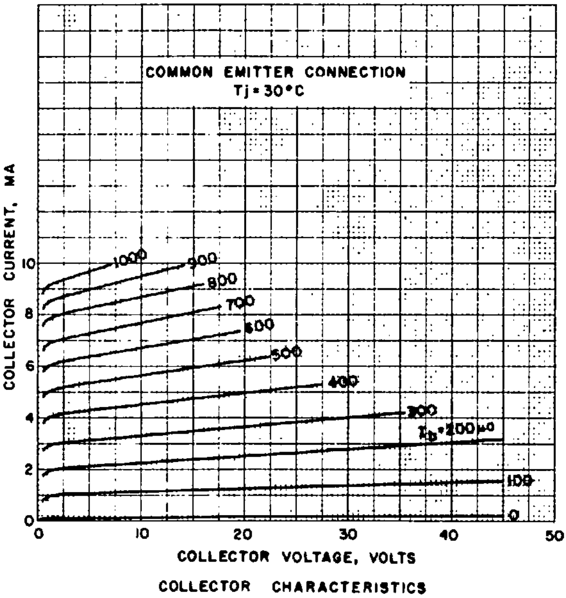


Fig. 4-7. Characteristic curve for a typical transistor.

against collector voltage, we obtain a graphic representation of transistor behavior in the common-emitter configuration. A set of curves for our example transistor of the previous chapter is given in Fig. 4-7.

The following valuable information can be obtained from these curves:

(1) As the collector voltage is increased, base current being held constant, the collector current increases. The increase is much more noticeable for the higher values of base current, as evidenced by the increasing slopes of the individual curves as we go higher on the graph.

(2) Small increases of base current have a much greater effect upon the collector current than do small increments in collector voltage. Consider, for example, the rise of collector current when the base current goes from 400 microamperes to 500 microamperes at a collector voltage of 20 volts. Following the 20 volt line up, we note that it intersects the 400 microampere curve at a collector current of 5.0 ma, and the 500 microampere curve at 6.2 ma. Thus, a change of 100 microamperes (only 0.1 ma) of base current results in a change of 1.2 ma of collector current.

(3) From (2), we can immediately obtain the common-emitter current gain, beta, of this transistor:

$$B = \frac{\Delta Ic}{\Delta Ib} = \frac{1.2}{0.1} = 12$$

This, of course, corroborates what we have previously stated: the current gain (beta) for the common-emitter circuit is greater than 1. For our hypothetical transistor, beta is 12 while alpha is only 0.92. Another way to say this is: THIS TRANSISTOR HAS A CURRENT GAIN OF 12 IN THE COMMON-EMITTER CONFIGURATION AND A CURRENT GAIN OF 0.92 IN THE COMMON-BASE ARRANGEMENT.

Other consequences of making the emitter the common element are the changes of input impedance, output impedance and power gain. For this transistor, these variations may be seen from the table below:

TABLE 4-1

(tj = 30°C, frequency = 1,000 Hz)

	Input Impedance	POWER GAIN	Output Impedance
Common-base	40 ohms	28	1,000,000 ohms
Common-emitter	450 ohms	36	60,000 ohms

Despite the fact that the output impedance is lower in the common-emitter connection, the power gain is greater because there is a current gain considerably greater than 1. Since power is a function of current squared, the increased current gain yields a higher power gain, despite the drop-off in output impedance. It is also interesting to note that the voltage gains of the two configurations are roughly the same in practical circuits.

SINGLE-BATTERY OPERATION

Beside the higher power gains available from junction transistors in the common-emitter connection, this configuration offers another significant advantage that helps explain why one sees more common-emitter circuits than any other kind. In the P-N-P circuit shown in Fig. 4-8A, the collector and emitter currents flow in opposite directions in the base. Although an amplifier using a single battery can be built in common-base configuration, an auxiliary resistor is required whose value is quite dependent upon the particular transistor being used. This makes the selection of the resistor critical. In the common emitter arrangement, on the other hand, the currents in the emitter due to the collector and base, are in the same direction, making a single-battery source practical without biasing resistors (Fig. 4-8B). The battery is connected to provide the correct polarity between the emitter and collector; in this case, negative for the collector and positive for the emitter. Base current flowing through Ri makes point 1 negative with respect to point 2 so that the base is negative with respect to the emitter, the condition necessary for correct forward and reverse bias.

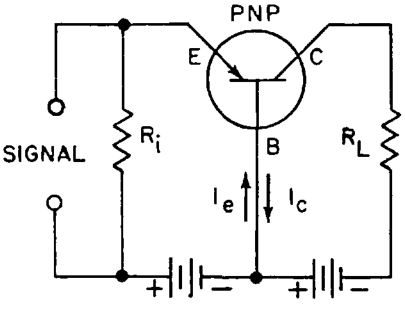


Fig. 4-8A. Common base circuit.

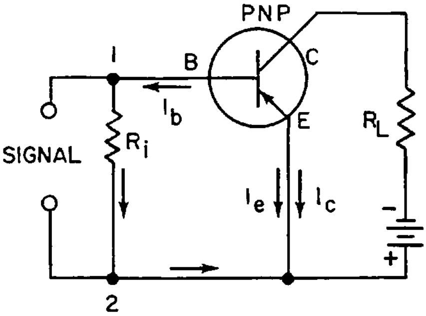


Fig. 4-8B. Single battery operation with common emitter circuit.

An interesting audio pre-amplifier intended to mount right in the handle or case of a dynamic microphone, is shown in Fig. 4-9. This is a common-emitter circuit in which the base is isolated from the microphone by a 1.0 mfd. coupling capacitor. Since this is an N-P-N transistor, the base must be made positive with respect to the emitter. This is accomplished in a somewhat different fashion, by returning the base to the positive side of the battery supply through a high resistance (1 megohm). This design does not depend upon the base current to establish the required positive base bias. The output of the amplifier is designed to work into a high-impedance load such as the grid circuit of a speech amplifier. With a 22.5 volt battery, the voltage gain of this single stage is 369! Thus, a normally low-output dynamic microphone can supply a high signal output.

Another popular arrangement of a common-emitter amplifier is shown in Fig. 4-10. The transistor in this circuit is a P-N-P type. The two principal points of departure of this circuit from that of Fig. 4-9 are the use of a voltage divider network comprising R1 and R2 and a stabilizing resistor (and associated capacitor) R3, C.

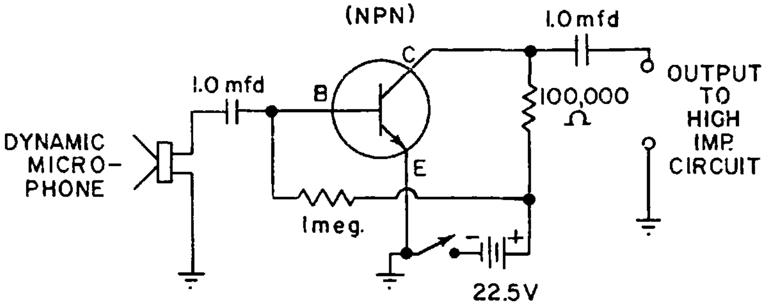


Fig. 4-9. A common emitter type of pre-amplifier.

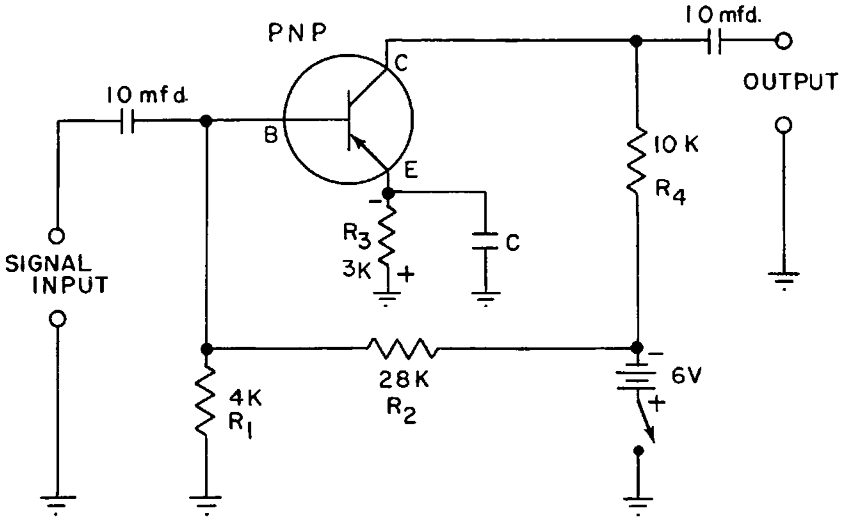


Fig. 4-10. A common emitter amplifier using stabilizing networks.

Many of the so-called "high-stability" circuits such as that of Fig. 4-10, were originally developed to overcome non-standardization in transistor manufacturing that was prevalent in the early days. By using a voltage divider arrangement, the same base voltage may be anticipated, even with abnormal variations in transistor characteristics. The use of an emitter resistor also contributes to the stability of the circuit by cancelling the temperature effects that tend to make the collector current (Ico) build up without limit until the transistor is destroyed. We have learned that Ico is temperature-sensitive. As the temperature of a junction rises, Ico tends to increase slightly; this increases the dissipation in the junction; Ico rises still further; the temperature goes up again and the run-away cycle continues until the rating of the junction is exceeded. R3 prevents this action by developing a voltage drop that bucks the increasing collector current. When Ico rises slightly, R3 becomes more negative at the top, due to increased voltage drop, making the forward bias of the base-emitter circuit SMALLER. The emitter current and base current both diminish, reducing the tendency of Ico to "run away".

PHASE RELATIONSHIP IN A COMMON EMITTER CIRCUIT

The common-emitter circuit differs from the common-base type in another significant way. You will recall that the output signal from a common-base amplifier is in phase with the input signal; that is, there is no phase shift from input to output. Let us see what phase relationships exist in the common-emitter circuit.

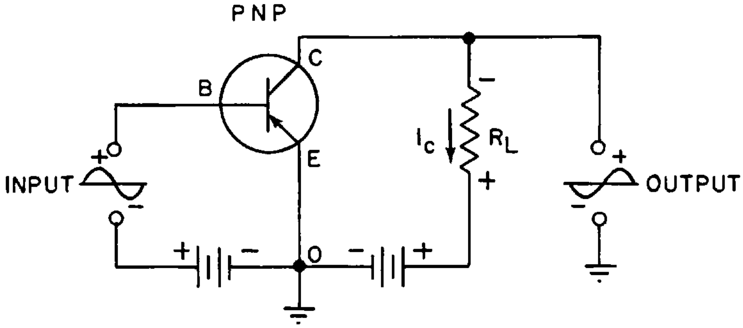


Fig. 4-11. Phase relationship in a common emitter circuit.

Referring to Fig. 4-11 in which a basic P-N-P common-emitter circuit is illustrated, assume that the input signal is POSITIVE-GOING at a given instant. The signal therefore ADDS to the forward bias, causing an increase in the base current. This causes the collector current to increase, and the voltage drop across RL increases with the polarity shown. This means that the first half-cycle of output voltage is NEGATIVE-GOING, while the first half-cycle of input voltage is positive-going. Input and output waveforms are out-of-phase by 180°. This is in contrast with the in-phase condition encountered in the common-base circuit.

COMMON-COLLECTOR CONNECTION

Fig. 4-12 illustrates the fundamental common-collector arrangement. For the sake of consistency and to provide a comparison with previous circuits, an N-P-N transistor is again shown.

This time, the signal is applied between the base and the common side of the collector battery, while the output is taken from RL located between the emitter and the collector. As we have previously emphasized, altering the common element does not change the polarities of the DC sources with respect to the various elements. As shown in both parts of Fig. 4-12, the base remains positive with respect to the emitter, and the emitter negative with respect to the collector. Remember, of course, that the polarities would have to be changed if a P-N-P unit were substituted for the N-P-N type illustrated. That is, the bias between the emitter and base is in the low-resistance (forward) direction and the bias between the emitter and collector is in the high-resistance (reverse bias) direction.

It is this last fact that explains why the input impedance of a common-collector circuit is high -- in the vicinity of 500, 000 ohms. The reverse bias applied between the base and collector forms a part of the input circuit so that the signal source "sees" a much greater

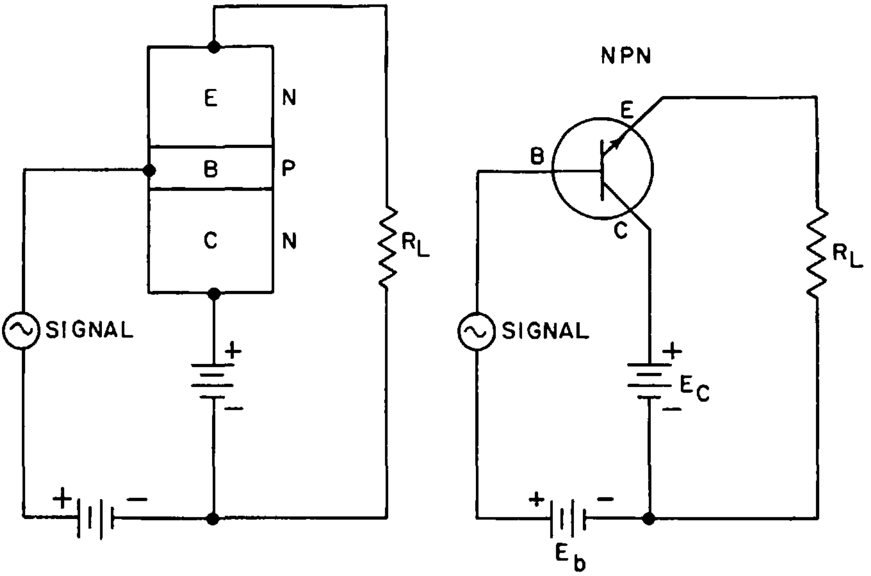


Fig. 4-12. A common collector circuit.

impedance than in either of the other two configurations. Similarly, the output impedance is quite low. A value of approximately 80 ohms is typical for commercial junction transistors. Again, this low value arises from the fact that the load (RL) is part of a circuit that has forward bias. The load, "looking back" into the transistor therefore, "sees" a much lower impedance than in the common-base or common-emitter arrangements. Thus, the common-collector connection provides a very high input impedance and a very low output impedance. As a result of its low output impedance, the voltage gain of the common-collector circuit is always less than 1. Furthermore, the power gain available from this type of circuit is substantially lower than either the common-base or common-emitter circuits. Its use, therefore, as a straightforward amplifier is hardly justified. In Table 4-2, a comparison of performance characteristics is given for an N-P-N transistor in each of the three different configurations.

TABLE 4-2

	Input Impedance	Output Impedance	Voltage Gain Into Recommended Load	Power Gain
Common Base	35 ohms	500, 000 ohms	125	30
Common Emitter	480 ohms	40, 000 ohms	375	37
Common Collector	9.5k ohms	200 ohms	0.8	12

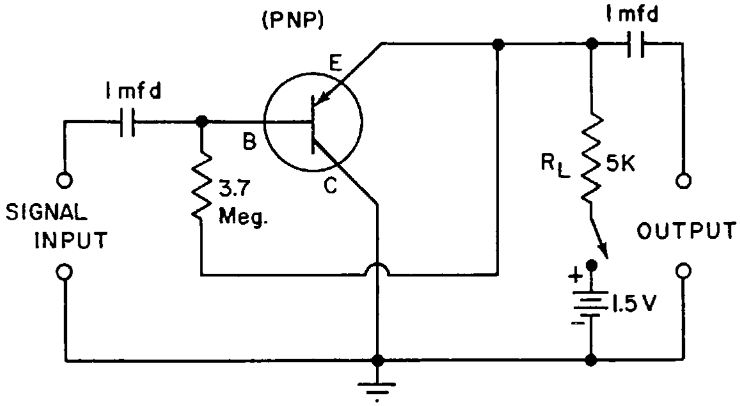


Fig. 4-13. A practical single stage common collector amplifier.

What reason could anyone have for using the common-collector circuit in preference to the others at any time or for any application? The most practical use for the common collector configuration lies in its value as an IMPEDANCE TRANSFORMER. Like the cathode-follower circuit in vacuum tube amplifiers, the common-collector is applied where a high-impedance output must be coupled to a low-impedance reproducer or some other low-impedance load. Matching transformers are undesirable in many applications and, in such cases, a transistor wired in a common-collector circuit may provide the performance required. In Fig. 4-13, a practical common-collector amplifier intended for impedance matching, is shown with component values and required voltage. Note the use of a single battery source. The input impedance of this single-stage amplifier is approximately 1 megohm at 1, 000 Hz, while its output impedance is in the order of 1, 500 ohms. Its voltage gain remains constant (approximately 0. 91) from about 30 Hz to 10, 000 Hz. This rather extended frequency response suggests the possibility of utilizing the common-collector circuit in high-fidelity pre-amplifier circuits, where the output of a common-base or common-emitter amplifier is to be coupled to a transmission line of low to medium impedance.

CHAPTER 5

TRANSISTORS IN CASCADED AMPLIFIERS

IMPEDANCE MATCHING

Any amplifier system may be considered as consisting of TWO SOURCES and TWO LOADS. (Fig. 5-1). The device in which the input signal originates is the primary source. The amplifier input circuit serves as the load on the primary source, while the amplifier output circuit behaves as a SECOND SOURCE of signal voltage. The output voltage is then transferred to the final load.

Whenever power is to be transferred from a source to a load -- and this applies to all electrical systems starting with pure DC and power AC, right through the highest radio frequencies -- the maximum realizable transfer is obtained when the impedance of the load is equal to that of the source. Although the procedure of matching source-to-load impedance is not always rigorously followed in practice, circuit designers endeavor to keep the impedances as nearly alike as conditions permit. Slight mismatches do not affect overall amplifier performance too seriously. For example, it is often impossible to achieve perfect matching with commercially available parts and, in other situations, it is possible to reduce amplifier distortion by making the load impedance somewhat different than the source impedance. In general, however, the impedances must be selected so that they are relatively close to each other in value.

One of the problems in impedance matching is that impedance varies with frequency. Consider, for example, an inductive load connected to the collector of a transistor. The impedance of the load depends on two factors - the resistance of the inductor and its reactance. The resistance will remain fixed and will not change with frequency. The reactance, though, is directly proportional to frequency. As frequency increases, so does the reactance. If the resistance of the load is small and the inductance is large (as is usually the case), then there will be wide swings in reactance - and therefore impedance - as the frequency changes.

In high-fidelity audio systems, the chief objective is true reproduction of the signal, rather than maximum signal power transfer. In such systems, you may find the impedance of the load deliberately made several times that of the source.

Suppose we wished to connect a phono playback cartridge to the input of a vacuum tube amplifier and then couple the output of the amplifier to a pair of headphones. The input impedance of a vacuum tube is normally very high (grid to cathode impedance); its output impedance, although not as high as its input impedance, is still quite

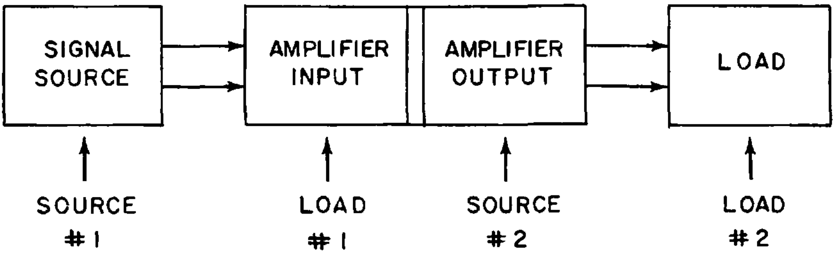


Fig. 5-1. Amplifiers consist of two sources and two loads.

large, especially in the case of pentodes and beam power tubes. Let us assume that we have before us two types of phono cartridges -- a high output crystal type and a magnetic cartridge --and two types of headphones --high impedance dynamic and low impedance magnetic. If we select the crystal cartridge as our source of signal and the high-impedance dynamic headphones as the amplifier load, the sys-

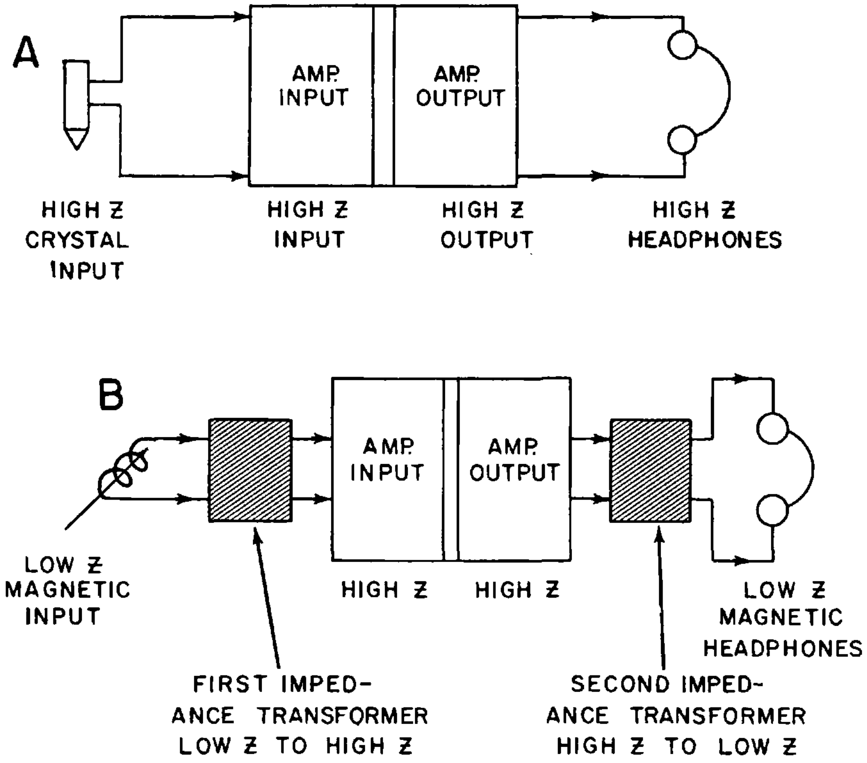


Fig. 5-2. Matching impedances.

tem could be interconnected without impedance matching devices (Fig. 5-2A), since the cartridge will match the high-impedance input of the tube and the dynamic headphones will match the output impedance of the tube. Should we decide to employ the magnetic cartridge and the magnetic headphones, however, we would find that direct connections would be completely inadequate and the over-all gain hopelessly low. In this situation, an impedance transforming device (such as a transformer or special transistor circuit) would be called for. This arrangement is illustrated in Fig. 5-2B.

It is common to use a transformer having primary and secondary windings with the correct impedances for impedance matching. In addition, special circuit arrangements, such as cathode-followers in vacuum tube circuits and common-collector configurations in transistor amplifiers, may also be advantageously applied in many cases. In any event, the problem of impedance matching must be given consideration whenever amplifiers are used, whether singly or in groups of two or more.

Consider the input and output impedances of a typical junction transistor as given in Table 4-2 (Chapter 4). Imagine that we wished to couple two transistors in cascade (one following the other) to take advantage of the voltage or power gain multiplication possible in this manner. Purely from the point of view of impedance matching, some circuit arrangements lend themselves better to direct cascading without the use of a matching transformer, than others. Table 5-1 has been drawn up to show this. A good match is considered to be one in which the impedances are of the same ORDER OF MAGNITUDE. This idea is carried throughout the table.

TABLE 5-1

FROM	TO	Common Base	Common Emitter	Common Collector
Common Base		very poor	poor to fair	good
Common Emitter		very poor	fair	good
Common Collector		good	good	very poor

In general, the impedance matching characteristics in the table permit this tentative conclusion: Where the impedance mismatch is very POOR, some form of auxiliary matching devise is mandatory; where the match is FAIR, acceptable performance from a pair of cascaded transistors may be obtained without an impedance transformer, but it most certainly could be improved with better matching; and where the match is GOOD, direct cascading methods may be used with good results. However, other very important considerations such as voltage-gain, power-gain and current-gain must enter into any design problem. In other words, whether or not two configurations are well-matched impedance-wise is not always the primary factor in selecting such a combination for a cascaded amplifier.

With reference to practical usage, the MOST COMMON cascaded combination in modern transistor circuits, is the COMMON-EMITTER GROUPING. Yet, the impedance match here is only fair. Thus, even when there is a mismatch, the voltage-gains and power-gains that can be realized from common-emitter configurations, more than make up for the losses in power transfer resulting from impedance mismatching.

OTHER CONSIDERATIONS IN TRANSISTOR CASCADING

In vacuum tube circuits, the plate circuit of a stage must be isolated from the grid circuit of the following stage, by means of a capacitor or transformer. Since the plate carries a comparatively high positive voltage and the grid of the subsequent tube is at either zero potential or some small negative potential (bias), these two elements cannot be connected directly together.

Does this also apply to transistors? The answer to this question must be both "yes" and "no". Just as two identical vacuum tubes cannot be directly coupled for the reasons given in the previous paragraph, two identical types of transistors will not perform in a direct-coupled circuit unless certain steps are taken to adjust the relative DC voltages. Fig. 5-3 shows the voltage relationships one would obtain by attempting to directly couple a pair of common-emitter N-P-N transistors. It is assumed that R1 = R2 and R3 = R4 to preserve the identity of the two circuits. In the first transistor (NPN 1), the collector and base are both positive with respect to the emitter.

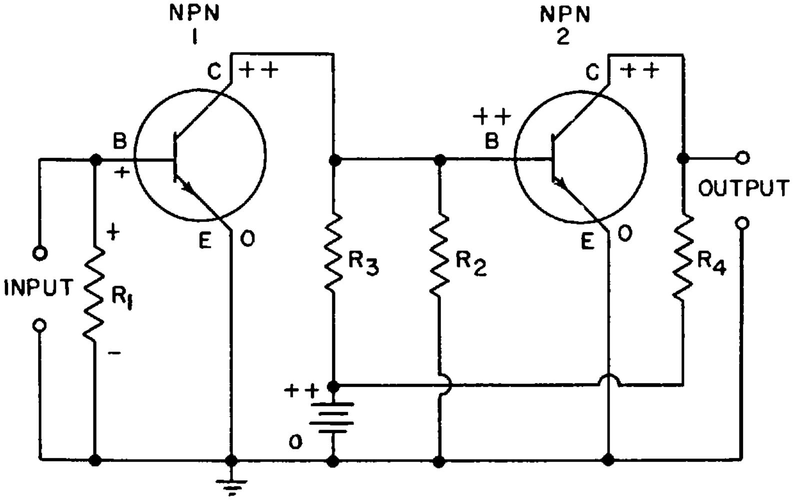


Fig. 5-3. A two-stage amplifier using identical components.

(The base is positive with respect to the emitter because of the voltage drop across R1). However, the collector voltage is considerably higher than that of the base, as it should be. With direct coupling, the base of the second transistor (NPN 2) is at the same positive potential as the first collector of NPN 1. Because of the circuitry, the base and collector of NPN 2 are at the same potential. Hence, NPN 2 does not have the correct voltage relationships between the collector and the base.

This may suggest that such a cascaded arrangement could be made to operate satisfactorily if the resistances are adjusted to produce the desired potentials on the various elements. That this is indeed true, will be demonstrated in a later section in which just such a circuit is described.

Further simplification of direct-coupled transistor amplifiers is also possible by combining one P-N-P and one N-P-N in a cascaded arrangement. This will be discussed later but, as we mentioned in an earlier chapter, there is only one kind of vacuum tube but two kinds of transistors, so that combining two types of transistors is a procedure that has no parallel in vacuum tube work.

RESISTANCE-CAPACITANCE COUPLING

To secure greater voltage gain, R/C coupled transistor amplifier stages may be cascaded in much the same way as vacuum tubes. The point was made in the preceding section that satisfactory performance might be obtained from two or more cascaded transistors, despite the impedance mis-match between them. Common-emitter cascades have enjoyed the greatest popularity in this regard because of their greater voltage and power gains. Even though impedances are far from being matched, a great enough over-all gain may be obtained for ordinary applications. On the other hand, the loss of gain in imperfectly matched transistor cascades necessitates a greater number of stages for a given amount of amplification than in equivalent tube amplifiers.

Fig. 5-4 illustrates a 4-stage amplifier, suitable for general use, with a maximum voltage gain of approximately 2500 when operating into a high impedance load. As a way of illustrating the comparative performance of vacuum tubes, it might be mentioned that a voltage gain of 9000 may be obtained from a PAIR of pentodes in cascade in a carefully constructed circuit. The compactness, low-voltage requirements and low power consumption of transistors, however, often more than make up for the need for a greater number of stages.

Although much of the theory of operation of the circuit in Fig. 5-4 has already been discussed, the additional circuit analysis that follows should assist in clearing up any questions that might still exist.

(a) C1, C3, C4, C5, C7 -- Coupling capacitors, 1 mfd. each.

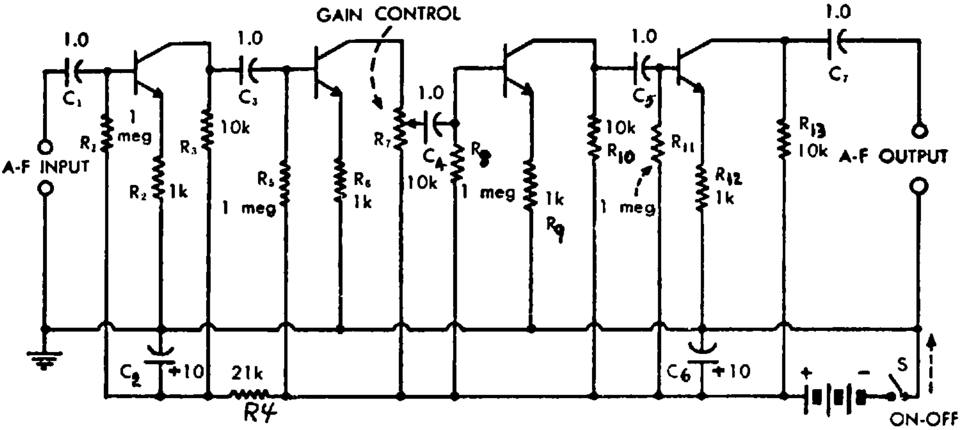


Fig. 5-4. A four-stage R-C coupled amplifier.

(Coupling capacitors in transistor circuits are higher in value than coupling capacitors used in tube circuits). These isolate the DC voltages on the collectors from the DC voltages on the following bases. They must offer a lower reactance to the audio voltages than the collector resistors R3, R7, R10 and R13, hence their comparatively large capacitance. These capacitors are available in ultra-miniature sizes for the operating voltages required in this circuit; in most cases they will be electrolytic so that the user must be careful to observe polarity.

(b) R1, R5, R8 and R11 -- Base bias resistors which develop the voltage drop needed to polarize the base correctly with respect to the emitter. The transistors used are N-P-N types so that the base must be positive with respect to the emitter.

(c) R2, R6, R9 and R12 -- Emitter series resistors for temperature stabilization and degeneration. Both of these effects have been explained previously.

(d) C2, C6 and R4 -- De-coupling network. When a multi-stage amplifier is powered by a single DC voltage source, there is a tendency for interaction between stages through the common impedance offered by the source. These two capacitors and the resistor, acting together, constitute a filter network that prevents signals present in the output stage from being fed back to the input stage. If positive feedback were permitted, oscillation might occur; if negative, the effect would be degeneration and consequent loss of gain.

(e) R3, R7, R10, R13 -- Collector load resistors. Output voltage for each stage develops across these resistors, to be passed on to the input of the next stage. (Note that collector load, R7, is also the volume control).

The frequency response of an R-C cascaded transistor amplifier system depends primarily upon three factors:

(1) The size of the coupling capacitors. These must be large enough to prevent low-frequency attenuation due to their capacitive reactance at frequencies under 100 Hz.

(2) The input and output capacitance of each stage. These capacitances tend to shunt the high frequencies to "ground" and must be kept low for good frequency response. Transistors designed for high frequencies are constructed with very small capacitances; some manufacturers are now using internal shields between elements to reduce capacitance even further.

(3) Internal transistor construction. Since the inception of transistor research, much progress has been made in speeding up the motion of the current carriers -- (the time required for movement of carriers from one element to another is called TRANSIT TIME, just as in vacuum tube nomenclature) -- with attendant improvements in frequency response.

TRANSFORMER COUPLING

The impedance match between a pair of transistors connected in the common emitter configuration, may be materially improved by inserting a properly wound coupling or interstage transformer between them. Consider a transistor amplifier connected with a common emitter -- its input impedance may be in the order of 500 ohms while its output impedance may be in the vicinity of 50,000 ohms. A transformer, having the proper turns ratio to match these impedances, would be of substantial assistance in transferring power from one stage to the next. A three-stage transformer and R-C coupled amplifier is shown in Fig. 5-5. This particular unit is a compact and versatile telephone pickup amplifier with which two people can listen to the same telephone conversation, without the need of an extension phone. The output can be fed to a tape recorder input instead

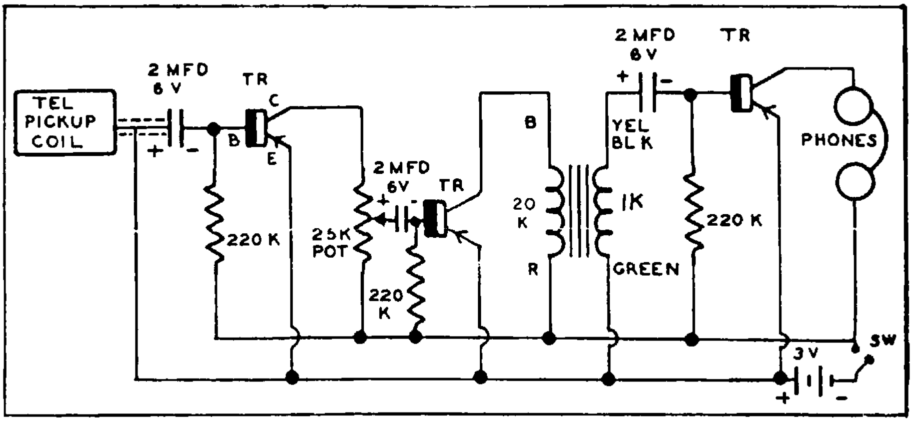


Fig. 5-5. A three-stage transformer-coupled amplifier.

of earphones so that the conversation may be recorded. The input will also take a crystal microphone, with a suitable matching transformer. Since the amplifier is completely self-powered and small, it can be used as a hearing aid or portable amplifier, as well as a telephone pickup device. The circuit is particularly interesting to us at this point because it combines R-C and transformer coupling. The objective of this design is to provide sufficient gain without involving two transformers, since the latter contribute to higher cost.

To assist the reader in comparing similar circuits, reference is made to Fig. 5-6. Except for the fact that A is transformer-coupled and B is R-C coupled, the circuit details are very closely matched. While the transformer-coupled circuit of A is somewhat more expensive to build, its overall gain is considerably greater than the R-C circuit of B. In planning amplifiers, one may reasonably assume that the gain of an R-C stage is from 6 db to 8 db lower than an equivalent transformer-coupled stage. This loss of gain requires the use of at least one additional R-C stage, and possibly more, to equal the gain of the corresponding transformer-coupled amplifier. Values of components have been omitted intentionally since these will depend upon the types of transistors used, the desired gain, the operating range, etc.

A word or two might be said at this point with reference to frequency response. Properly designed R-C circuits, in general, are capable of wider frequency response than transformer-coupled arrangements. This, of course, explains why one sees so many high-

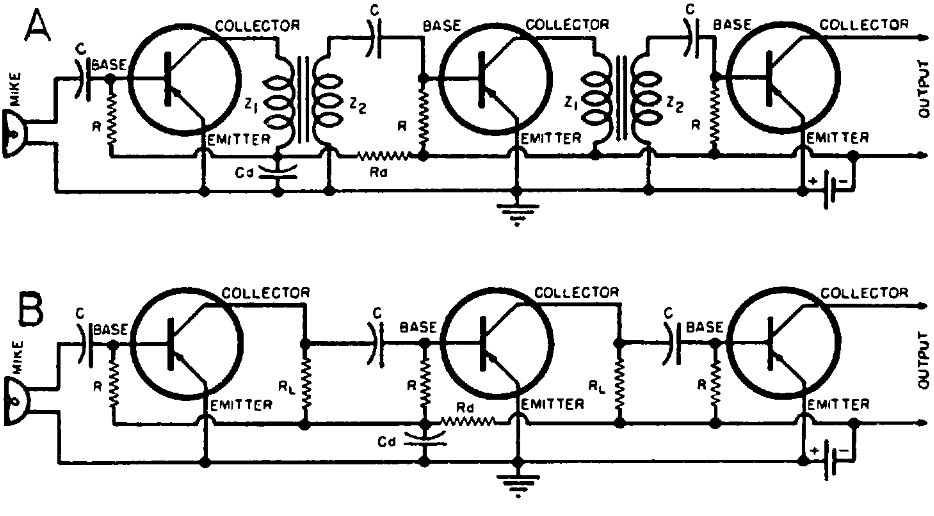


Fig. 5-6. Equivalent R-C and transformer coupled amplifiers. The circuit in A has at least 18 db greater gain than the B circuit.

fidelity circuits incorporating a number of R-C stages. However, a well-engineered transformer can, in many instances, provide a frequency response that approaches closely the curve of an R-C stage, but "bargain" transformers or replacement grade may be expected to give very inferior performance.

DIRECT COUPLING

Direct coupling between identical transistors is sometimes used despite the difficulties mentioned previously. A particularly effective direct coupled relay circuit, employing two P-N-P transistors, is illustrated in Fig. 5-7. The input device is an International Rectifier Corp., type B2M selenium photocell, which operates a Sigma 4F (8000 ohm coil) relay. Reliable operation was obtained with only 1 ft-candle of illumination on the cell. Greatly increased sensitivity can be realized by substituting a more delicate relay, such as the Edison Model 219 (23,600 ohm coil) with which operation was obtained with only .008 ft-candles!

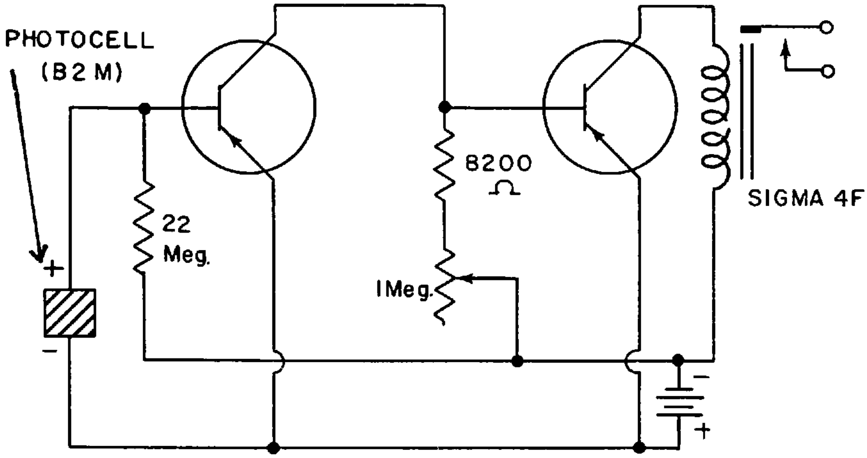


Fig. 5-7. A direct coupled two-stage relay amplifier.

Several advantages are gained with direct coupling of this type. All coupling capacitors and their respective input-return resistors are eliminated. There is also a gain in the temperature stability, due to the fact that a thermally initiated DC change in the second stage can be passed back to the first in a direction that tends to cancel the first variation. Direct coupling gives good frequency response because specific attenuating components, such as coupling capacitors, distributed capacitance of transformers, shunting effect of bias resistor wiring, etc., are not present.

A second type of direct-coupling arrangement is shown in Fig. 5-8. Note that the first stage is set up in the common-collector configuration and the second as a common-emitter amplifier. As you will recall, the input impedance of a common collector circuit is quite high -- in the order of 10,000 ohms or more, while the output impedance is low, ranging around 500 ohms (Table 4-2). Table 5-1 indicates that the impedance match between a common-collector and common-emitter stage is quite good, so that the circuit shown in Fig. 5-8 would seem to have excellent possibilities. When it is recalled, however, that the voltage gain of a common-collector arrangement can approach unity and can go no further, it immediately becomes evident that the common-collector transistor in the amplifier of Fig. 5-8 serves as an impedance-matching device, rather than as a voltage amplifier. There are a number of applications, however, where impedance-matching of this type is necessary; the direct-coupled circuit of Fig. 5-8 is an example of an application of this nature. Crystal microphones and phono-pickups have the characteristic of high impedance and must work into a high-impedance circuit. The common-collector stage may then be used, as illustrated, to "bring down" the high impedance of the input device enough to match the input impedance of the following common-emitter stage so that efficient energy transfer is obtained.

R1 and R2 form a voltage divider, shunted across the battery, that helps to hold the base bias of the first transistor constant; this is often called "DC stabilization". As mentioned earlier, it is also

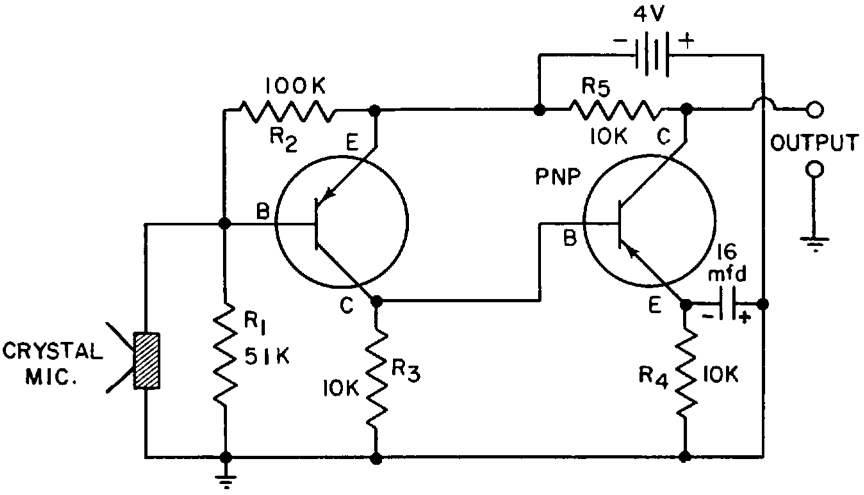


Fig. 5-8. A direct-coupled amplifier using a grounded collector stage as an impedance matching device.

a method for using a single battery to supply both forward and reverse bias. The use of an un-bypassed emitter resistor (R2) introduces some degeneration and improves the stability still further.

COMPLEMENTARY-SYMMETRY DIRECT COUPLING

An NPN transistor may be said to be the COMPLEMENT of its corresponding PNP counterpart because they differ only in the polarity of the applied voltage. Because these two transistors are selected to have identical ratings (biases, collector voltage, emitter voltage, collector dissipation, alpha, beta, etc.), they are perfectly SYMMETRICAL in an electrical sense. Advantage may be taken of this complementary symmetry in direct coupled circuits, as shown in Fig. 5-9. This is an arrangement that is intended specifically for audio amplification and utilizes emitter resistors for stability. Its operation may be described as follows:

With zero signal input, the NPN unit will show a very small Ico (collector current, zero base input) which flows through R2 in the direction shown by the arrows. The top of R2 thus becomes negative with respect to the bottom, applying, therefore, bias of proper polarity to the base of the PNP transistor that follows. This sets up the correct DC conditions for Class A audio amplification, if the resistors are carefully selected with a view to linear operation. A signal input to the base of the NPN transistor will then result in an amplified reproduction of the signal in the base-emitter circuit of the PNP unit. It has a phase inversion of 180°, as explained in a prior section. A second phase inversion occurs in the emitter-collector

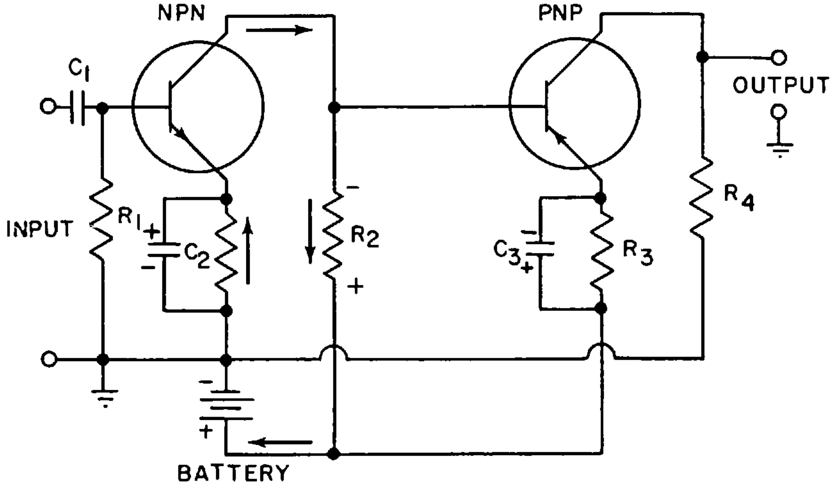


Fig. 5-9.
Complementary-symmetry in a direct-coupled circuit.

circuit of the PNP output transistor, so that the final signal has the same phase as the input signal. Although this is of no importance in audio amplification, it is very significant in television and radar, where the phase of the voltage applied to the picture tube determines whether the image will be like a photographic negative or positive.

An extremely simple complementary symmetry circuit is shown in Fig. 5-10. This arrangement is used for ultra-sensitive relay operation in which a power input of about .03 microwatts results in approximately .01 WATTS, for a power gain of BETTER THAN 400,000! In this circuit, no forward biasing resistors are used and no attempt is made to place the transistor operating points on the linear portion of their curves. That this is not required is a result of the fact that only DC is being amplified. The overall current gain of a direct-coupled complementary symmetry circuit of this variety is normally well over 700.

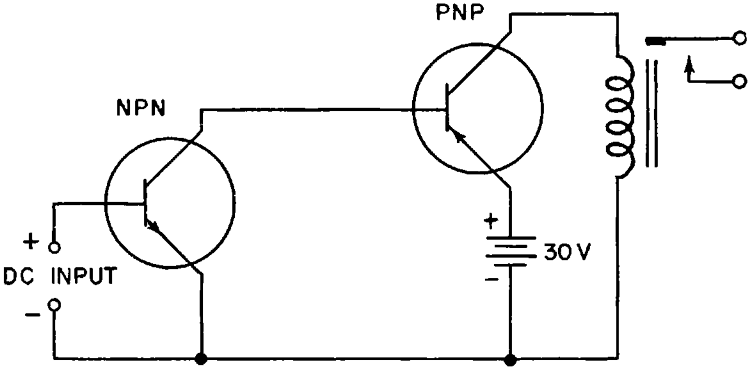


Fig. 5-10. A complementary-symmetry relay circuit.

TRANSISTOR POWER AMPLIFIERS

The activation of a speaker, a record cutting head, a magnetic tape recording head, or a recording stylus on a lie detector, are just a few examples of amplifier applications in which relatively large amounts of power are required. Power may be obtained by increasing either voltage, current, or both. Consider a vacuum tube amplifier: Since a single power supply, whose weight and cost are generally prime considerations, is used for all tubes -- voltage and power amplifiers, both -- it has become common practice to design tubes so that the required power is obtained through the medium of larger currents rather than increased voltages. Since the heat generated in any power-dissipating device is equal to the resistance of the device, multiplied by the SQUARE of the current, it is clear that any current increment will result in proportionately larger quantities of generated heat. Transistors, being temperature sensitive, are subject to severe alterations of characteristics if their temperatures are permitted to rise too high. Thus, the heat produced must be dissipated almost as fast as it appears if power transistors are to be successful.

From the physical standpoint, the elimination of heat from any solid may be pictured as the flow of energy from the hot body to cooler surroundings. The rate at which this flow occurs determines the final temperature of the body under given conditions of heat intake. Hence, the problem of maintaining the temperature of a transistor at a safe value becomes one of forcing the heat to flow from it to its environment at as high a rate as conditions permit.

Flow-rate may be increased in any one (or a combination of more than one) of the following ways:

(1) LARGE SURFACE AREA. Exposing a large area to the air encourages both radiation and convection. The former is important only if the equilibrium temperature of the transistor is substantially higher than that of the surrounding air. Convection, for normal temperatures, is by far, the more important of the two methods of heat transfer. It is common practice to increase surface area by using so-called "radiating fins". (Fig. 5-11.)

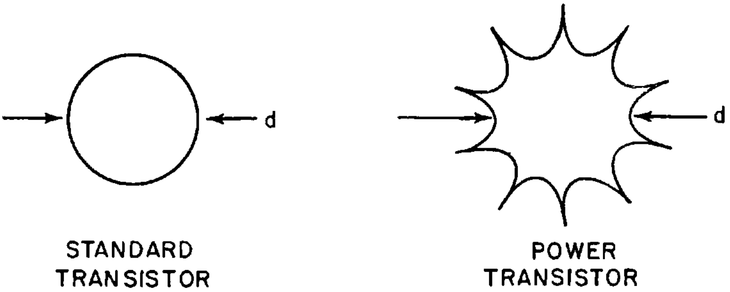


Fig. 5-11. Fins increase the radiating and convecting area of the power transistor. Both transistors have the same basic diameter.

(2) FORCED COOLING. Either moving air or liquid carries heat away faster than the same fluid in a still state. With present constructional methods, it is difficult to visualize forced water-cooling, but forced-air cooling is entirely feasible.

(3) HEAT SINKS. By encasing the transistor body in metal and then placing the metal in intimate contact with a chassis or some other good heat conductor, we form what is known as a HEAT SINK. This method of heat transfer depends almost entirely on CONDUCTION so that the use of metals is almost mandatory, since these are the best conductors of heat. In practice, the collector of the transistor is soldered to the metal housing to enhance the conduction process.

SINGLE-ENDED OPERATION OF POWER AMPLIFIERS

As the power to be transferred to the load is large in a power amplifier, coupling is virtually always accomplished with the help of a matching transformer. Other than this, there are few significant differences between the circuit of a transistor voltage amplifier and a transistor power amplifier.

As with tubes, operation may be carried on in either Class A or Class B for audio work. For single-ended operation, however, only Class A may be used, with Class B conditions being reserved for push-pull output arrangements. Fig. 5-12 is a diagram of a typical single-ended Class A power amplifier; the power output of this particular circuit is approximately 0.4 watt with 50 millivolts input to the primary of the input transformer. The transistor selected for use in this amplifier could offer many possibilities in power applications. Despite its small size and low operating DC voltage, it is capable of 2.5 watts (or more) dissipation in free air and about double this amount when in contact with a good heat sink, such as an aluminum chassis. In Class A, as a single-ended stage, the collector efficiency would be 35 percent and the power gain better than 15 db. It would also work well up to frequencies in the 10,000 Hz region. The final ratings would depend on the power transistor selected.

Before going on to push-pull power amplifier circuits, it would

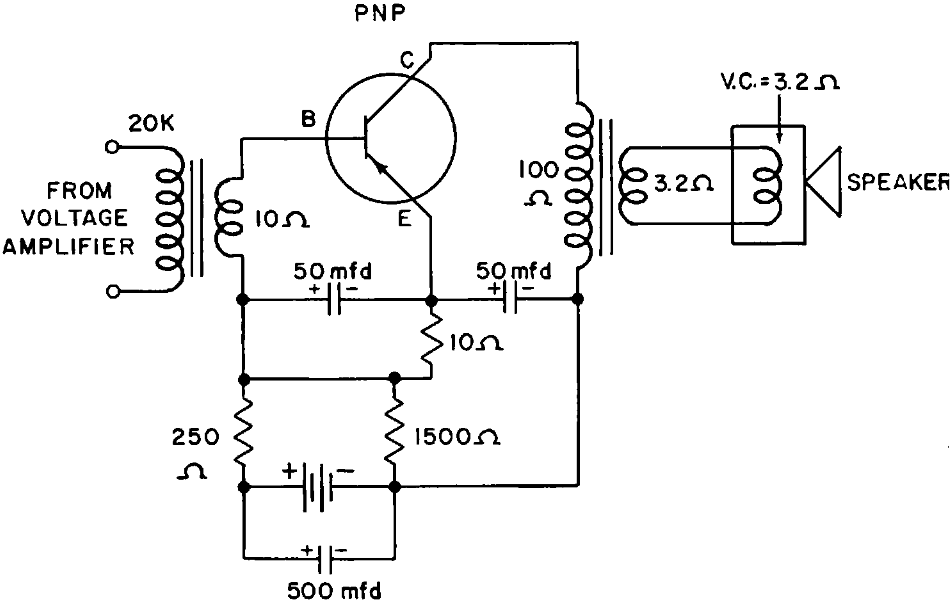


Fig. 5-12. A Class A single-ended power amplifier.

be helpful to the reader to review the characteristics of two hypothetical power transistors. Their characteristics are shown in Table 5-2.

TABLE 5-2

	(PNP)	(NPN)
	MAXIMUM RATINGS	
Total dissipation, free air	2.5 watts	1.5 watts
Total dissipation, heat sink	4.0 watts	4.0 watts
Collector-base voltage	-30 volts	60 volts
Collector current	-1.5 amperes	0.8 ampere
Junction temperature	75 deg. C.	75 deg. C.
	TYPICAL RATINGS	
Current gain, base to emitter	40	40
Alpha cut-off frequency	0.4 Mc.	0.6 Mc.
Power gain	24	26

STANDARD PUSH-PULL OPERATION OF POWER TRANSISTORS

A power output system operating in push-pull requires that the input to each individual amplifier be 180° out-of-phase with the input to the other amplifier. In vacuum tube circuits, the necessary phase shift is usually brought about by either a transformer used for interstage coupling or by a phase-inversion system consisting of resistors, capacitors and often an additional triode.

With regard to transistors in push-pull, R-C phase inversion is not popular. Special center-tapped transformers are available as drivers so that transformer coupling is almost universally used in commercial circuits.

Either standard voltage amplifier transistors or power transistors can be used in standard push-pull circuits, as shown in Fig. 5-13 and Fig. 5-14. Both of the circuits illustrated are operated in Class B for greater power output. In each, a resistor from emitter to base establishes a voltage drop of sufficient magnitude to make the collector current very small, with no input signal. As the signal reaches each base out-of-phase, first one transistor, then the other draws current through the primary winding of the output transformer to reproduce the input waveform in the customary Class B fashion.

Since the transistors used are low power units, the total output to the speaker does not exceed about 500 milliwatts. This is sufficient to drive a three or four inch speaker. This particular amplifier is designed to take a signal from a transistor radio that normally works into a 3,000 ohm headset and bring it up to small-speaker volume.

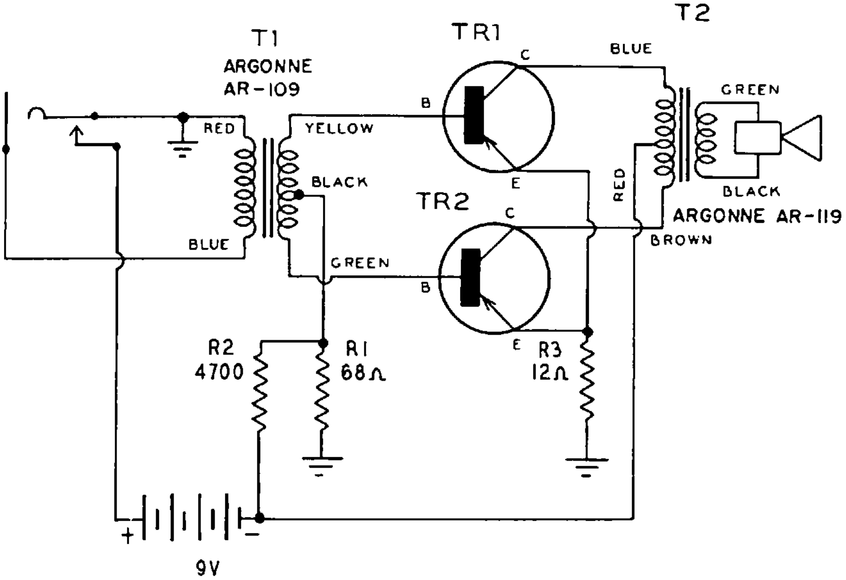


Fig. 5-13. Class B audio output using standard transistors.

The arrangement given in Fig. 5-14 uses power transistors and is capable of approximately 5 watts of audio power. The 0.5 watt of audio driving power needed to obtain this output is provided by a third power transistor in Class A. It is transformer-coupled to the push-pull pair. However, 50 milliwatts of audio input are demanded by

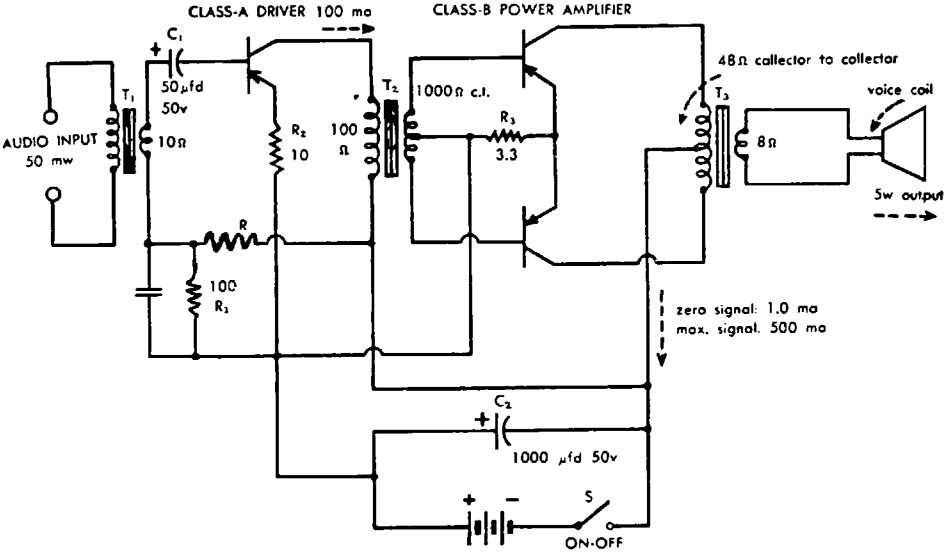


Fig. 5-14. Class B audio output using power transistors.

the Class A driver for full output, hence a voltage amplifier section of sufficient gain must precede this equipment. Any one of the two or three-stage voltage amplifiers discussed in previous chapters will provide this order of drive. The collector current in the Class A driver stage is adjusted for 100 ma by actual measurement, as follows: The resistor marked R is set for about 10, 000 ohms to start with. With a milliammeter in series with the collector lead, R is gradually reduced until the collector current stabilizes at 100 ma. For most transistors, this occurs when R is in the order of 3, 000 ohms. With the driver collector current adjusted to 100 ma, the collector current in the Class B stage will be about 0. 5 ma for each transistor with zero signal input (Ico). At full output, the total collector current of the two push-pull transistors will rise to about 550 ma. The output transformer T3 must be capable of handling a current of this magnitude.

PUSH-PULL OPERATION BY COMPLEMENTARY SYMMETRY

The complementary symmetry feature of transistors of different types (PNP or NPN) makes possible a kind of push-pull operation that has no parallel in vacuum tubes. Not only is phase inversion unnecessary, but satisfactory circuits can be set up without transformers of any kind. We shall refer to the circuit of Fig. 5-15 in the discussion of the theory of complementary symmetrical push-pull operation which follows.

For convenience of analysis, four 10-volt batteries are shown in series with the bases connected to potential midpoints to establish the correct bias. Note the following:

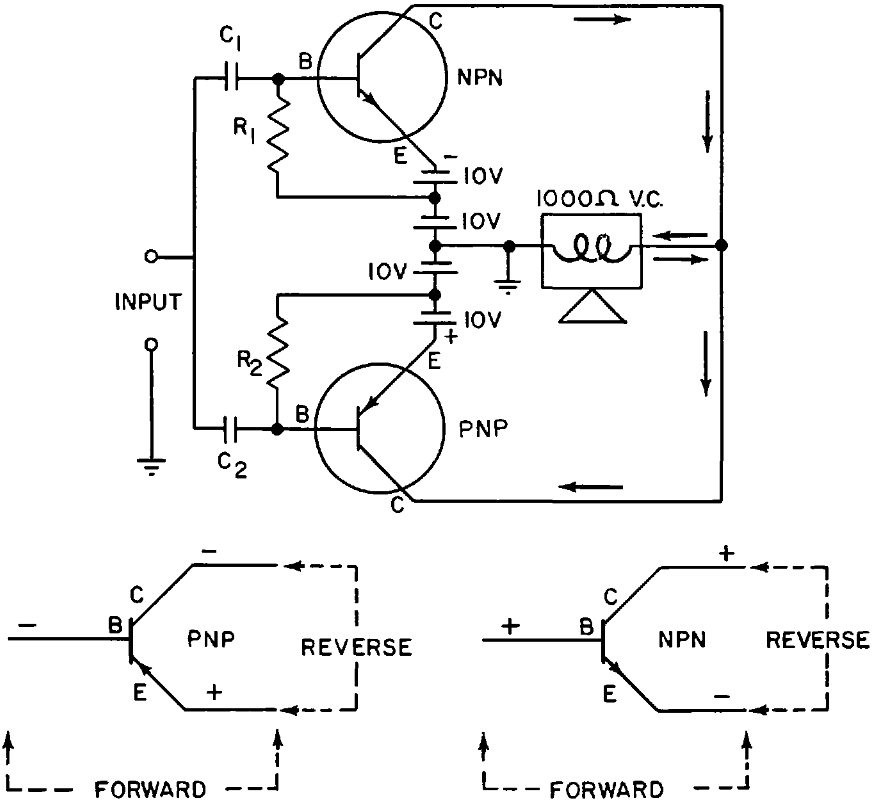
(a) The NPN transistor is biased so that its base is positive with respect to its emitter (forward bias) and its collector is more positive than either the base or the emitter (reverse bias).

(b) The bias of the PNP unit is such that the base is negative with respect to the emitter (forward bias) and the collector is more negative than either the base or the emitter (reverse bias).

(c) Both collectors receive their voltages through the voice coil of the speaker.

(d) A 1, 000 ohm speaker voice coil is used so as to eliminate the need for an output transformer.

To follow the action involved in complementary symmetry, let us assume a sine-wave input signal which, at the moment under consideration, is NEGATIVE-GOING. Since there is the same kind of coupling to both bases -- capacitive in this circuit -- then both bases will be driven in a negative direction simultaneously by the input wave. For the NPN unit at the top, a negative-going voltage represents a SUBTRACTION from the forward bias. Thus, with this input signal, the emitter current and consequently the collector current,



Negative-going input adds to forward bias.

Negative-going input subtracts from forward bias.

Fig. 5-15. Complementary-symmetry push-pull output stage.

drops. On the other hand, a negative-going signal ADDS to the forward bias of the PNP transistor, producing an increase in collector current. This reasoning will be clarified if you refer to the bias diagrams in Fig. 5-15.

Both collector currents flow through the voice coil of the speaker. Assuming equal collector currents (transistors and voltages perfectly matched), the voltage drop across the voice coil is zero with no signal input. This is because these currents flow in opposite directions through the voice coil, as shown by the solid arrows. Suppose, for example, that the voltage drop caused by the current through each transistor is 10 volts across the voice coil with zero signal. Since one of these drops makes the right side of the voice coil positive with respect to the left (PNP) and the other has the reverse effect, the two voltages cancel each other, leaving zero potential across the voice coil. Now consider the effect of a negative-going signal. The PNP collector current increases, bringing the voltage drop up to, say, 15 volts; the NPN collector current diminishes, making its resultant voltage drop 5 volts. Now the two potentials oppose each other so that the resultant voltage across the voice coil is now 15 volts - 5 volts or 10 volts.

On the next half-cycle, when the input signal is positive-going, an identical effect takes place in the opposite direction. That is, the peak voltage that appears across the voice coil is again 10 volts, but this time with opposite polarity. Thus, complementary-symmetry provides an alternating voltage across the load in the collector circuit, due to the fact that one transistor "pushes" while the other "pulls". Although the bases of the two units are connected in PARALLEL, the collector outputs are 180° out-of-phase and push-pull action results.

GAIN CONTROL CONSIDERATIONS

As in vacuum tube amplifiers, gain or volume controls are needed to meet the requirements of the listener under varying acoustic conditions. The problems encountered in designing transistor gain control circuits, however, differ somewhat from those of vacuum tube amplifiers. Transistors are current operated devices, while vacuum tubes are essentially voltage operated, and here is where the difference exists.

A transistor gain control circuit must be installed so that it does not change the DC operating conditions of the transistor while it controls the signal or AC conditions. In addition, the gain control should vary source and load impedances very little, if at all, otherwise a significant increase of distortion may occur. Examine the two input gain control arrangements presented in Fig. 5-16 in the light of these two factors. In (A), the coupling capacitor isolates the DC circuits so that variation of the potentiometer does not affect the operating point of the transistor; the load impedance is not changed because the control is in the input circuit of the transistor; the source impedance is changed very little because it is low to begin with and a relatively large resistance (the potentiometer) has virtually no effect upon it when connected in parallel. Thus, the gain control arrangement of (A) is quite satisfactory. The circuit illustrated in (B) is unsatisfactory, however, because (1) it varies the base current, being a part of the DC path and (2) it varies the collector current, completely changing the DC operating conditions.

When a transistor amplifier system contains more than one stage, care must be exercised in selecting the exact point in the circuit for the gain control so as to avoid overloading. A gain control too far forward -- that is, too near the input source in a high gain amplifier -- is prone to introduce noise in operation; one too near the

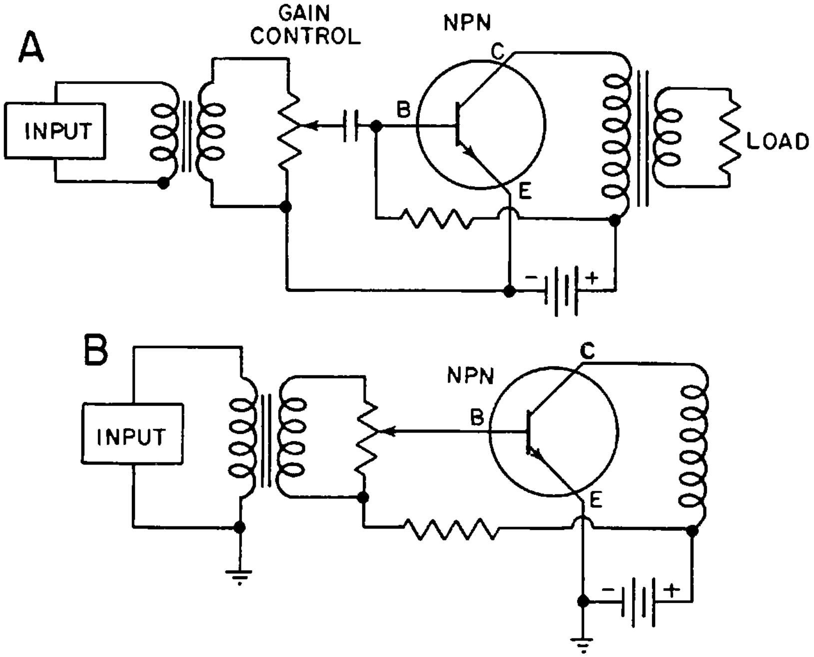


Fig. 5-16. Two gain - control arrangements.

output end may permit overloading of prior stages. We must therefore compromise on the exact placement of the control.

Fig. 5-17 illustrates many of the concepts discussed in this chapter. It is a 4-transistor intercommunications set, in which all the stages are common-emitter with standard push-pull output. This two-station unit provides convenient intercommunication facilities for the home or office, as well as offering a "baby-sitter" feature. In intercom use, battery drain occurs only when the talk switch on the master or the remote station is operated. Battery drain is very little when the system is used for baby-tending.

CIRCUIT STABILITY

We have mentioned that transistors are temperature sensitive devices. There are a number of ways of protecting the transistor against the effects of temperature. Two of the most economical ways are through the use of either current or voltage feedback, or both. As an example, consider resistor R1, shown in Fig. 5-18. As you can see, our circuit makes use of an NPN transistor. This means that for a condition of forward bias, the base is biased positive with respect to the emitter. Assume that at a particular moment, a rise in transistor temperature increases the current flowing through the transistor from emitter to collector. This increased current will

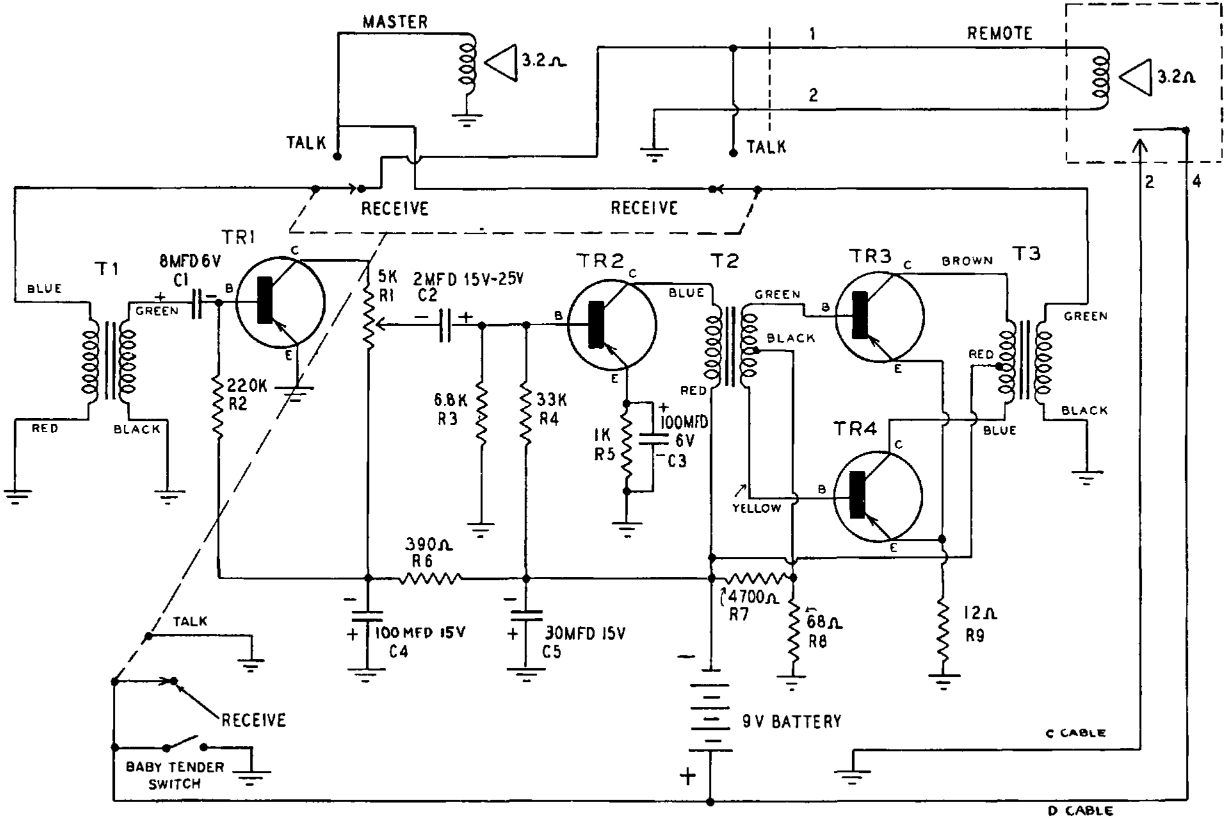


Fig. 5-17. A complete, practical four-transistor intercom and baby sitter.

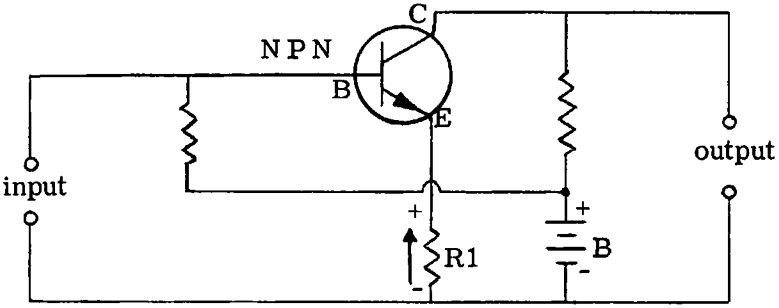


Fig. 5-18. Method of supplying current feedback for transistor stabilization.

flow through resistor R1, producing a voltage drop across R1 with the polarity shown. But this voltage drop opposes the forward bias, since the top end of R1 is positive and is connected to the emitter, while the bottom end of R1 is negative and is connected to the base through the input.

Since the voltage across R1 opposes the input and is out of phase with it, the effect is equivalent to negative feedback. The position of R1 is such that it is common to both input and output circuits. This means that the voltage drop across R1 is also part of the DC voltage applied to the output. Since R1 and the emitter-collector circuit are in series, and this series combination is shunted across the battery, B, any voltage drop across R1 must be subtracted from the collector voltage. In other words, the voltage between collector and emitter, plus the voltage drop across R1, is equal to the battery voltage. Thus, R1 stabilizes the transistor in two ways. (1) It supplies out-of-phase feedback to the input and (2) It reduces the collector-emitter voltage. These factors help stabilize the transistor; that is, they oppose any increase in current due to a rise in transistor temperature. The feedback supplied by R1 is known as current feedback since it is basically produced by the current flowing through the resistor.

Another type of feedback, known as voltage feedback, is shown in Fig. 5-19. The feedback resistor is R2 and, as you can see, it is connected between the collector and base. Now consider a rise in temperature which causes the transistor's current to increase. This current will flow through R3, making the top end of that resistor negative-going. But this negative-going voltage is partially applied through resistor R2 to the base. For a forward biasing condition, though, the base should be positive. The negative-going voltage acts to reduce the amount of forward bias. This, in turn, decreases the current flowing through the transistor.

Note, also, in Fig. 5-19 that we really have two stabilizing re-

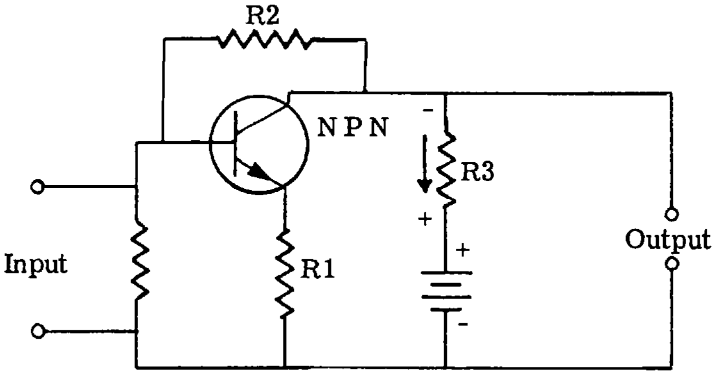


Fig. 5-19. Method of supplying voltage feedback for transistor stabilization.

sistors - R1 and R2. This is quite a common and economical way of protecting transistors against current overloads.

THERMISTORS

The larger current flowing through power transistors sometimes calls for more protection than that supplied by stabilizing resistors. To protect the power transistor against thermal runaway, a device known as a THERMISTOR can be used. The circuit arrangement is shown in Fig. 5-20. Unlike metals, a thermistor has a negative temperature coefficient. This means that as its temperature goes up, its resistance goes down. The decrease in resistance is quite pronounced.

In Fig. 5-20 the thermistor is shown as a variable resistor. The transistor used is a PNP type. Bias for the input is taken from a voltage divider, R1 and R2. These two series-connected resistors are shunted across the battery. The base receives its forward bias-

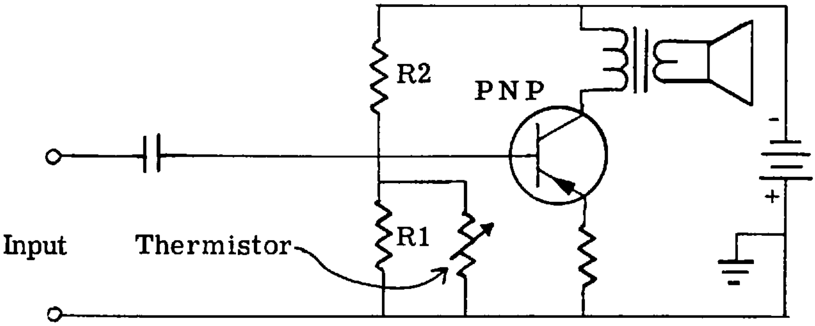


Fig. 5-20. The thermistor is a temperature-sensitive resistor having a large negative temperature coefficient.

ing voltage from the voltage drop appearing across R1.

Suppose that for some reason, the temperature of the transistor rises. The thermistor, placed close to the transistor, will be affected by this temperature increase and, as a result, its resistance will decrease. But the thermistor is shunted across R1 and so the overall resistance of this parallel combination will go down. As a result, the DC voltage on the base becomes less negative (or more positive). Since this is the same as decreasing the forward bias, the current flowing through the transistor decreases. As soon as the condition causing the transistor to heat is removed, operation becomes normal once again.

In its unheated condition, the resistance of the thermistor is so high that its shunting effect across bias resistor R1 is of no consequence. But once the thermistor's temperature rises, its resistance becomes so low that the equivalent resistance of the thermistor and R1 in parallel is far below normal.

Thermistors are made in a variety of shapes and sizes and consist of a combination of cobalt oxides, plus manganese and nickel.

CHAPTER 6

TRANSISTORS IN OSCILLATOR CIRCUITS

THE NEED FOR TRANSISTOR OSCILLATORS

One of the most serious drawbacks of early transistors was their inability to perform satisfactorily at moderate to high radio frequencies. Subsequently, engineers, stimulated by the public clamor for miniaturized portable radios with long battery life, bent their efforts toward the improvement of transistor high-frequency characteristics so that transistorized local oscillators for the tiny superheterodyne receivers would become feasible. This aim was quickly realized with the development of junction transistors that would oscillate reliably in the broadcast band. Much progress has been made since. Today one can purchase, at reasonable cost, a triode transistor that will oscillate at frequencies up to 240 megacycles.

Among other oscillator applications for which transistors are admirably suited, are code practice and other low-power audio oscillators, crystal-controlled frequency standards such as 10 kHz and 100 kHz oscillators of portable nature, square wave generators for radio and television testing, radio-frequency oscillators for small, compact signal generators, oscillators for automobile and shipboard receivers and 3.58 mHz subcarrier frequency oscillators for color TV receivers.

REVIEW OF OSCILLATOR FUNDAMENTALS

An oscillator is a controlled generator of AC voltages and currents. This broad definition is meant to include relaxation oscillators (R-C types), multivibrators and the more familiar sine-wave generators of the coil-capacitor variety.

In general, oscillators are characterized by four basic "musts" as follows: (Refer to the standard oscillator in Fig. 6-1).

(a) There must be an oscillatory (tuned circuit) circuit which determines the frequency at which sustained oscillation can occur. This may be a coil-capacitor combination, as in Fig. 6-1, or may take other forms such as a resistor-capacitor network, as found in multivibrators.

(b) There must be amplification. As we have explained earlier, transistors are capable of voltage, power and current amplification. Thus, they may be made integral parts of oscillator circuits.

(c) There must be a positive feedback system wherein a part of the output energy is fed back to the input to make up for the losses in the oscillatory circuit. Positive feedback implies in-phase feed-

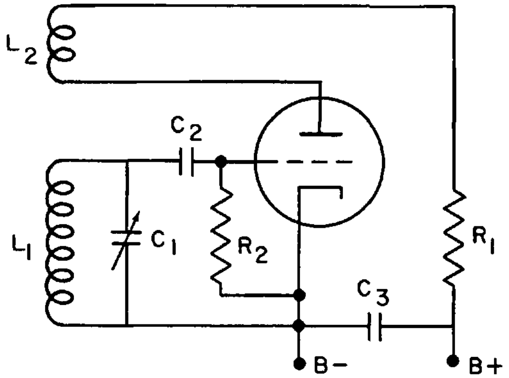


Fig. 6-1. A standard oscillator circuit.

back; that is, in Fig. 6-1, the plate circuit energy fed back from L2 to L1 must be in the correct phase to reinforce the polarity of the oscillating voltage in L1 and C1.

(d) Provision must be made for SELF-STARTING of oscillations and SELF-LIMITATION of oscillation amplitude. Practical oscillators, such as the standard Armstrong type in Fig. 6-1, are self-starting because they use grid-leak bias. When the B+ voltage is first applied to the plate, the bias is zero and so, there is a surge of current to the plate. This current flows through L2, producing an expanding magnetic field around it. This field, moving across coil L1, induces a voltage across it. If the top end of L1 becomes positive at this time, it has the effect of making the control grid positive. The grid draws current which flows down through R2, back to the cathode. R2 is essentially in parallel with C2, through the low resistance of L1. Consequently, C2 becomes charged by grid current flowing through R2.

In the meantime, the voltage across L1 has also charged variable tuning capacitor C1. The current, flowing through the tube, reaches saturation. This results in a steady magnetic field around L2 and so the induced voltage across L1 no longer exists. The tube remains momentarily cut off while C2 discharges through R2, continuing the bias voltage across R2. A current, known as tank-current, circulates between C1 and L1, as C1 alternately charges and discharges.

The bias voltage across R2 starts a decreasing current action through the tube. The magnetic field around L2, no longer steady, induces a voltage across L1, but with reverse polarity. The top end of L1, previously positive, now becomes negative. This negative voltage, applied to the control grid, rapidly drives the tube current into the cutoff region. The entire process then repeats.

ARMSTRONG OSCILLATOR

A low-frequency Armstrong oscillator containing very few parts is illustrated in Fig. 6-2. Even in this simple form, a strong 1,000 Hz note can be obtained for audio testing, code practice and so on.

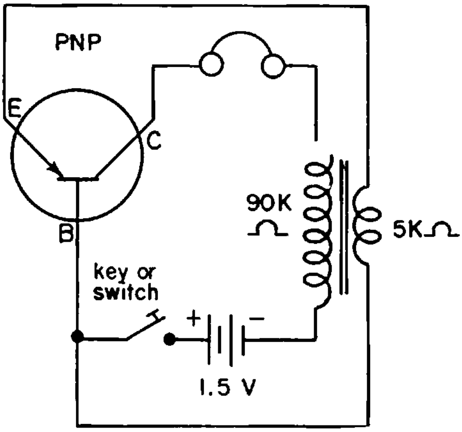


Fig. 6-2. A simple transistor oscillator.

Its operation may be described as follows: The complete DC circuit for the battery may be traced through the high impedance winding of the transformer (which may be anything from a 3:1 to a 6:1 interstage type), thence through the headphones and the collector-base circuit, back to the battery. When the key is depressed, a very small collector current surges through the 90k ohm transformer winding (Ico), inducing a voltage across the other winding which, in turn, produces a small current flow in the emitter-base circuit of the transistor.

If the secondary of the transformer is correctly phased, (its leads connected to the emitter and base in such a way that the induced voltage produces some forward bias), the emitter current will cause an increase in Ico by normal transistor action. As the collector current rises, the growing magnetic field will likewise give rise to increasing current in the collector circuit. Thus, the collector current surges upward, increasing until magnetic core saturation is reached.

At this point, any further increase of collector current cannot induce a further change of emitter current, so that a static condition is attained for an instant in which the currents in both circuits cease changing. Without a rise or fall of current, electromagnetic induction cannot occur; therefore, the emitter current (which has been sustained by electromagnetic induction) begins to drop off, causing the collector current to do likewise. The next half cycle begins when both emitter and collector currents reach and slightly pass their initial states. That is, the "inertia" of the collapsing magnetic field, as in vacuum tube oscillators, carries the collector current below its normal Ico value and, after the overshoot, Ico starts on its way back to its normal value again, causing the induced emitter current that starts the next cycle.

It is informative to correlate the action just described with the four basic "musts" for oscillators described in a prior paragraph.

(a) There is a tuned circuit. This consists of the inductance of the high impedance winding of the transformer and the distributed capacitance between its turns. An actual capacitor, added in parallel with this winding, is sometimes used to reduce the frequency of oscillation.

(b) There is amplification. The transistor is a current amplifier in this application.

(c) There is a positive feedback system. Feedback, as explained, occurs through the electromagnetic coupling between transformer windings. The feedback is made positive by connecting the secondary winding terminals to provide the correct phase of feedback.

(d) Self-starting is accomplished by means of the collector current surge when the switch is closed. Self-limitation is obtained by transformer core saturation, as explained previously.

A somewhat different arrangement of an Armstrong-type oscillator is shown in Fig. 6-3. Here, the transistor is arranged in the common-emitter circuit. A 220K resistor (R2) is employed to provide the small amount of base bias needed. The transformer (T1) is

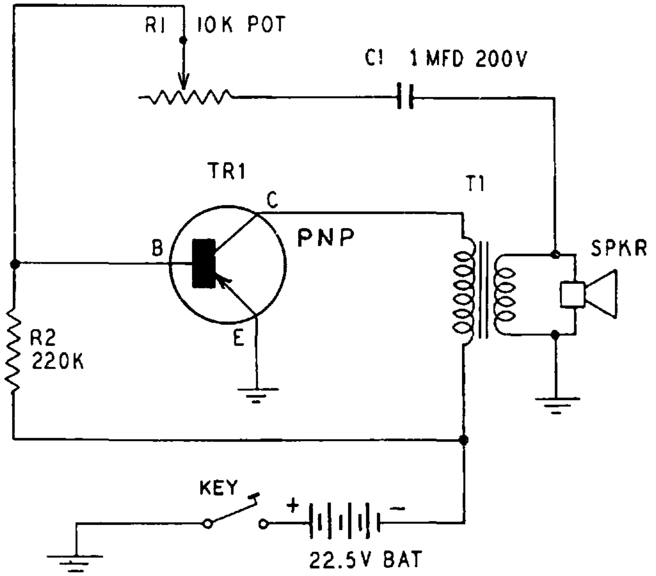


Fig. 6-3. Another simple transistor oscillator.

an output type with the speaker connected directly across the secondary winding. Positive feedback is obtained through normal transformer action, but in this case, a capacitor (C1) and variable resistor (R1) are connected in series in the feedback loop to control the oscillator tone (frequency). We vary the frequency in this circuit by changing the reflected impedance; a variation of R1 modifies the secondary impedance in the base-emitter circuit, causing the primary impedance to change as well. This makes the effective primary inductance different than it was before, resulting therefore, in a rising or falling tone, depending upon the direction of motion of the center arm of R1.

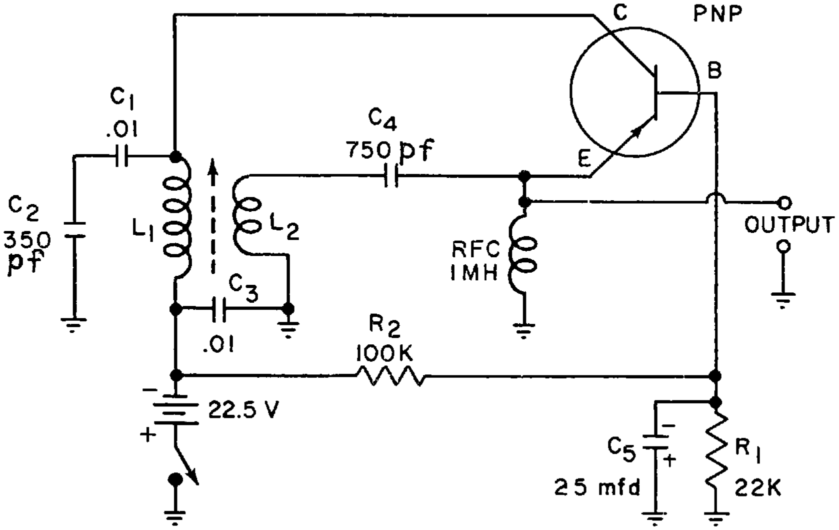


Fig. 6-4. An RF oscillator.

Fig. 6-4 illustrates a radio-frequency oscillator of the Armstrong variety. The operational theory is similar to the others just described, the difference being that the resonant circuit consisting of L1, a broadcast-band Ferriloopstick, and C2, can be set in the broadcast band or at the standard AM intermediate frequency (455 kHz). Adjustments for frequency changes are made by varying the position of the core in L1. The tickler winding, L2, is 7 turns of any type of wire and must, of course, be phased properly to sustain oscillation. Radio-frequency or intermediate-frequency output is taken as a voltage drop across the RFC in the emitter return lead.

COLPITTS OSCILLATORS

The standard Colpitts split-capacitor network, so common in vacuum tube oscillators, may also be adapted to transistor oscillators. In the Colpitts arrangement, feedback is accomplished by ca-

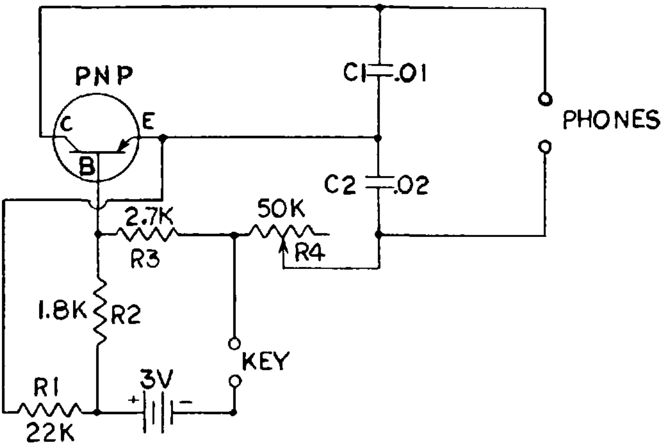


Fig. 6-5. A Colpitts-type transistor oscillator.

pacitive rather than inductive means. For example, in the circuit of Fig. 6-5, the headphones serve as the tuning inductance which is tuned by the two capacitors (C1 and C2) in series. The emitter, however, is connected to the junction of the two capacitors so that any oscillatory signal that appears across the tuned circuit is fed back to the emitter in the correct phase to sustain oscillation. Note that the emitter-base circuit is connected across C2 (through R4 and R3). Thus, an oscillatory voltage that appears across both C1 and C2 is divided into two parts, one of which is the feedback potential. In this oscillator, R4 serves as a tone control, with R1, R2 and R3 forming a voltage divider network for biasing the emitter-base circuit.

A similar Colpitts arrangement is used in the radio-frequency oscillator shown in Fig. 6-6. This circuit was originally designed as a 100 kHz frequency standard for use in calibrating receivers, but can be employed in any other application where a radio-frequency signal in this frequency range is required. R1 and R2 comprise a voltage divider that establishes the fixed base bias required in this common-emitter circuit; R3 provides temperature stabilization as described in Chapter 4; C4 and C5 are bypass capacitors that permit the tops of R1 and R3 to remain at ground potential, regardless of signal voltage drops that may appear across R1 and R3; the radio-frequency voltage drop across L1 permits the feedback voltage from C2 to appear at the emitter to sustain oscillation. C1 and C2 are in series and act as the "tank" capacitor. Capacitor C3 brings the bottom of L2 to ground potential for the oscillatory signal, thereby improving stability and reducing body capacitance effects. The circuit can be tuned by adjusting the iron core for L2, or for L3, or both.

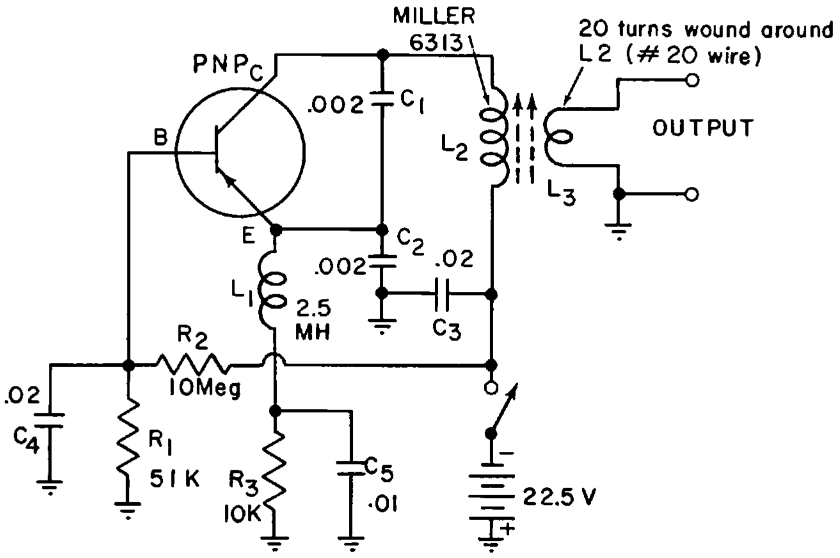


Fig. 6-6. A Colpitts-type 100 kHz oscillator.

An oscillator such as this is very handy as a calibrating device, despite the fact that it is not crystal controlled. With reasonable care, the oscillation frequency may be made the same as that of the 100 kHz signal from WWV by the common zero-beat method by means of the core adjustment on the oscillator coil.

THE HARTLEY OSCILLATOR

The basic Hartley oscillator, shown in Fig. 6-7, bears a strong resemblance to its vacuum tube counterpart. This transistor oscillator is also very similar to the Colpitts oscillator of Fig. 6-5. However, instead of using a split capacitor arrangement, the Hartley oscillator makes use of a tapped coil, L. While the tuning capacitor is across the entire coil, one part of the inductor acts as the feedback coil. The coil can be considered as consisting of two inductors, L1 and L2.

When the circuit is first turned on, current flows from the negative terminal of the battery, through L1, to the collector, through the transistor to the emitter, back to ground to the positive side of the battery.

The flow of current through L1 produces a magnetic field which cuts across L2 and induces a voltage in it. This results in an increase in forward bias, producing a further increase in collector to emitter current. When transistor current reaches saturation, the magnetic field around L1 becomes steady and no voltage is induced across L2. This results in a decrease in forward bias and so, the current through the transistor starts to decrease. The collapsing magnetic field around L1 induces a voltage of opposite polarity across L2. This voltage now opposes the forward bias, reducing the collector current still more. Finally, the transistor is driven into cutoff, and then the action repeats. As you can see, the action is quite similar to that described for the oscillator circuit of Fig. 6-1. Actually, the behavior of the Armstrong oscillator and the Hartley oscillator is very much the same, the essential difference being in the feedback coil arrangement.

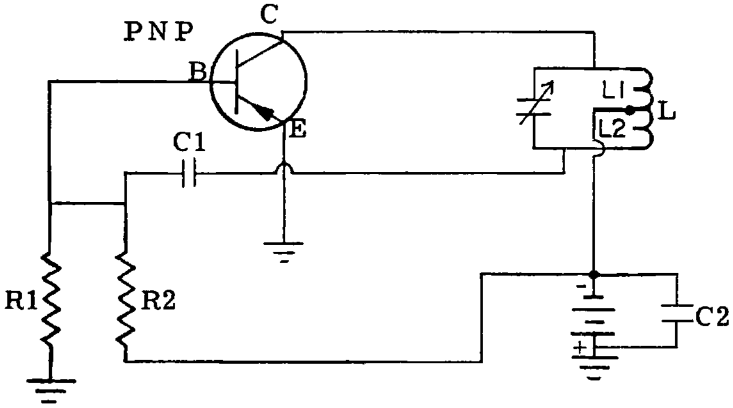


Fig. 6-7. A Hartley oscillator.

In Fig. 6-7, R1 and R2 supply the voltage divider arrangement for forward bias. C2, shunted across the battery and these resistors, helps keep this bias voltage steady.

MULTIVIBRATORS

A multivibrator is a resistance-capacitance (R-C) oscillator consisting of two amplifiers with a feedback loop from the output of one to the input of the other. The fundamental explanation of multivibrator action is more easily presented with vacuum tubes than with transistors, although the basic concepts may be carried over from one to the other with little change. Consider the circuit of Fig. 6-8. Assume for the moment that V1 and V2 are identical in every respect and that the plate current in each one is the same at the start. Let us further assume that a slight change in one of the tubes, say V1, causes it to draw a bit more plate current. As this occurs, the voltage drop across R1 increases slightly, the plate end of it becoming more negative than it was before. This negative-going voltage is transferred to the grid of V2 through C1, causing the plate current

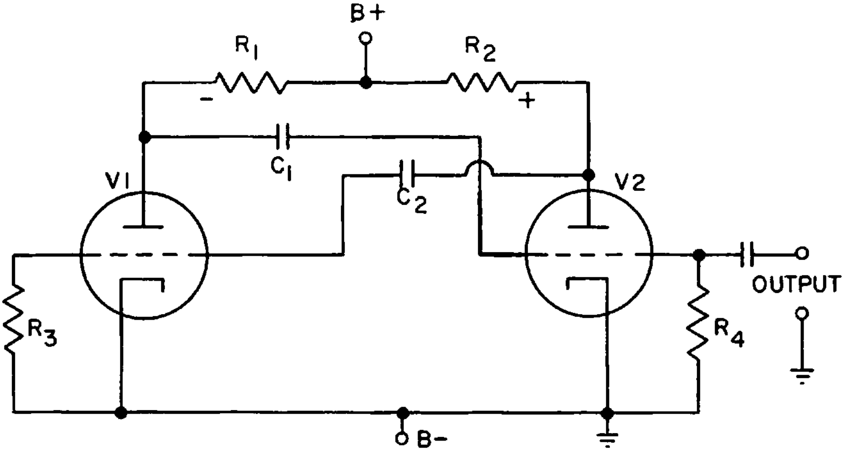
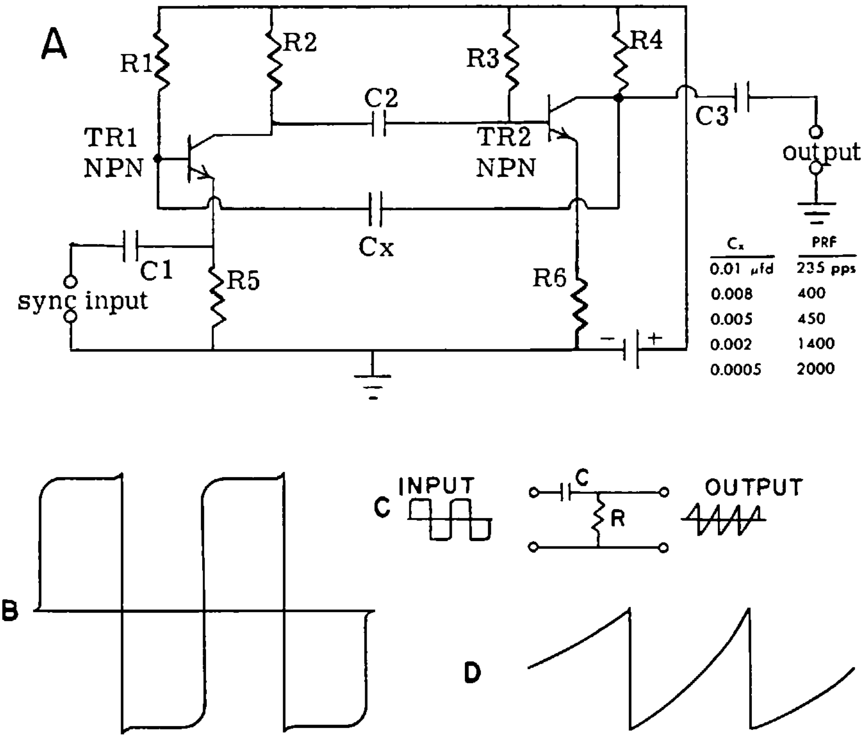


Fig. 6-8. Basic vacuum-tube multivibrator.

of V2 to decrease. The voltage drop across R2 decreases so that the plate end of it becomes somewhat more positive than it was. The positive-going voltage is now passed on to the grid of V1 through coupling capacitor C2, to produce a further increase of plate current in V1. This action should suffice to show that this is a form of positive feedback in which a change in the plate current of V1 affects V2 in such a manner as to cause it to force the plate current of V1 still higher. Similarly, as this action proceeds, the plate current of V2 drops lower and lower until it reaches zero. At the instant that the current in one tube drops to zero, any further changes cease and the cycle reverses. The current in V2 starts to climb, while that of V1 plunges downward. The back-and-forth action is due, of course, to the symmetry of the circuit.

The operation of a transistor multivibrator follows the same basic pattern. As in the tube circuit, the repetition rate of the seesaw action between transistors depends upon the values of the two grid resistors and coupling capacitors (R3, R4, C1, C2). In the practical transistor multivibrator shown in Fig. 6-9, it is found that the repetition rate may be changed over a wide range by merely altering the value of Cx. Thus, as shown in the table accompanying the figure, the pulse repetition frequency (PRF) may be varied between about 235 pulses per second and 2000 pulses per second, by substituting capacitors from 0.01 to 0.0005 µf. for Cx. Like vacuum-tube multivibrators, the transistor type may be synchronized by applying an external synchronizing voltage at the proper point (across R5 as given in the diagram). For reliable synchronization in this particular arrangement, the synchronizing voltage must have a peak value of at least 7.0 volts.

The output of a properly adjusted multivibrator approaches a



Cx	PRF
0.01 μfd	235 pps
0.008	400
0.005	450
0.002	1400
0.0005	2000

NORMAL OUTPUT OF
MULTIVIBRATOR APPROACHES
SQUARE WAVEFORM

SAWTOOTH WAVEFORM
AFTER DIFFERENTIATION

Fig. 6-9. A transistor multivibrator.

square waveform (Fig. 8-9B). This may be changed to a sawtooth waveform by means of differentiation circuits, like those used in television receivers. (Fig. 6-9C and Fig. 6-9D).

To assist in analyzing the transistor multivibrator, a table of corresponding components between the vacuum tube and transistor multivibrators is given below.

CORRESPONDING COMPONENTS

Fig. 6-8 Vacuum Tube Multivibrator	Fig. 6-9 Transistor Multivibrator
V1	TR1
V2	TR2
R1 and R2	R2 and R4
R3 and R4	R1 and R3
C1	C2
C2	Cx

Note that R5 and R6, used in the transistor circuit, do not appear at all in the tube circuit. It will be recalled that these resistors are inserted to improve the temperature stability of the transistors. Since temperature instability is not nearly as serious a problem with vacuum tubes and since resistors in the cathodes of the tubes would not improve stability, even if the problem were serious, these are not present in the tube circuit.

CRYSTAL OSCILLATORS

Quartz crystals, mounted in suitable holders, may act as either series resonant or parallel resonant components. Thus, a quartz crystal may be substituted for a tuned circuit or used in conjunction with it to form a highly stable oscillator. For example, the Pierce oscillator is one in which the crystal replaces the resonant circuit. In the standard crystal oscillator consisting of a tuned plate circuit and a crystal-controlled grid circuit, the crystal is used in conjunction with the resonant network. (This crystal oscillator is generally referred to as a Miller circuit, while its L-C counterpart is the familiar tuned-plate, tuned-grid type). Fig. 6-10 shows both the Pierce and Miller type circuits.

The Pierce oscillator is the crystal version of a Colpitts oscillator in which the interelectrode capacitances form the voltage divider necessary for capacitive feedback. The crystal replaces the tuned circuit. The blocking capacitor is necessary, of course, to prevent the positive supply voltage from reaching the grid of the tube. On the other hand, in the Miller circuit, the crystal is the resonant element in series with the grid, replacing the grid tank circuit of the tuned-plate, tuned-grid oscillator. In this case, the tuning of L

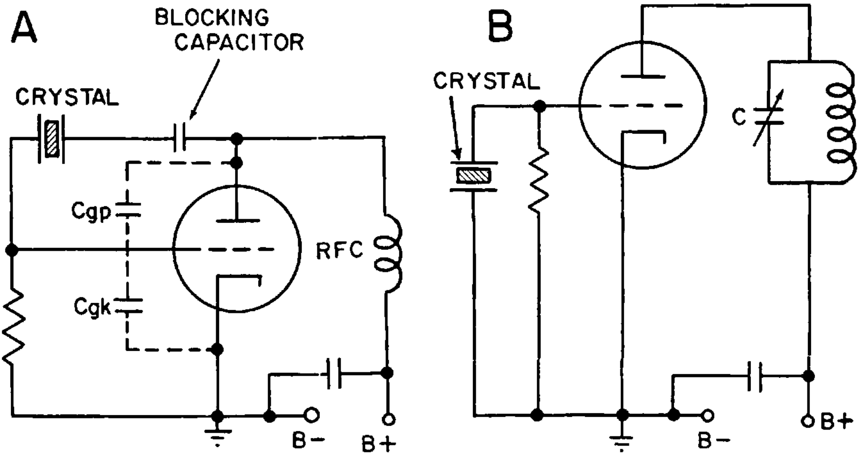


Fig. 6-10 (A) Pierce crystal oscillator. (B) Miller crystal oscillator.

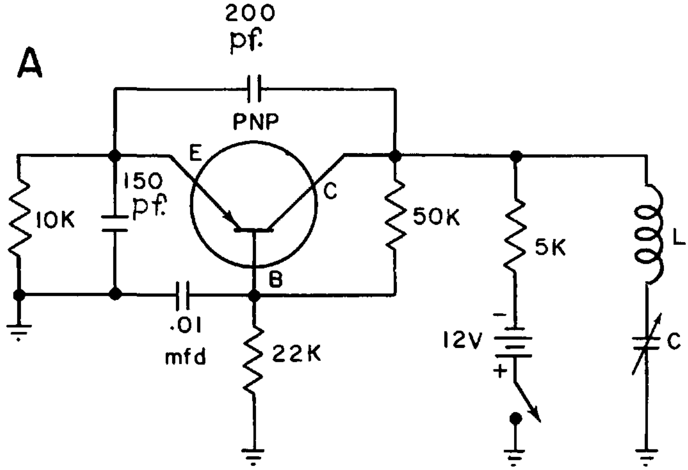


Fig. 6-11A. L-C Clapp oscillator.

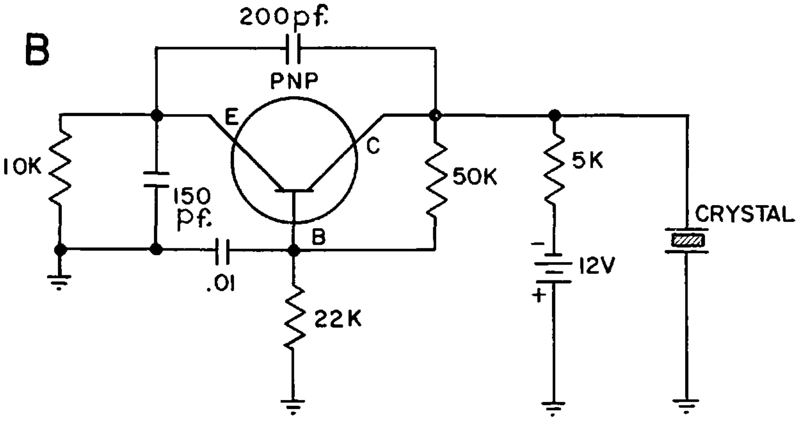


Fig. 6-11B. Crystal controlled Clapp oscillator.

and C must be such as to approach closely the natural crystal frequency. These oscillator types have been mentioned at this point because they are unquestionably the most familiar of all the varieties to radio amateurs, experimenters and hobbyists. Neither of these oscillator types, however, is easily adapted to transistor oscillator crystal control.

Somewhat less familiar is the Clapp oscillator. This type is very similar to the Colpitts; the major difference between them is the use of a series resonant, rather than a parallel resonant circuit for tuning. Since a crystal will behave either as a series or parallel resonant component, it may be substituted directly for the plate tank without any other alterations in wiring or parts values. Fig. 6-11 illustrates transistor Clapp oscillators in both forms. Feedback is provided by the voltage divider consisting of the 200 pf capacitor between collector and emitter, and the 150 pf capacitor from the emitter to ground.

Another form of transistor crystal oscillator has achieved widespread use. This one has no common counterpart in the vacuum tube field since the crystal is connected directly across the collector and emitter terminals. As is evident from the schematic diagram in Fig. 6-12, a tuned circuit in series with the collector lead is made resonant to the desired frequency; the RF voltage which appears across L and C in the collector circuit is fed back to the emitter via the crystal. Here again, the series-resonant characteristic of the crystal will pass only that RF signal which corresponds to its natural frequency. Thus, the emitter circuit is excited under controlled conditions. Bias is provided by the 750K resistor in the base lead. Both the bias resistor and the battery are heavily by-passed to permit the RF voltage developed across the tank circuit, to be applied between the collector and base with as little loss as possible. The bypass capacitor across the base resistor also helps in keeping the emitter RF voltage drop (that which develops across the RF choke) as large as possible.

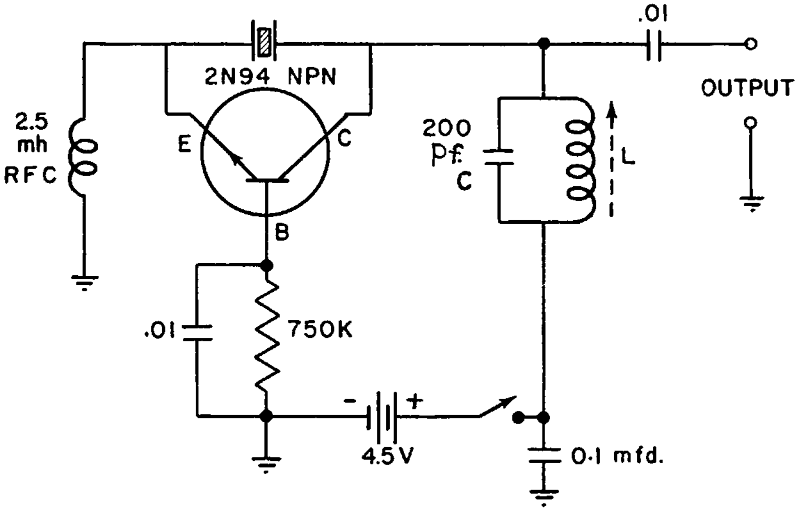


Fig. 6-12. A transistor crystal oscillator.

PHASE-SHIFT OSCILLATOR

There are several kinds of resistance-capacitance (no inductance) oscillator designs that are capable of providing sine-wave output. (The only R-C oscillator described thus far is the multivibrator which yields rectangular waves). Among the sine wave types are the Wien Bridge, the bridged T form and the phase-shift oscillator. The latter will be described here, since it is, by far, the easiest to understand and the simplest to construct. The following discussion is based upon Fig. 6-13 and Fig. 6-14.

A common-emitter transistor amplifier produces a 180° phase shift between the input signal to the base and output signal taken from the collector circuit. If we could now take the collector output voltage and re-invert its phase so that it could be fed back to the base-emitter circuit, such feedback would be in phase with the emitter signal voltage and oscillation will result. In the multivibrator, phase re-inversion is accomplished by passing the output signal from one transistor through a second transistor which adds another 180° to the phase-shift.

In the phase-shift oscillator, the same task is performed by a triple R-C combination, thus saving one transistor. Furthermore, the output of this oscillator is sinusoidal in contrast to the square-wave voltage available from a multivibrator. Let us refer first to Fig. 6-13A. An AC voltage is applied across the series combination of C1 and R1. The current flowing through the combination will lead the applied voltage by an amount determined by the ratio of the capacitive reactance of C1 to the resistance of R1.

The AC output voltage taken across R1 will be in phase with this leading current since resistors never produce a change of phase between voltage and current. Since the phase-shift caused by a simple circuit like this can be made to approach 90° by proper choice of C, R, and the frequency of the AC, there is certainly one specific frequency for which the output voltage leads the input voltage by exactly 60°. Let us now use the output voltage from R1 as input voltage to a second pair of R-C components, as in Fig. 6-13B. The double-phase-shift thus produced, results in an over-all change of 120° between the input voltage and the output voltage. Finally, with the addition of a third pair of R-C components, the output voltage phase and input voltage phase bear a 180° relationship, and the conditions required for in-phase feedback are met. (Fig. 6-13C). Since the transistor inverted the original voltage phase by 180° and the R-C phase-shifting network repeated the process, the total phase change is 360°. Thus, we have succeeded in obtaining a condition where the output can be fed back in phase with the input to sustain oscillation.

In the diagram of Fig. 6-14, C1, C2, C3, R1, R2 and R3 correspond to the capacitors and resistors of the same numbers in Fig. 6-13C. The selection of values for these parts was made on the basis of approximately 600 Hz oscillation. To raise the frequency, all three capacitors should be reduced in capacitance by the same

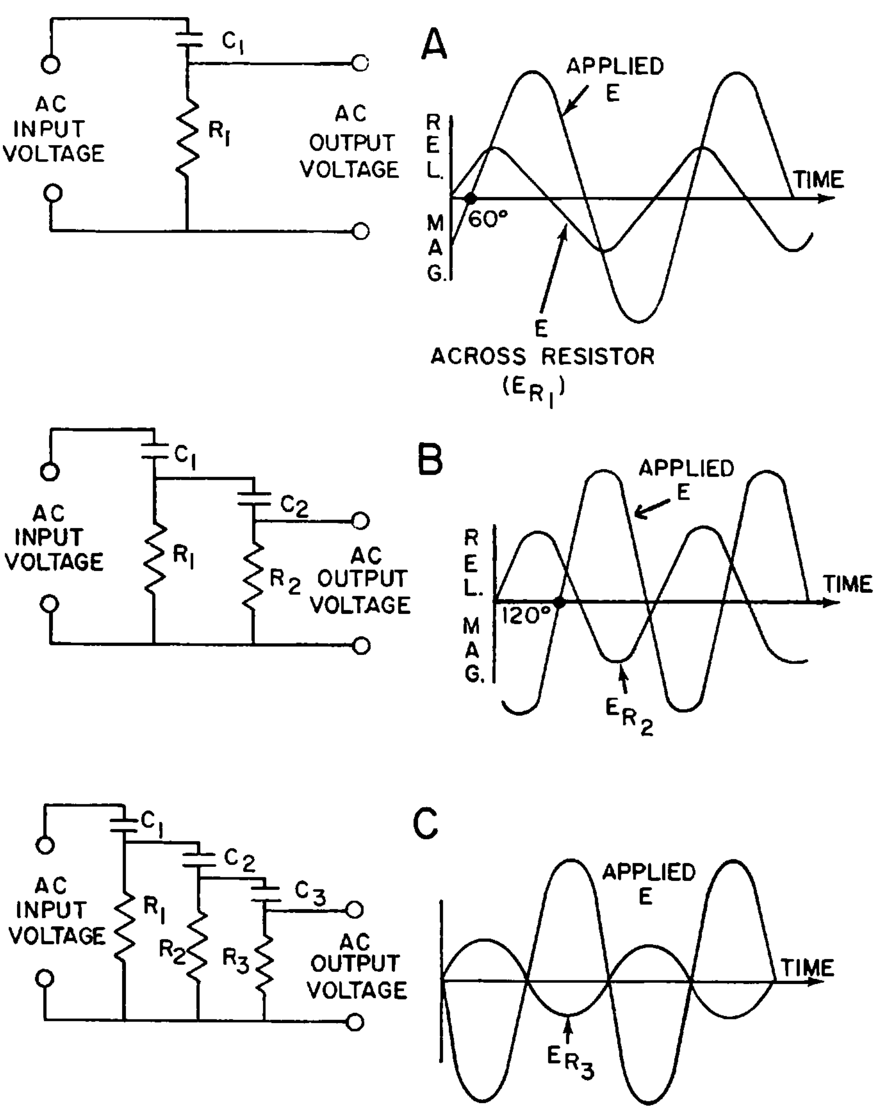


Fig. 6-13. Producing a 180° phase shift.

amount. For example, if C1, C2 and C3 are all changed to .002 mfd, the frequency of oscillation will be in the order of 2,500 Hz. Output voltage is taken from R5. Base bias is established by R4. The sinusoidal output from a phase shift oscillator makes it useful as a source of single frequency audio of pure waveform for amplifier testing. Also, this type of oscillator is substantially more stable than those utilizing transformers and inductances.

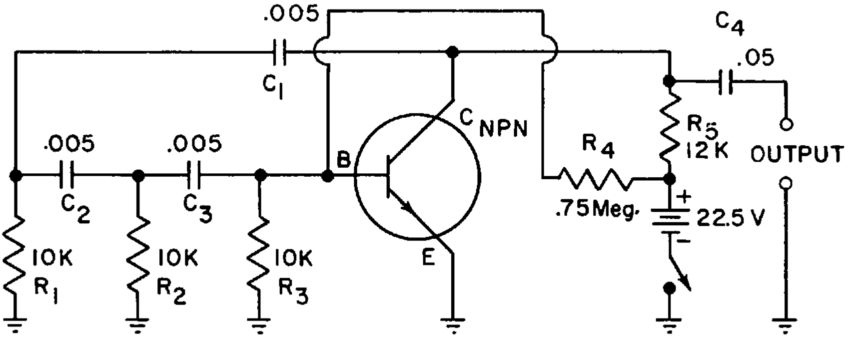


Fig. 6-14. A transistor phase shift oscillator.

DESIGN AND OPERATING PRECAUTIONS

Transistors are mechanically rugged and virtually vibration-proof; yet, they are sensitive to high temperatures and must be protected from damage due to improper operation. The experimenter would do well by checking the points listed below before applying power.

(1) Is the battery polarity correct for the particular transistor being used?

(2) Is the collector circuit loaded? That is, is there a power dissipating component in the collector circuit? If not, the transistor will be called upon to dissipate all the power present and may overheat.

(3) Is the base circuit biased correctly? Large bias resistors insure against cumulative build-up of collector and emitter currents.

(4) Have you provided for adequate heat dissipation? For voltage amplifier transistors, ventilation is important. Don't crowd everything into the tiniest spaces just to achieve miniaturization, unless you are sure that the transistors can get rid of their heat easily enough. When using power transistors, don't forget the importance of a good heat sink.

CHAPTER 7

TRANSISTOR APPLICATIONS

CONSTRUCTION

There are many advantages in working with diodes and transistors. They are small in size and their associated components are also small. Resistors may be rated at 1/4 watt and capacitors can be tiny because they are designed for low DC working voltages. This means that transistor projects can be constructed in a small amount of space. Since the projects are battery operated, they are readily portable.

One of the difficulties in constructing tube projects is that they involve a considerable amount of manual labor. These tube projects generally use a metal chassis. This meant drilling, reaming and bending metal, plus mounting sockets and terminal boards. All of this is eliminated when working with transistors. Instead of a metal chassis, you can use a pre-punched pegboard. Consequently, no holes need be drilled. Components can be mounted above the pegboard; all wiring can be done below it, using the nearest available holes in the pegboard for wires to pass through. Sockets are needed for power transistors, but all other transistors may be permanently soldered to their connections. No terminal boards are needed. Components such as relays or speakers must be firmly mounted, however.

For soldering, use a lightweight rosin-core solder and an iron rated at about 35 watts. When soldering transistors in place, use a heat shunt. This is just any mass of metal, attached to the lead of the transistor being soldered, and placed between the tip of the iron and the body of the transistor. For example, a pair of pliers whose jaws are kept closed by a rubber band, makes a very convenient heat sink.

Another advantage of working with semiconductor projects and pegboards is that the components may easily be disassembled and used over and over again for a variety of other projects.

This idea of the re-usability of components has been taken advantage of by a number of manufacturers who offer transistor project kits that enable the experimenter to construct as many as twenty or more transistor circuits. The advantage of a kit is that all components are supplied and so, there is no need for shopping. The disadvantage is that you are restricted to the projects the kit manufacturer describes. Some kits use small springs to which leads of parts can be attached. This eliminates soldering and makes kit assembly faster.

AVAILABILITY OF PARTS

There are thousands and thousands of transistors, all carrying different transistor numbers. It would be unreasonable to expect supply houses, such as electronics parts jobbers, to carry a full line in stock. Many transistors are directly interchangeable and actually differ only in the number that has been assigned to them. If you plan to substitute a transistor for one that isn't available, first make sure that it is the same basic type - that is, it should be a PNP if you need a PNP, and an NPN if you need an NPN. The next step is to make certain that the substitute transistor has electrical characteristics that are reasonably similar to the original, unavailable transistor. If you do not wish to bother checking transistor characteristics, you can obtain a transistor substitution manual. These manuals are obtainable in book form from electronics parts jobbers. Some semiconductor manufacturers also publish lists or charts of possible transistor substitutions.

The other components, such as capacitors, resistors, relays, phototubes, switches, etc. may also be replaced by substitutes or reasonable equivalents. The transistor projects described in this chapter aren't critical, and the tolerances are wide enough for you to make substitutions, should you need to do so.

PRACTICAL AUDIO AMPLIFIERS

HEARING AID

This is a transformer-coupled audio amplifier, employing three NPN transistors. An interesting difference between transistor amplifiers of this type and the corresponding vacuum tube amplifiers is evident in this circuit. It is the use of three 1.0 mfd coupling capacitors IN ADDITION to the transformers. The reason for this is as follows: A normal vacuum-tube voltage amplifier is biased by a cathode resistor, across which the bias voltage develops. In the case of transistors in a common-emitter circuit, forward bias must be applied to the base-emitter circuit; this bias potential must be obtained from the battery. For NPN transistors, as in Fig. 7-1, the base must be positive with respect to the emitter, and since the latter is connected to one end of the interstage transformer, the base must be isolated from it with respect to DC. This is accomplished by the 1.0 μf coupling capacitors.

The high impedance of the tiny crystal microphone necessitates the use of a step-down impedance matching transformer (T1) having an impedance ratio of 200 to 1. R3 and R4 (also R8 and R9) form a voltage divider network across the 1-1/2 volt battery, to provide stable base bias. R2, R7 and R11 permit a small amount of emitter degeneration to occur, thereby stabilizing the gain of the amplifier so that it will not change should transistors, having slightly different

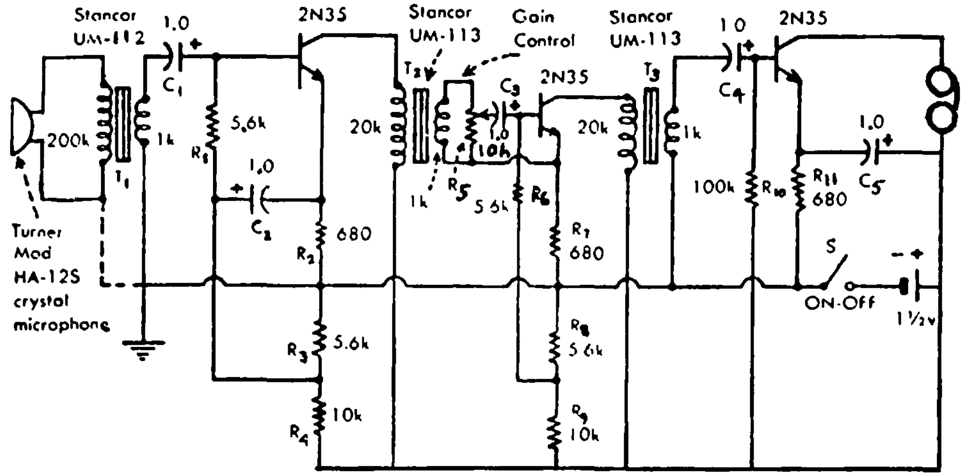


Fig. 7-1. Hearing Aid.

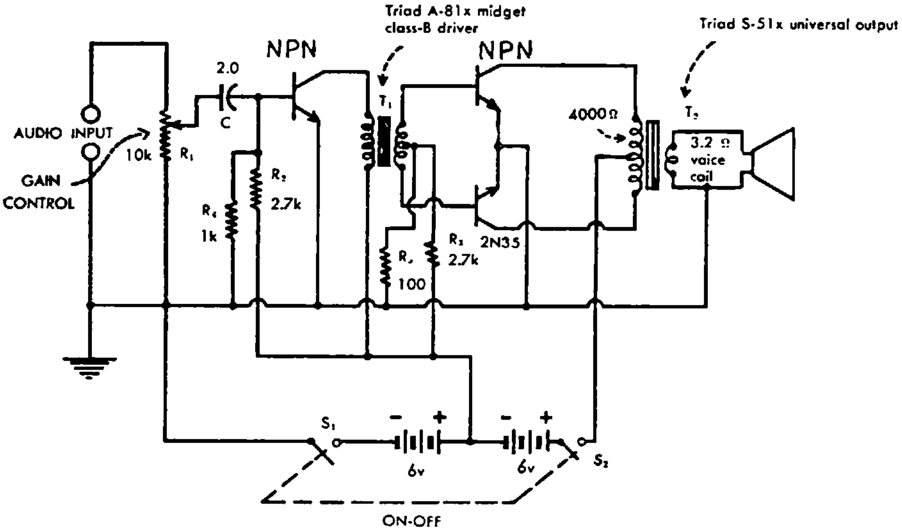
characteristics, be used. These resistors also help to reduce the detrimental effects of temperature variations.

The earpiece designated in the diagram forms a part of the collector circuit of the last transistor and acts as the load. Since it is in series with the collector electrode, collector current flows through it; hence it cannot be of the crystal variety. Capacitors C2 and C5 are emitter bypass units which do not permit the gain to be cut down too severely by the degenerative action of the emitter resistors.

Note the use of a single 1-1/2 volt cell. This may be of the penlite type and will give many hours of service.

50 MILLIWATT CLASS A SPEAKER AMPLIFIER

Fig. 7-2 shows a voltage amplifier using an NPN transistor, driving a pair of transistors in Class A push-pull in the output stage. This circuit was selected for discussion here because of the rather unusual manner in which biases are supplied. There are NO COUPLING CAPACITORS between the bases of the output transistors and the interstage transformer T1, as there were in the circuit of Fig. 7-1. These are avoided by using two batteries rather than one. The 6-volt battery on the left powers the single voltage amplifier, while the two 6-volt batteries in series supply collector-emitter voltage to the push-pull output stage (12 volts). The midpoint of the batteries, however, is connected to the push-pull bases through the voltage divider consisting of R3 and R5. In this manner, the bases are held positive with respect to the emitters - as required for forward bias in NPN transistors - without recourse to blocking capacitors. In the voltage amplifier, however, a 2.0 mfd blocking capacitor (C) is employed for the same purpose as those in Fig. 7-1. It is interesting



FREQUENCY (CPS)	50	100	500	1000	5000	10,000	20,000
RESPONSE (% of Maximum Voltage Output)	34.2	68.2	91	100	79.6	52.3	13.3

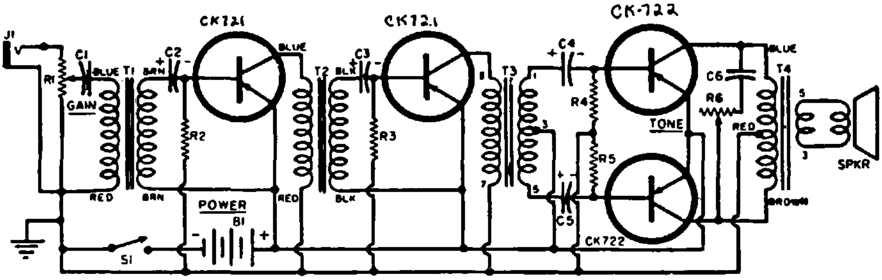
Fig. 7-2. 50 milliwatt Class A speaker amplifier.

to observe that voltage-divider, base-bias stabilization appears to be very popular in most audio amplifier designs.

This amplifier will drive a 12-inch speaker at medium volume. At full gain, the noise level is under 2.0 millivolts. This is a satisfactory figure for all but high-fidelity requirements. The frequency response is not as flat as we would like it, but could probably be substantially improved by using large size, high-quality transformers in the interstage and output positions. In all but high-fidelity systems, a high and low frequency response, equal to at least 70.7% of the mid-range gain, is considered adequately flat. In this case, therefore, we might say that the amplifier is flat from about 200 Hz to about 7,000 Hz.

GUITAR AMPLIFIER

The circuit illustrated in Fig. 7-3 is offered as a completely straightforward example of a transformer-coupled audio amplifier used for amplifying the sound output of a guitar. The microphone used in the original equipment had a relatively high impedance which is matched to the common emitter pre-amplifier stage through T1 (30,000-ohm primary to 50-ohm secondary). Neither emitter nor



R_1—2 megohm pot ("Gain" control)
R_2—560,000 ohm, 1/2 w. res. (see text)
R_3—2.2 megohm, 1/2 w. res. (see text)
R_4, R_5—18,000 ohm, 1/2 w. res. (see text)
R_6—25,000 ohm pot ("Tone" control)
C_1—.5 μfd., 200 v. metallized paper cap.
C_2, C_3, C_4, C_5—10 μfd., 25 v. elec. cap.
C_6—.05 μfd., 150 v. cap.
J_1—Open-circuit or closed-circuit jack (see text)
T_1—Sub-Ouncer trans. (UTC #SO-4, 30,000 ohm pri., 50 ohm sec.)
T_2—Sub-Ouncer trans. (UTC #SO-3, 25,000 ohm pri., 500 ohm sec.)
T_3—Ouncer trans. (UTC #SO-2, 10,000 ohm pri., 90,000 ohm sec.)
T_4—Universal audio output trans. (Stancor A-3856 or equiv.)
CK721—"p-n-p" type junction transistor (Raytheon) (two required)
CK722—"p-n-p" type junction transistor (Raytheon (two required)
B_1—6-volt battery (RCA Type VSO-68)
S_1—S.p.s.t. rotary sw.
Spkr.—6" PM loudspeaker

Fig. 7-3. A guitar amplifier.

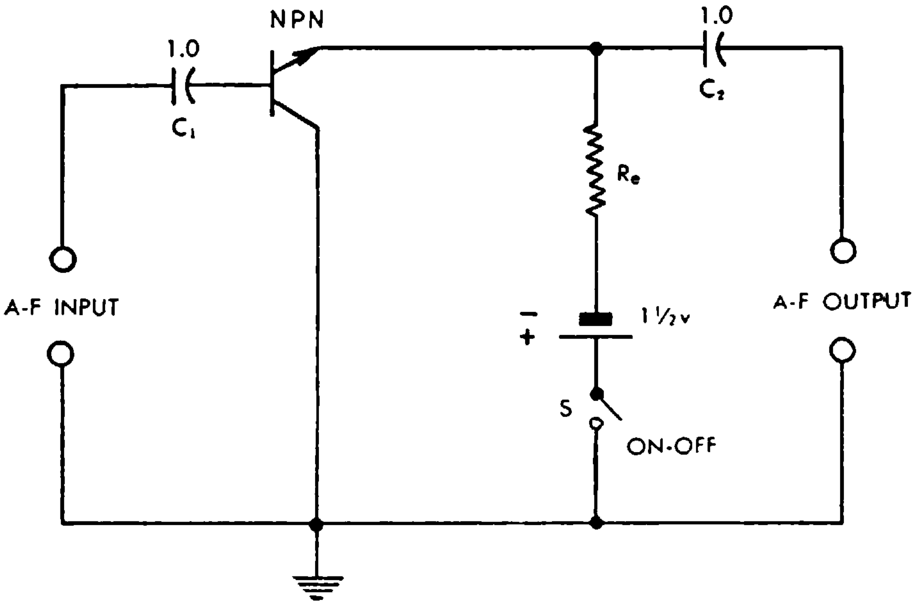
base stabilization is utilized. This suggests that this amplifier might be somewhat temperature and voltage sensitive.

Note the use of blocking capacitors (C2, C3 and C4) in ALL the base leads. As previously explained, these are necessary in all common-emitter amplifiers where a single battery supplies all the potentials needed for operation. C6 and R6 comprises a standard treble-attenuation tone control. The power output of this amplifier approaches 100 milliwatts, thus providing sufficient volume for SMALL audiences. Its power is limited, but it does have the advantages of light weight and portability.

COMMON-COLLECTOR PRE-AMP

A glance at the frequency-response chart associated with this circuit (Fig. 7-4) demonstrates why a common-collector transistor pre-amplifier is often to be preferred over an impedance matching input transformer. The response is remarkably flat from 50 Hz to 10, 000 Hz, making it well-suited for high fidelity input applications. Since this circuit has a high input impedance, the audio input may come directly from a crystal microphone, phono cartridge, or any other high impedance device. Although a common-collector stage has no voltage gain, a power gain of the order of 15 db may be anticipated.

In this particular circuit, high input impedance is insured by using a low collector voltage and a "floating base" arrangement. Observe that no DC bias is applied to the base since it is isolated from the DC portion of the circuit by C1.



Frequency Response

Frequency (Hz)	50	100	1,000	5,000	10,000
Response (% of Max.)	100	100	97.5	97.5	97.5

Fig. 7-4. A common-collector pre-amplifier.

The input impedance, output voltage and voltage gain are all affected by the size of the emitter resistor Re. The table of values, given below, is very helpful in selecting the exact input impedance desired. The output impedance of the common-collector stage is quite low and may be used to match the input impedance of a common-emitter stage connected to the terminals marked "AF OUTPUT".

Supply Voltage (d-c v)	Current Drain (d-c μa)	Emitter Resistor, R_e (ohms)	Input Impedance (ohms)	Input* Voltage (rms volts)	Output Voltage (rms volts)	Voltage Gain
1.5	40	50,000	100,000	0.40	0.38	0.95
1.5	42	25,000	100,000	0.42	0.40	0.952
1.5	90	10,000	100,000	0.41	0.38	0.928
1.5	120	1,000	40,000	0.10	0.071	0.71
1.5	125	500	22,000	0.052	0.027	0.52

Operating Characteristics of the
Common-Collector Preamplifier.

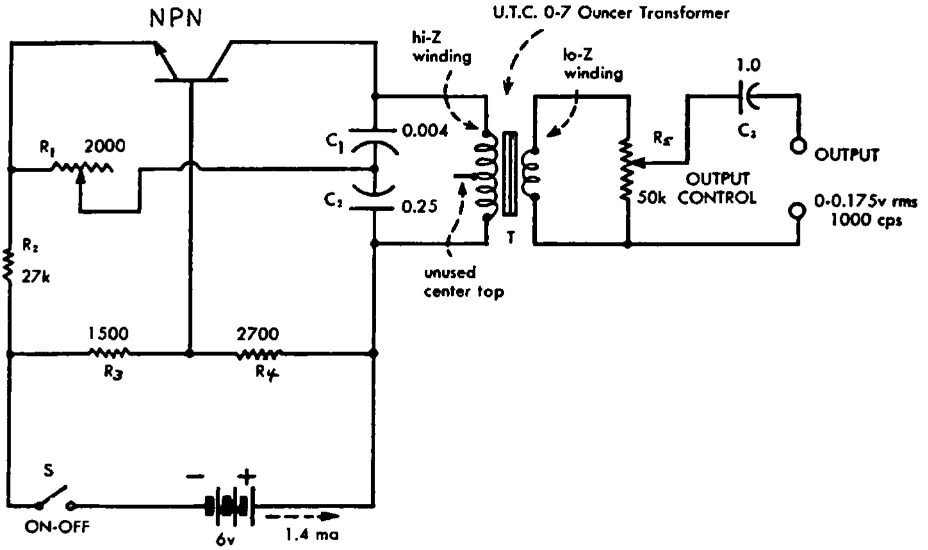


Fig. 7-5. Single-frequency sine-wave oscillator.

PRACTICAL OSCILLATOR CIRCUITS

SINGLE-FREQUENCY SINE WAVE OSCILLATOR

Oscillators of the type shown in Fig. 7-5 have many applications, particularly in test equipment. Excellent as an audio frequency signal injector, one recommended use of this oscillator is as a signal source for an impedance bridge.

Feedback for sustaining oscillation is obtained by means of a Colpitts-like capacitor regenerative system. Oscillatory currents flowing in the collector circuit, pass through the tank circuit, which consists of C1 and C2 in series and the high-impedance winding of the iron-core transformer. A small portion of the voltage drop across the tank coil (about 1/50) is fed back to the emitter from the junction of C1 and C2 through R1, to sustain oscillation. R2 is the emitter current-limiting resistor, while stabilized base bias is provided by the voltage divider made up of R3 and R4.

When capacitors having the values shown in the figure are used for C1 and C2, the oscillation frequency is very close to 1000 Hz. This may be varied slightly (from about 700 Hz to about 1400 Hz) by changing the value of C1. The open-circuit rms output voltage is rated at 0.175 volt maximum with a 6-volt battery and is determined by the adjustment of the output control R5. The feedback resistor, R1, is adjusted to give the best sine-wave as viewed on an oscilloscope. Note that this is a common-emitter circuit, despite the fact that the orientation of the transistor makes it appear as a common-base configuration.

100 KC BUREAU OF STANDARDS CRYSTAL OSCILLATOR

One of the most highly stable transistor crystal oscillators developed to date is that shown in Fig. 7-6. According to measurements carried on at the Bureau of Standards in Washington, D. C., the frequency is constant to approximately one part in 100 million per degree Centigrade. A variation of 0.1 volt in the supply potential causes a frequency shift of only one part in 100 million.

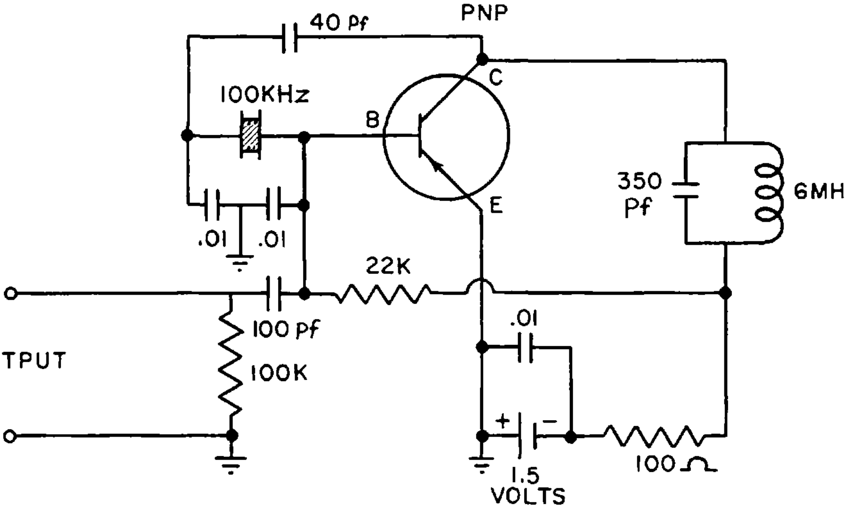


Fig. 7-6. A stable 100 kHz crystal oscillator.

As is evident from the circuit, the oscillatory voltage in this common-emitter configuration is developed across the 6 mh coil and 350 pf capacitor. This combination is in series with the collector. Oscillatory drive for the crystal is obtained through the 40 pf capacitor. The 0.01 μf capacitors connected to common ground from each side of the crystal assist in maintaining the phase-shift in the crystal feedback circuit constant. The resistor in series with the tank circuit and battery (100 ohms) is inserted for safety purposes; without it, the DC resistance in series with the collector would be virtually zero and the current would rise to damaging figures. Thus, the 100-ohm resistor serves to limit the DC flowing through the collector circuit at all times. DC base bias is applied to this electrode through the 22K ohm resistor. The output is taken from the base via the 100 pf capacitor, while the 100K ohm output resistor serves as a constant load on the circuit.

BEAT FREQUENCY OSCILLATOR FOR COMMUNICATIONS RECEIVERS

A beat frequency oscillator (BFO) is used for the reception of continuous wave (CW or code) radio transmissions. The frequency of the BFO is chosen so that an audible note is produced when the BFO is heterodyned with the intermediate frequency of the communications receiver.

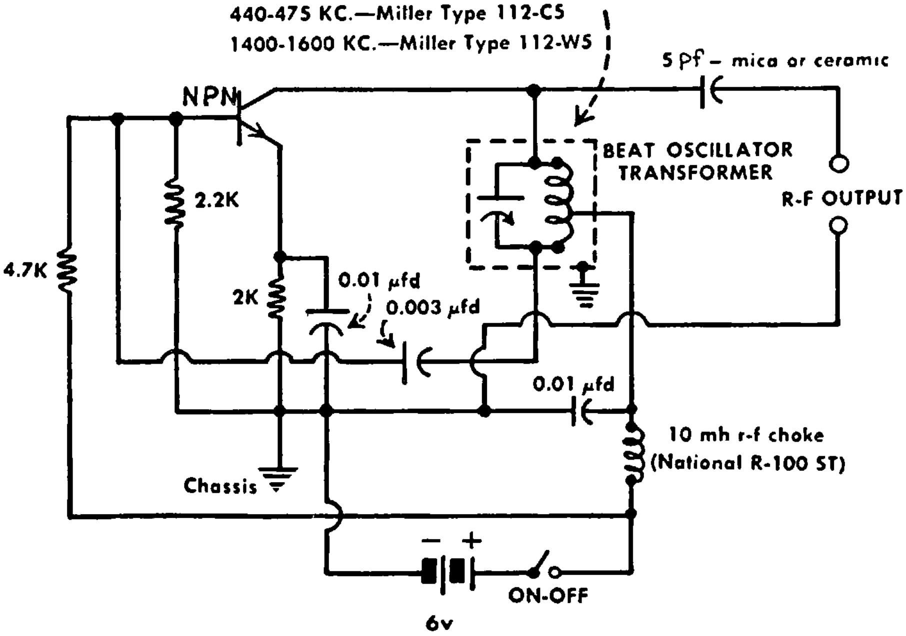


Fig. 7-7. BFO for communications receiver.

This circuit uses a Hartley-type oscillator in which the tank circuit forms a part of the collector return. Oscillatory voltage developed in the beat oscillator transformer is fed back to the base through the .003 μfd capacitor connected directly from the bottom of the coil to the base electrode. Stabilized base bias is available from the junction between the two resistors that comprise the DC voltage divider (4.7K and 2.2K). The RF filter, consisting of the 10 mh RF choke and the 0.01 mfd capacitor, prevents the return of radio-frequency energy to the battery. The 2K resistor, in series with the emitter, provides the customary emitter temperature stabilization and is bypassed with the 0.01 mfd capacitor to prevent degeneration. Output is taken from the collector through the 5 pf capacitor.

Note that two different types of BFO transformers are mentioned in the diagram. For a fixed-station communications receiver where the I.F. is 455 kHz (or similar), transformer No. 112-C5 would be used. In many mobile receivers using short-wave converters, however, an external BFO is called for, the heterodyne process taking place between the BFO and the second conversion I.F. of 1600 kHz. For such applications, the No. 112-W5 BFO transformer would be suitable.

Using a 6-volt battery, the total current drain through the transistorized BFO is only 2 milliamperes.

SENSITIVE R.F. RELAY

The circuit shown in Fig. 7-8 is a "natural" for any application in which a received R.F. carrier is to trigger a relay. Radio-controlled receivers, carrier-actuated systems such as Conelrad receivers and many other uses, immediately suggest themselves. The sensitivity is such that only 20 microamperes of DC output from the detector circuit are needed for relay activation. A single tuned RF amplifier (transistor or tube) preceding this stage, will supply enough RF from a normal broadcast signal to operate the system.

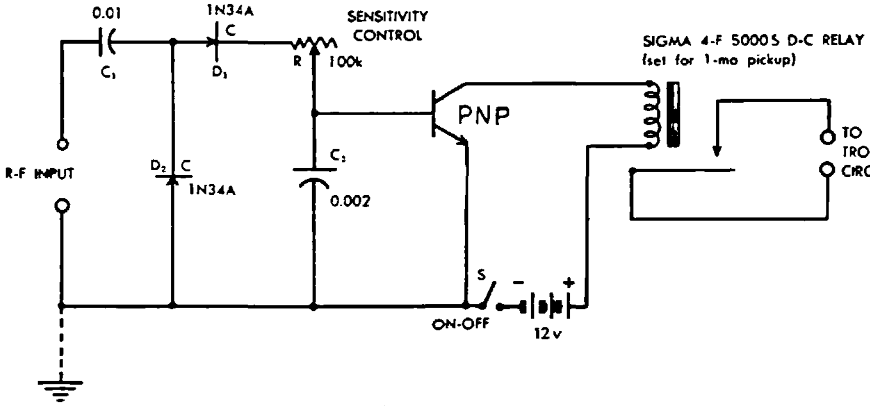


Fig. 7-8. A sensitive RF relay.

A standard shunt-diode circuit, consisting of diodes D1 and D2, make up the detector. C1 isolates the small diodes from any DC that might be present in the source from which the RF is taken. Excessive RF is prevented from reaching the base of the transistor by the filter network comprising the sensitivity control R and capacitor C2.

With no RF input, the base-emitter circuit is open (for DC) and the collector current Ico is very small, i.e., well below 0.1 milliampere. When a radio frequency voltage is impressed across the input terminals, the base of the transistor is driven positive by the rectified voltage coming from the diodes, thereby causing the collector current to rise sharply. The relay, a sensitive 1 ma pull-in type, is activated by the collector current and the controlled circuit is closed.

Virtually all trigger and relay circuits start with an open base-emitter circuit so that the standby collector current is negligible. This enables the designer to use a relay that can be adjusted to pull in at one milliampere or less.

The transistor shown in Fig. 7-8 is an NPN type. This circuit will perform just as well with a PNP transistor, provided that the polarity of the battery is reversed and the diodes are oriented in the circuit in the reverse direction. This will enable a negative DC voltage to appear at the base when the RF energy is received.

TIMER FOR PHOTO ENLARGING

Most good darkrooms are equipped with some form of electronic timing device to extinguish the enlarger lamp after a pre-determined exposure time. Such devices, once calibrated, retain their precision over long periods of time because they are designed with long-lived and reliable timing elements. Among their disadvantages, however, are their relatively high cost and their heating effects in small, closed darkrooms. The need for an AC line cord is often inconvenient as well.

The transistorized photo-timer, illustrated in Fig. 7-9, operates without heat and contains its own power supply. This eliminates the disadvantages mentioned above. On the other hand, since its operation depends upon a slowly decreasing base current supplied

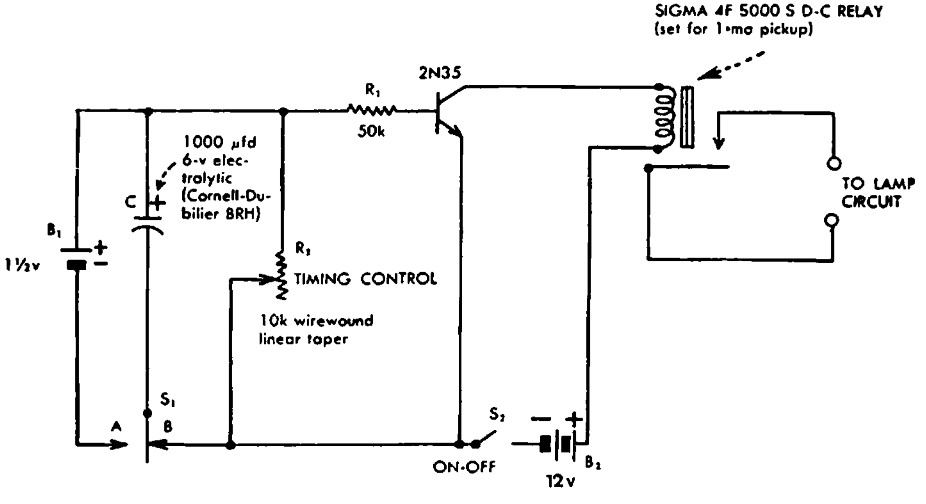


Fig. 7-9. Photographic enlarger timer.

solely by a capacitor, the latter must be of very high capacitance; hence, it must be an electrolytic type. Such capacitors are not nearly as dependable as oil-impregnated paper varieties used in tube timers. The transistor type timer must, therefore, be periodically recalibrated. Since this is a relatively easy procedure and often worth the trouble to obtain the advantages mentioned, many amateur photographers are using transistorized timers such as the one shown here.

Switch S1 is a spring-loaded pushbutton normally in position B. In this position, the base is floating with respect to DC and the current in the collector circuit is too small to energize the relay. To start the timing interval, the button is momentarily depressed, causing C to charge to 1-1/2 volts from B1. Upon the release of the pushbutton, discharge current begins to flow from C through both R1 and the base-emitter circuit and through the timing control R2. R1 limits the base current to a safe value during the initial portion of the discharge period since the fully charged capacitor would supply an excessive amount of current if R1 were omitted. As soon as the base current commences to flow, the collector current rises enough to pull in the relay and the enlarger lamp goes on. Gradually, as the charge on C is dissipated through the parallel paths mentioned above, the base current slowly decreases until the accompanying collector current can no longer hold the relay down. This is the end of the timing interval.

Selectable timing periods are obtained (from 1/2 to 30 seconds) by adjusting R2. As R2 is made smaller in resistance, C discharges faster, thus shortening the timing interval. The relay of Fig. 7-9 normally comes from the factory adjusted for 1.6 ma pull in. It is provided with a spring tension screw, however, which permits reducing the activation current to 1 ma. This is necessary because a 12-volt source would have difficulty in supplying much over 1 ma through the relay and collector circuit resistance.

SELF-CONTAINED RAIN DETECTOR

A rain detector is a device that will sound an alarm the instant a few drops of rain fall. It warns the housewife to take the clothes from the washline or to close the windows in vulnerable parts of the house. It can also be used to detect basement condensation, as well as an overflowing washing machine. The circuit for such a device is shown in Fig. 7-10. Completely self-contained, its audio oscillator produces a sharp, loud tone when the sensor becomes wet. The sensor consists of several pieces of aluminum foil, cemented to a small piece of masonite, with alternate strips connected in parallel. The strips should be spaced no more than 1/32" apart. The relay should be a sensitive type with a 5, 000 ohm coil and a pull-in

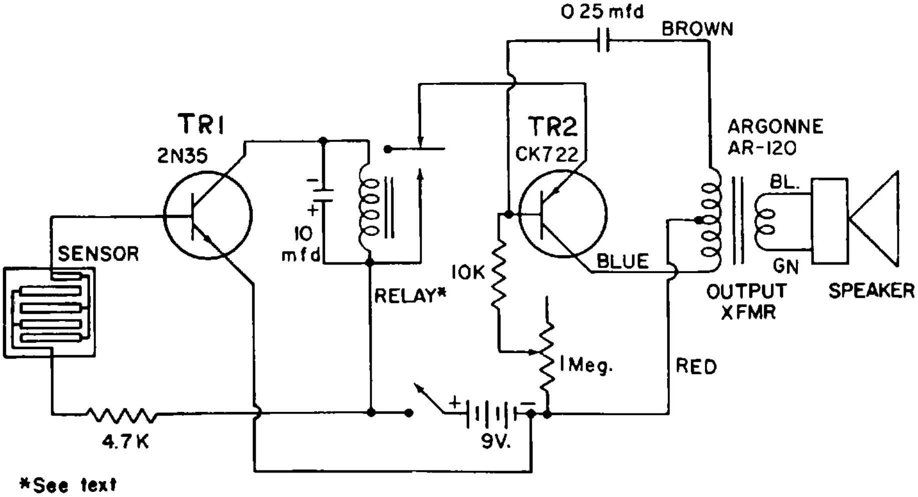


Fig. 7-10. Self-contained rain alarm.

rating of 1 ma or less (such as the Advance type 1, 200).

The first transistor (TR1) is wired as a DC amplifier to provide the necessary sensitivity. As long as there is no continuity between sensor strips, the base circuit is open and the collector current very small. The slight conductivity of pure water across the strips is sufficient to apply a positive voltage to the base, thereby increasing the collector current enough to pull in the relay armature. Contact of the relay arm with the bottom point then connects the emitter of the second transistor (TR2) to the positive end of the battery, completing the collector circuit. This transistor, with its associated components, is wired as an audio oscillator. The 1 megohm potentiometer controls the tone of the output sound.

A few words might be said about this oscillator circuit. Its closest vacuum tube counterpart is the familiar blocking oscillator used in television receiver sweep circuits. As in the Hartley oscillator, feedback to the base occurs through the center tap of the primary winding of the transformer. In a blocking oscillator of this type, the collector current is held at cut-off by the charge developed across the 0.25 mfd capacitor. Since the capacitor can discharge through the transformer and the 10K and 1 megohm resistors, this charge gradually leaks off. When enough of it has disappeared, the circuit breaks into oscillation as a normal Hartley type, but this oscillation is short-lived because in a few cycles, the charge on the capacitor is again built up to cut-off value. Thus, a blocking oscillator starts and stops at a frequency determined by the resistance in series with the capacitor and the value of the capacitor itself. The inductance of the transformer primary has little to do with the frequency in this case.

PRACTICAL INSTRUMENTS

MICROAMMETER FOR DC MEASUREMENTS

One of the most valuable applications of simple transistor circuitry lies in extending the usefulness of existing instruments. Fig. 7-11 shows a microammeter circuit with a range of 0 to 20 microamperes, in which the basic meter movement is an inexpensive 0-1 milliammeter. This current gain corresponds to a beta of 50, which is not at all difficult to obtain with standard transistors.

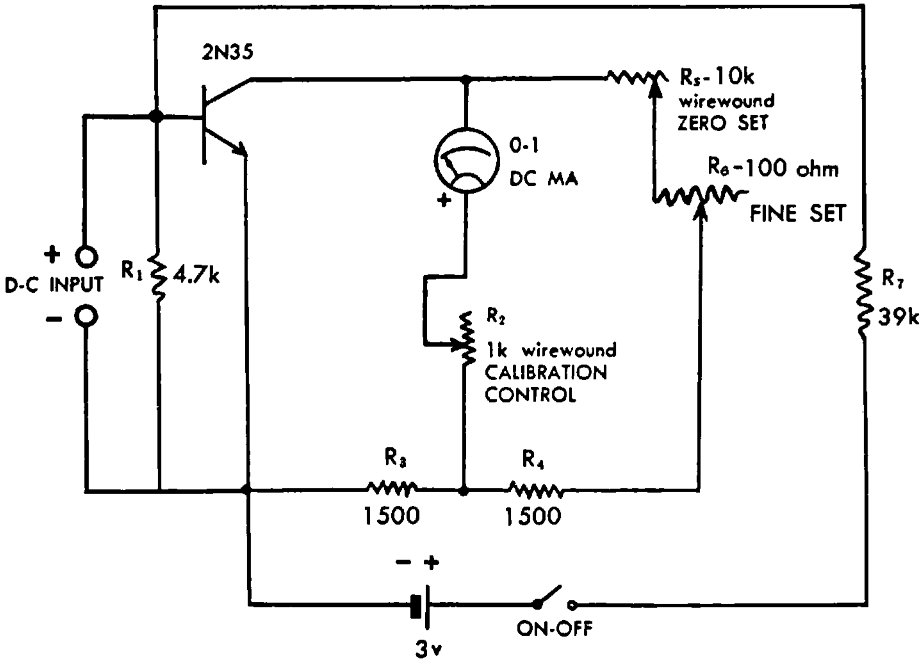


Fig. 7-11. A microammeter for DC measurements.

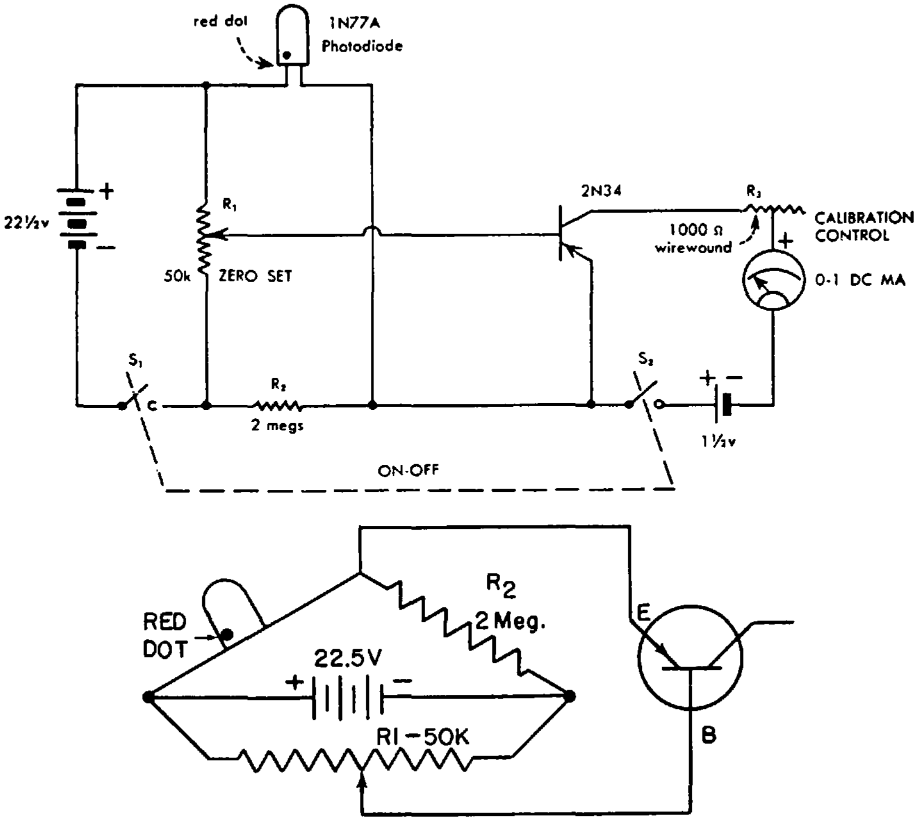
When no voltage is applied to the input terminals, a small static current flows in the collector circuit, causing the milliammeter to show a reading that has no meaning insofar as the application of the instrument is concerned. In this circuit, the static current is balanced out electrically by means of the bridge arrangement consisting of four arms: the collector resistance, R5 + R6, and each of the two 1500 ohm resistors (R3 and R4).

Adjustment is made as follows: With zero input and the input terminals open, R5 and then R6 are carefully adjusted so that the milliammeter reads zero. A voltage, large enough to produce about 20 microamperes, is then applied (approximately 0.15 volts) to the input terminals and R2 adjusted for a full-scale deflection. The input terminals are again opened and the bridge readjusted for a zero reading once again. By alternating these two adjustments several times, settings will be obtained that will give zero and full-scale deflection reliably each time the instrument is used. R1 and R7 form the familiar voltage divider for stabilized base bias.

LIGHT METER

Light meters are useful in the home, factory and office to determine whether or not the illuminated levels are adequate for the kind of activity entailed in these places. Illumination level charts are easily available; these provide detailed information relative to light values required for minimum eye-strain and maximum safety. Since commercial light meters usually contain a sensitive microammeter movement, they are expensive and delicate.

The light meter illustrated in Fig. 7-12 makes use of a rugged 0-1 milliammeter. Only 70 foot candles of light will produce a full-



RE-DRAWN BRIDGE CIRCUIT

Fig. 7-12. A sensitive meter with a rugged indicator.

scale deflection. A photodiode, two batteries and three resistors are arranged so that light falling on the photodiode increases the forward bias of the transistor sufficiently to give full-scale deflection for this low light intensity. The milliammeter is connected in a bridge circuit to permit a zero adjustment of the instrument when no light falls on the photodiode. The bridge arrangement is easily seen by redrawing it as shown in the insert in Fig. 7-12.

The instrument is adjusted in the following sequence:

(1) With no light reaching the photodiode, set the balance potentiometer R1 for minimum meter deflection.

(2) Since ordinary frosted incandescent lamps produce about 2/3 of a candlepower per watt, to obtain 70 foot-candles falling on the photodiode, set a 60 watt lamp about 10 inches away from it.* R3 may then be adjusted for full-scale deflection of the meter.

The photodiode is equipped with a built-in lens and it can be mounted in any small cylindrical probe, such as the case of a mechanical pencil.

FIELD STRENGTH METER

This instrument is an interesting combination of a transistorized DC microammeter and a resonant diode detector. Its sensitivity is high, permitting amateur antenna adjustments to be carried on at reduced transmitter input. (See Fig. 7-13).

The rectified radio frequency signal picked up by the plug-in coil, is filtered by C2 and applied as a DC voltage to the base-emitter circuit of the transistor. The rectifier is polarized so that the potential at the base is positive with respect to the emitter, thereby adding to the forward bias of this NPN unit. With the collector current first adjusted so that the milliammeter reads zero without signal input, this increase in base forward bias will cause a positive collector current that can be read on the milliammeter.

A short length of stiff wire serving as the antenna will usually suffice, even for low-powered transmitters. The instrument requires only 100 millivolts of RF input for full-scale deflection, thus providing extremely good sensitivity. Without calibration, the field strength meter provides only comparative readings of field strength; this is usually all that is desired for adjusting beam antennas.

MEASUREMENT OF THE FREQUENCY OF AUDIO SIGNALS

The instrument illustrated in Fig. 7-14 combines many unusual

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* A 60 watt lamp produces about 40 candlepower of emission. Since the intensity of light is governed by the inverse square law, then distance equals the square root of candle power divided by foot-candles desired. This is 0.84 feet or close to 10 inches.

COIL TABLE

BAND	SPECIFICATIONS
14 Mc.	11 turns No. 22 enamelled wire on 1 -diam. form. Space ½ .
28 Mc.	5 turns No. 22 enamelled wire on 1 -diam. form. Space ¼ .
50 Mc.	5 turns No. 22 enamelled wire on ¼"-diam. form. Space ¼ .
144 Mc.	3 turns No. 20 enamelled wire airwound ¼ -diam. Space ¼ .

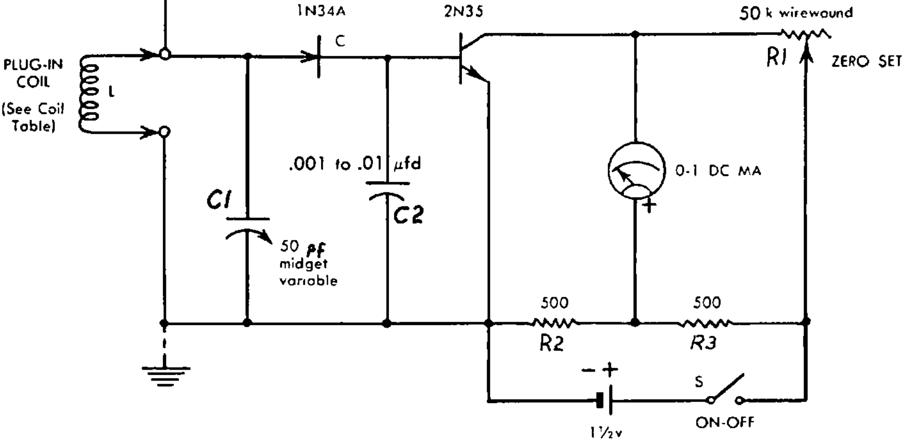
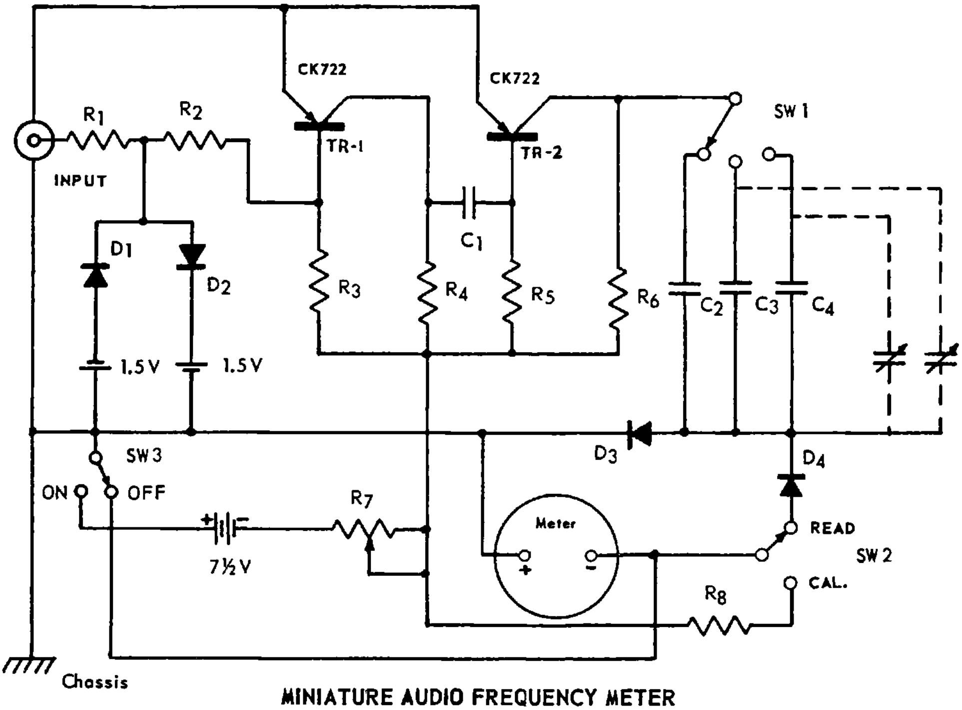


Fig. 7-13. Field strength meter.

functions of both diodes and transistors. The input signal whose frequency is to be measured, is applied to a clipping circuit consisting of R1 and the two diodes (D1 and D2) with the 1.5-volt batteries in their return leads. The input voltage across these biased diodes cannot exceed 3 volts peak-to-peak because, when it tends to rise above this value, the diodes conduct and effectively short-circuit the input voltage. Thus, the input transistor cannot be overloaded by the signal. (Despite the unusual method of drawing, the transistors are actually hooked up as a common emitter).

The first stage functions as a limiter amplifier. A small bias (negative) is supplied to the base of this stage through R3, and its collector current is quite small. The forward bias on TR-2, however, is much greater so that about 140 microamperes of base current flows. The collector current of TR-2 is therefore quite high -- approximately 2 ma --- resulting in a large voltage drop across R6, about 6.6 volts. Since the supply voltage is slightly greater than this, the potential across the discharge capacitor (C2, C3 or C4, depending upon the position of SW1) is quite small.

When the positive half-cycle of the signal potential reaches the base of TB-1, its collector current rises, causing a positive pulse of voltage to be transferred to the base of TR-2 through C1. This



MINIATURE AUDIO FREQUENCY METER

PARTS LIST

Chassis	"Channel-Lock" Box, 5x4 x3 inches
J_1	Amphenol 75-PCIM
D_1, D_2, D_3, D_4	CK706 or CK705 Raytheon Germanium Diodes
P_1, P_2	CK722 Raytheon Junction Transistors
M_1	0-100 Microammeter, Triplett, type 321-T
SW_1	Centralab S.P. 3 Pos. Type 1461
SW_2, SW_3	Wirt S.P.D.T., Type 724
R_7	Centralab Type B, 500 ohms
C_1	0.1 MFD., Sangamo "Redskin" 400 volts
C_2	.05 MFD., Sprague 400 volts
C_3, C_4	.005 MFD. and 500 MMF. Centralab TCZ

All Resistors ⅓ watt
IRC Type BTR

R_1	15,000 ohms
R_2	8,200 "
R_3	0.1 meg.
R_4	12,000 ohms
R_5	47,000 "
R_6	3,300 "
R_8	0.1 meg.

Fig. 7-14. Measurement of the frequency of audio signals.

pulse is in the nature of reverse bias for TR-2, so that its collector current drops sharply and the discharge capacitor can charge through R6. On the next half of the input cycle, C2 (or C3 or C4, depending on the setting of SW1) can discharge partially through the meter movement, causing the needle to register a reading.

The natural damping of the meter adds up the unidirectional charging pulses to give a steady reading, which depends upon the frequency of the pulses in a linear manner. The meter may be marked off up to 30 Hz, so that the amount by which the scale reading is to be multiplied depends only upon the size of the discharge capacitors. In the original instrument, C2, C3 and C4 were selected to have the ratio of capacitances equal to 1:10:100 as measured on a bridge; slight changes in their capacitances were obtained by small trimmers in parallel with them. This ratio then provides multiplication factors of 10, 100 and 1000 for switch positions 1, 2 and 3, respectively.

The precision of this instrument depends, in some measure, on the constancy of the supply voltage. To make certain that a constant voltage is always used, SW2 is thrown to the CAL. side and R7 adjusted so that the meter reads a predetermined value selected when the instrument is first calibrated. Switch SW3 serves to open the battery circuit in its OFF position and it also short-circuits the terminals of the meter. This provides heavy damping on the movement so that it is less likely to be damaged during transportation.

RADIO RECEIVERS

TWO-TRANSISTOR POCKET RADIO RECEIVER

Although a radio receiver can be constructed around a single transistor, its performance can be substantially improved by making

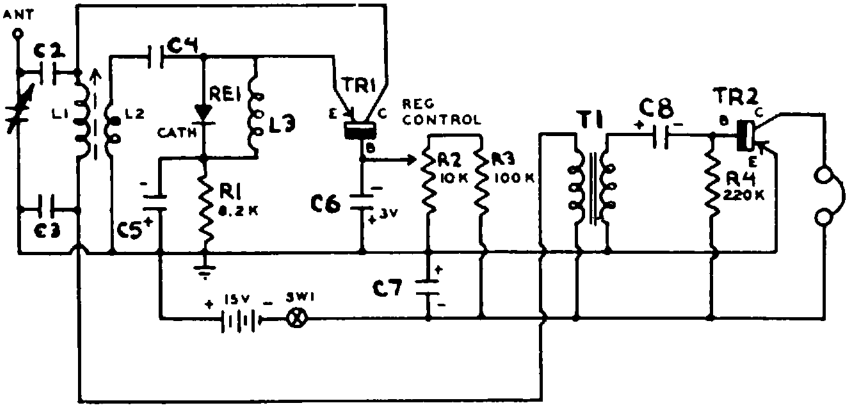


Fig. 7-15. A two-transistor pocket radio receiver.

the detector regenerative and adding an audio amplifier. These are the features of the receiver shown in Fig. 7-15.

Let us follow an RF signal through the receiver. The signal enters the antenna and is fed into L2 from L1 by transformer action. The signal then passes through C4 (a blocking capacitor performing the usual function of preventing the DC bias from being short-circuited) to the diode, RE-1 and the emitter of TR-1. Now consider what happens at the emitter first: The RF choke, L3, prevents the RF from passing into ground through C5, the radio-frequency voltage drop across it being applied between the emitter and base. This radio-frequency energy is amplified by the transistor and then transferred back into L1 in the proper phase to produce regeneration and increased amplification.

Now, let us trace the radio-frequency signal through the diode. As the RF is rectified by the diode, capacitor C5 develops a voltage drop across it which varies with the modulation. Thus, RE-1 behaves as a diode detector, with the audio voltage appearing across C5. This voltage is transferred through the RF choke, L3, to the emitter, where it varies the emitter bias. This causes the base-emitter current to change in accordance with the modulation.

The question will arise as to why C5, a large electrolytic capacitor, does not by-pass all the audio to ground. If this were a vacuum tube circuit, this is exactly what would happen. In this case, however, the emitter circuit (in parallel with the capacitor) has a LOWER IMPEDANCE than C5 for all but the highest audio frequencies. The result is that audio currents flow through the emitter rather than C5, causing the collector output current to vary with the modulation.

The demodulated signal in the collector circuit then goes to the primary of T1, an interstage audio transformer. Following this, it is amplified by the second transistor TR-2 and sent on to the headphones.

REMOTE CONTROL RADIO RECEIVER

The receiver in Fig. 7-16 is designed to control rudder motions and wing motions on model planes. It may also be used for controlling the steering of a model boat or car. The transistor is used in a basic grounded-emitter circuit, capacitively coupled to a gas-tube detector (RK-61 or equivalent). The receiver operates on the popular citizens' band of 27.255 Mc.

When its associated transmitter is keyed, the reception of an RF signal at the resonant circuit (L1, C1) causes an increase in gas-tube current. This augmented current, flowing through L2, down through R3 and R2 and back to the 45-volt source, develops a negative voltage at the top of R3 so that the base current of the transistor

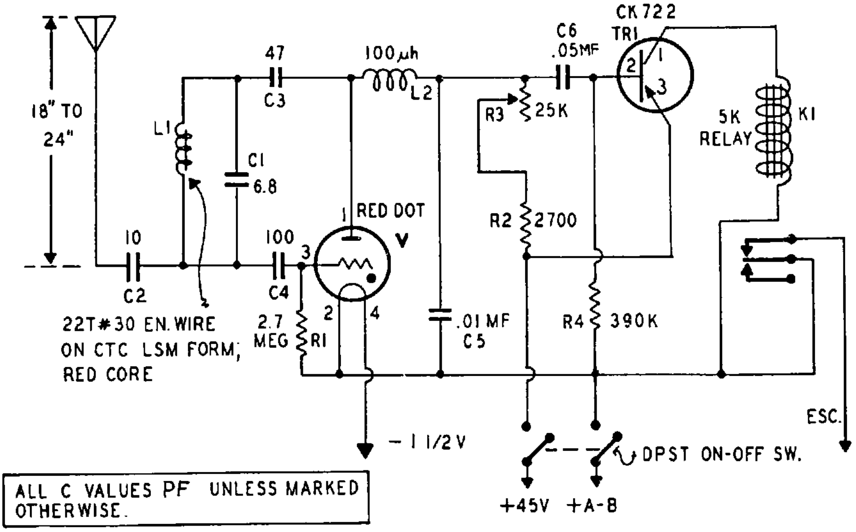


Fig. 7-16. Remote control radio receiver.

increases. The resulting increase in collector current pulls in the relay and operates the escapement. The latter is connected to the controlling surfaces in the plane or boat. The relay used in this equipment is a 5,000 ohm sensitive type, having a 1.0 ma pull-in rating.

SIX-TRANSISTOR BROADCAST RECEIVER

A piecemeal analysis of the circuit in Fig. 7-17 would be too lengthy and time consuming. It is unnecessary, since many of the circuits it contains are now familiar to the reader. However, we shall discuss some of its more important features.

THE CONVERTER: Using a high frequency PNP transistor (TR-1), the converter functions as both an RF amplifier mixer, by virtue of the tuned loop circuit, and as an Armstrong-type oscillator with the help of oscillator transformer L2 and tuning capacitor C1B. Negative base bias is provided through R2; R4 and C10 provide decoupling to prevent undesirable positive feedback.

THE INTERMEDIATE FREQUENCY AMPLIFIERS: These are normal common-emitter amplifier stages (TR-2, TR-3), except for two things:

(1) In order to prevent these transistors from oscillating as tuned-plate, tuned-grid oscillators, neutralizing capacitors are required. The two 5 pf capacitors (C15 and C16) provide exactly the

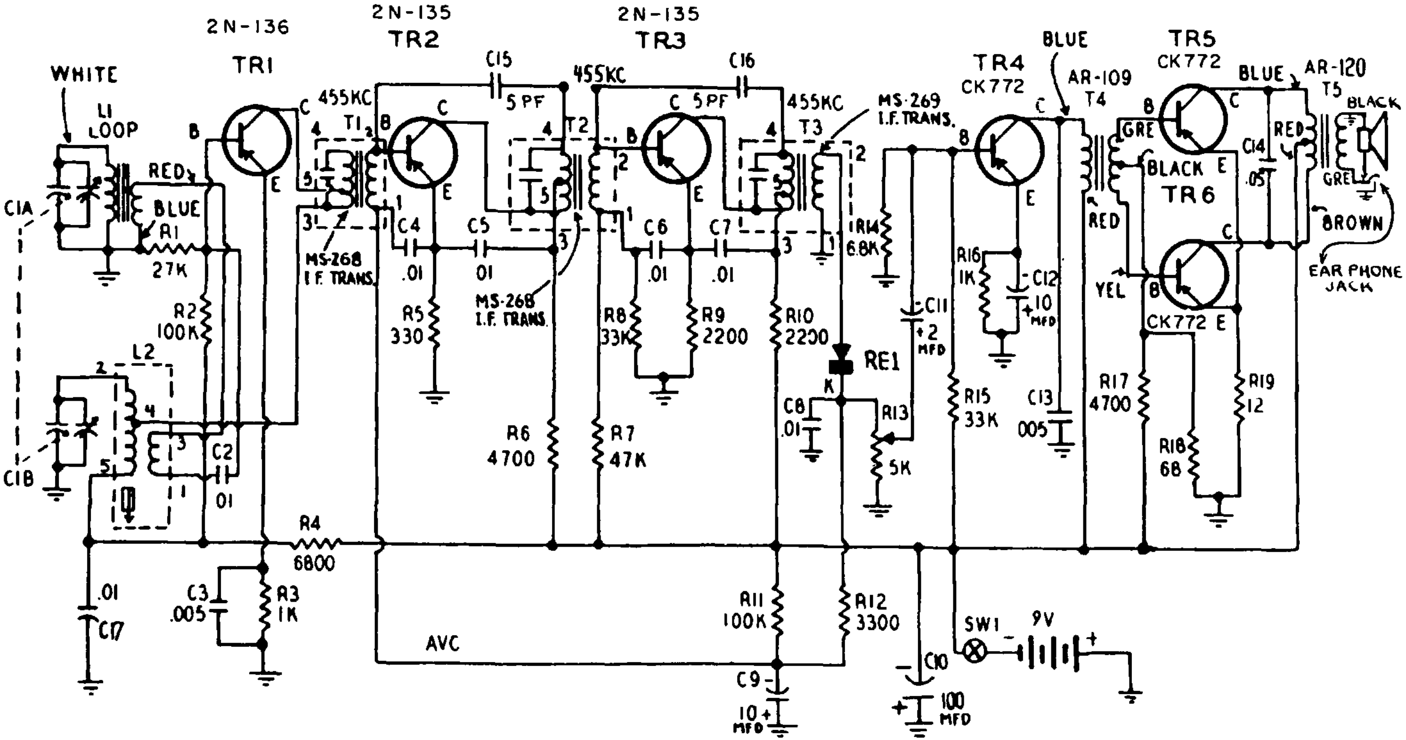


Fig. 7-17. A six-transistor broadcast receiver.

right amount of neutralizing capacitance to cancel the collector-to-emitter capacitance inside the I. F. transistors.

(2) Base bias for one of the two I. F. stages, TR-2, is AVC controlled. Note the AVC bus which runs to the TR-2 base.

THE SECOND DETECTOR: This receiver uses a diode detector (RE1) to demodulate the intermediate frequency signal and to develop the AVC voltage. The audio voltage is fed to the base of TR-4 from R13 and through C11. C11 is an audio coupling capacitor; note that its value is 2 microfarads, a much larger capacitance than is normally found in vacuum tube audio circuits. There is good reason for this large capacitance -- since C11 is in series with the very low input impedance of the transistor TR-4 (about 1000 ohms), its low-frequency reactance would be much too great if it were the usual .01 or .05 mfd capacitor encountered in vacuum tube coupling circuits. Remember that the input impedance to the grid circuit of a tube is in the order of 0.1 to 1.0 MEGOHM; this permits low-frequency response to be good, even with low capacitance couplers.

The DC AVC bias develops across C8 which, together with R12 and C9, comprises the AVC filter network. Note here again the extremely large value of C9 -- 10 mfd, in contrast with the .05 mfd capacitor one finds in vacuum tube AVC circuits. It will be remembered that the AVC system is a filter network that must have the correct time constant; should the time constant be too short, receiver gain is decreased by audio "wash-out". If the time constant is too long, the AVC action is slow and does not follow signal intensity variations closely. In a vacuum tube radio, the DC ground return from the AVC capacitor usually takes place through a resistor of at least 1 megohm. This yields:

Time constant = RC = 1.0 x .05 seconds
(R in megohms and C in microfarads) = .05 second.

In the transistor receiver, the ground return resistor totals approximately 8,000 ohms (R12 plus R13). This, in conjunction with a 10 mfd capacitor, gives a time constant = RC = .008 x 10 = .08 second, which is of the correct order.

THE AUDIO SYSTEM: This consists of a standard voltage amplifier driver (TR4) and an equally standard grounded emitter push-pull output stage.

MISCELLANEOUS APPLICATIONS

WIRELESS PHONO OSCILLATOR

A phono oscillator (Fig. 7-18) is always a welcome addition to the gadgets around the home, especially if it is fully portable and does not place too much of a drain on the batteries. The circuit

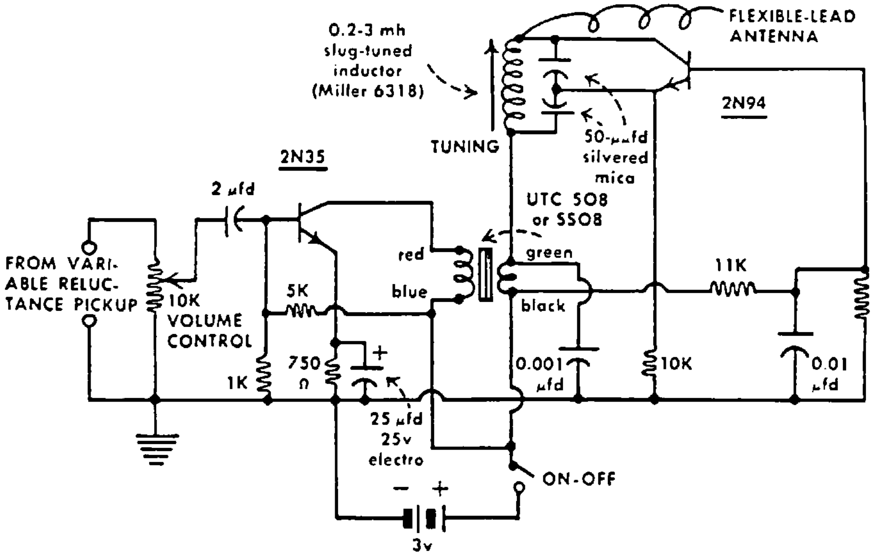


Fig. 7-18. A wireless phono oscillator.

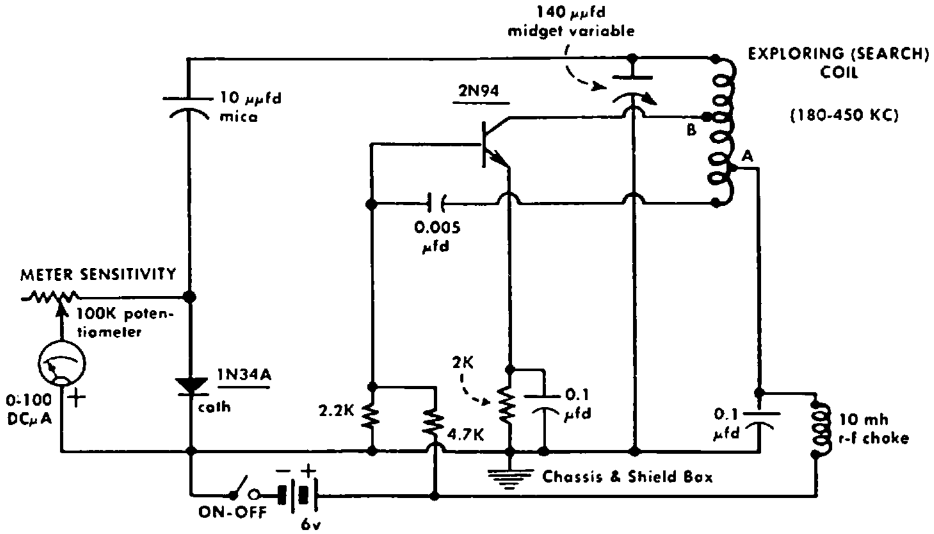
shown here is particularly effective and operates with excellent quality.

The RF oscillator is a Colpitts type with a split tank capacitor and a slug-tuned commercially available coil that resonates in the AM broadcast band. With a short length of antenna wire (four or five feet), the oscillator has more than enough power to give good reception on a receiver at the other end of a large room. The high-frequency transistor offers no oscillation problem in the broadcast band.

The audio amplifier has adequate gain to operate directly from a variable-reluctance pickup. A crystal pickup cannot be used directly because of its high impedance, but should give satisfactory performance if connected to the transistor input through a suitable step-down transformer. The amplifier circuit is quite conventional with stabilized voltage-divider base bias and emitter stabilization. Modulation of the RF carrier is accomplished by employing a miniature interstage transformer (T1). This is analogous to plate modulation in vacuum tube transmitters, since the collector current is varied by the changing audio voltage across the secondary of the transformer.

METAL LOCATOR

The metal locator (Fig. 7-19) described here is not satisfactory for finding metal objects buried deep under the soil. The RF output of the device is not great enough. On the other hand, it is a very



EXPLORING COIL SPECIFICATIONS:

230 turns No. 32 enamelled wire closewound on 4"-diameter, 2½" high form. Tap A 40 turns from low end. Tap B 100 turns from low end.

Fig. 7-19. A metal locator.

worthwhile gadget for the home owner because it will locate pipes in plaster walls, baseboard nails for determining the position of the wall studs, and the location of BX wall cables.

The oscillator uses a high-frequency transistor in a modified Hartley circuit. With the search coil shown, the oscillator tunes from about 150 kHz to 450 kHz. The indicator is a 0-100 DC microammeter which operates as an RF voltmeter with the assistance of a 1N34A crystal diode.

The basic principle of operation is this: The RF output of a low powered transistor oscillator varies substantially from one frequency to another. The meter is adjusted for a given reading - say half-scale - for one frequency. If the frequency is then changed by altering the inductance of the search coil, the RF output will then change either upward or downward, depending upon whether the tuned system has a higher or lower Q for the new frequency. Pieces of metal brought close to the search coil have just this effect -- they cause the oscillator frequency to change, thereby affecting the original meter reading.

The higher frequencies in the tuning range of this oscillator appear to be more effective in locating small metal objects like nails. In constructing the metal locator, all parts should be mounted very rigidly so that they cannot vibrate when the box is carried.

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